CRANFIELD UNIVERSITY

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# UNDERSTANDING THE EFFECTS OF PRODUCT MONITORING LEVELS ON MAINTENANCE OPERATIONS: A SIMULATION APPROACH

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# Understanding the effects of different levels of product monitoring on maintenance operations: A simulation approach

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# ABSTRACT

The move towards integrating products and services has increased significantly. As a result, some business models, such as Product Service Systems (PSS) have been developed. PSS emphasises the sale of use of the product rather than the sale of the product itself. In this case, product ownership lies with the manufacturers/suppliers. Customers will be provided with a capable and available product for their use.

In PSS, manufacturers/suppliers are penalised for any down time of their product according to the PSS contract. This has formed a pressure on the service providers (maintenance teams) to assure the availability of their products in use. This pressure increases as the products are scattered in remote places (customer locations).

Authors have urged that different product monitoring levels are applied to enable service providers to monitor their products remotely allowing maintenance to be performed accordingly. They claim that by adopting these monitoring levels, the product performance will increase. Their claim is based on reasoning, not on experimental/empirical methods. Therefore, further experimental research is required to observe the effect of such monitoring levels on complex maintenance operations systems as a whole which includes e.g. product location, different types of failure, labour and their skills and locations, travel times, spare part inventory, etc.

In the literature, monitoring levels have been classified as Reactive, Diagnostics, and Prognostics. This research aims to better understand and evaluate the complex maintenance operations of a product in use with different levels of product monitoring strategies using a Discrete Event Simulation (DES) approach. A discussion of the suitability of DES over other techniques has been provided. DES has proven its suitability to give a better understanding of the product monitoring levels on the wider maintenance system.

The requirements for simulating a complex maintenance operation have been identified and documented. Two approaches are applied to gather these generic requirements. The first is to identify those requirements of modelling complex maintenance operations in a literature review. This is followed by conducting interviews with academics and industrial practitioners to find out more requirements that were not captured in the literature. As a result, a generic conceptual model is assimilated.

A simulation module is built through the Witness software package to represent different product monitoring levels (Reactive, Diagnostics, and Prognostics). These modules are then linked with resources (e.g. labour, tools, and spare parts). To ensure the ease of use and rapid build of such a complex maintenance system through these modules, an Excel interface is developed and named as Product Monitoring Levels Simulation (PMLS).

The developed PMLS tool needed to be demonstrated and tested for tool validation purposes. Three industrial case studies are presented and different experimentations are carried out to better understand the effect of different product monitoring levels on the complex maintenance operations. Face to face validation with case companies is conducted followed by an expert validation workshop.

This work presents a novel Discrete Event Simulation (DES) approach which is developed to support maintenance operations decision makers in selecting the appropriate product monitoring level for their particular operation. This unique approach provides numerical evidence and proved that the higher product monitoring level does not always guarantee higher product availability.

Keywords:

Simulation, Maintenance, Monitoring level, Discrete Event Simulation, Product Maintenance, System, Process modelling.

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2- Alabdulkarim, A. A., Ball, P.D. and Tiwari, A. (2014). “Influence of Resources on Maintenance Operations with Different Monitoring Levels: A Simulation Approach”, *Business Process Management Journal*, vol. 20, no. 2, (In press).

3- Alabdulkarim, A. A., Ball, P.D. and Tiwari, A. “Assessing Asset Monitoring Levels for Maintenance Operations: A Simulation Approach”, *Journal of Manufacturing Technology Management*, (Revision submitted).

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1- Ball P. D., Tiwari A., Alabdulkarim A, Cuthbert R. and Thorne A. (2010). “Using Discrete Event Simulation to Investigate Engineering Product Service Strategies”. In *Proceedings of 8th International Conference on Manufacturing Research*, edited by V. I. Vitanov, and D. Harrison, 318-323. Durham, UK: Durham University.

2- Alabdulkarim, A. A., Ball, P.D. and Tiwari, A. (2011). “State of the art of Simulation Applications in Maintenance Systems”, In *Proceedings of the 44th CIRP International Conference on Manufacturing Systems,* Madison, Wisconsin, USA.

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4- Alabdulkarim, A. A., Ball, P. D., and Tiwari, A. (2012). “Examining the Effect of Spare Part and Labour Availability As Maintenance Constraints On Different Monitoring Levels”. *Operational Research Society Simulation Workshop 2012 (SW12),*edited by B. Tjahjono, C. Heavey, S. Onggo, & D.-J. van der Zee,192-199. The OR Society,UK.

# 1 INTRODUCTION

During the researcher's working period at the Al-Salam Aircraft Maintenance Company in Saudi Arabia, and his educational background (MSc in Logistic and Optimisation, BSc in Industrial Engineering), the researcher developed an interest in pursuing research towards a PhD. At various points in this development period, the researcher has been exposed to various distinct works involving Discrete Event Simulation (DES). Simulation modelling has always fired the researcher's attention and this powerful tool has been much appreciated. This area of research is exciting in that knowledge towards simulation can be further developed which can then be used in new fields.

Since the early stages of this PhD research, there has been a growing interest from research communities and producers to incorporate advanced services into their products offering (Baines et al,. 2011). From the middle of the 1990s, the inclusion of this integration solution has grown tremendously as companies take advantage of the potential development in integrated design and open standards in industries, and respond positively to market demands for more complex solution based products and services (Li, 2011). Over the last decade, a body of business strategy literature has identified the primary elements of integrated solution provision and shows how firms might reposition themselves by integrating forwards into the provision of services (Wise and Baumgarter, 1999; Oliva and Kallenberg, 2003).

This increase in awareness has caused the development of the Product Service System (PSS) principle whereby instead of the product sale itself, the focus is more on the sale of use and where the ownership of the product rests on the manufacturer/supplier (Mont, 2002a; Phumbua and Tjahjono, 2011). The aerospace division of Rolls-Royce is one of a few instances where major organisations have taken the initiative to put into practice the integration of the product and services; they are currently generating a large segment of their business revenues through availability-based maintenance contracts (Baines et al., 2013). Table 1-1 shows the differences between contract types according to the National Audit Office.

A business model, where contracts are based on capability and availability, offers purchasers products that are fit to use whilst the possible servicing and repair, should the products fail, are left with the manufacturers/suppliers. For PSS in particular, the product manufacturers are encouraged to give the product availability and danger of being penalised if they fail to do so. As such, it is necessary for manufacturers/suppliers to prepare a robust maintenance regime in servicing a customers' product in an effort to reduce breakdown time which in turn decreases compensation costs associated with breakdowns.

**Table 1-1 Types of Contract (adapted from National Audit Office, 2007).**

| Contract Type | What is the contract? | What is involved? |
|---|---|---|
| **Spare Inc.** | Contractor supplies spare parts. | Supplier and customer jointly responsible for repair/overhaul. |
| **Spares and Repairs** | Spares and repairs plus overhaul and repair. | Customer responsible for repair/overhaul. |
| **Contracting for availability** | Performance-based agreement. | Supplier delivers "fit for purpose" equipment.<br>Spares, resource provision maybe shared. |
| **Contracting for capability** | Supplier responsible for delivery of capability. | The customer does not own the equipment.<br>The risk and responsibility lies with supplier. |

This section of the introduction begins by reviewing the point of departure of the research. The scope of the thesis and the description of the research's aim and objectives will follow this. After this, the structure of the thesis is presented.

## 1.1 Point of departure

Manufacturers, consultants, businesses and researches have shifted their focus lately from manufacturing goods to offering services (Davies et al., 2007; Gebauer and Fleisch, 2007; Vargo and Lusch, 2008). As mentioned by Moussa and Touzanni (2010) in their literature review, service research has formed the largest focus area in major marketing and management journals from 2004 until recently.

Of late, the evolution of a new Product Service System (PSS) business model has emerged and this has been used in major organisations specialising in manufacturing. Based on studies by Mont (2002a), Manzini and Vezzoli (2003), and Baines and Lightfoot (2013), the definition of PSS is an integrated product and service that extends the traditional functionality of a product by incorporating additional services. The transformation from selling the products to offering PSS, means that products and services cannot be separated; this is called ‘servitisation’ of products (Almeida et al., 2008). In contractors’ terms, this kind of service is known as a capability contract whereby manufacturers are obligated to supply products that are worthy of being sold to purchasers for the agreed purpose, and the purchasers pay to use the product instead of its purchase (National Audit Office, 2007). Based on the available PSS literature, (e.g., Mont, 2002b; Alonso-Rasgado et al., 2004; Baines et al., 2007; Sakao et al., 2009; Greenough and Grubic, 2011), business models such as Rolls-Royce’s Power-by-the-Hour, and Xerox’s Document Management Solution are notably good cases of PSS. In the case of Rolls-Royce, which is an Original Equipment Manufacturer (OEM), an aircraft engine is sold along with the service and spare part support that are negotiated on the basis of the actual flying hours of the engine (Baines et al., 2009). Likewise, the Xerox PSS model is quoted as providing a new, expanded and integrated business solution that sees the integration of the products (photocopiers) and the services Xerox offers to support them (Baines et al., 2007).

One may question the relevance of adopting such a business model. It is important to identify the advantages of having PSS realised in the context of manufacturers/suppliers and customers. As mentioned by Mont and Lindhqvist (2003), adopting PSS in businesses is useful for consumers, producers, governments and the environment. The advantages stated in the literature for consumers, producers and governments are listed in Table 1-2.

**Table 1-2 Benefits of PSS on different stakeholders' levels**

| | For Customers | For Manufacturers | For Governments |
|---|---|---|---|
| **Benefits of PSS** | • Provide with value through more customisation.<br>• Provide higher quality of product.<br>• The service component is flexible, can also deliver new functionalities better suited to customers' needs.<br>• Remove administrative or product monitoring task from the customers to the manufacturer. | • Strategic market opportunities.<br>• Alternative standardisation and mass production.<br>• Improving total value for customer by increasing service elements.<br>• Competitive edge is enhanced.<br>• Environmental benefits are realised as the manufacturers become responsible for product-service through take back, recycling, refurbishment and waste reduction through the product's life. | • Lead to reduced resources used and reduced waste generated since fewer products are manufactured using fewer materials per use.<br>• Offset loss of jobs in traditional manufacturing through the increase of sales and services.<br>• Due to environmental issues governments favour PSS. |
| **Sources:** Goedkoop et al., 1999; Manzini et al., 2001; Mont 2002a; Cohen et al., 2006; Cook et al., 2006; Baines et al., 2007. | | | |

Despite all the advantages, PSS faces some challenges in its implementation. In adopting PSS, the main obstacles concern both customers and manufacturers: consumers may not be enthusiastic about ownerless consumption, and the manufacturers may be concerned with pricing, absorbing risks, and shifts in the organisation, which require time and money to facilitate (Baines et al., 2007).

Despite the potential advantages at various levels, there are manufacturers/suppliers who are not in favour of PSS, the main reason being the taking up of risk. In some cases, where manufacturers/suppliers are contracted to supply certain products to purchasers, manufacturers/suppliers still have to absorb any charges due to downtime. As a result, robust methods are required by manufacturers/suppliers to analyse and enhance their maintenance department for the provision of good service (Datta and Roy, 2011).

Usually, it is a requirement for the OEM to take risks for advanced product-centric services on product performance, availability, and reliability. The increased risks have led to the development of technological advances by the manufacturers in order to improve visibility of their products which are located remotely. These technological systems combine sensor and wireless technologies with signal processing and analysis techniques to identify the current and predicted ‘health’ of a product (Lightfoot et al., 2011). Technology is extremely important for manufacturers who implement the concept of PSS as it plays a leading part in providing customer services (Bitner et al., 2000; Froehle and Roth, 2004; Johnstone et al., 2009).

Maintenance plays a key role in product performance and availability. It is essential that the maintenance operation is effective and flexible to anticipate unforeseen circumstances so that product availability under PSS can always be guaranteed. The stock inventory for spare parts should be managed efficiently and rapid response time for maintenance must be kept to the minimum.

The definition of maintenance as described by Geraerds (1985), is “All activities aimed at keeping an item in or restoring it to, the physical state considered necessary for the fulfilment of its production function”. In the current competitive market, maintenance management plays an increasingly important role in challenging competition by reducing equipment downtime and associated cost and unscheduled disruption (Abdulnour et al., 1995). Ben-Daya and Duffua, (1995) described that the quality of the product dictates the importance of the maintenance function whereas Al-Najjar and Alsyouf (2003) stated that the purpose of maintenance is to improve the availability, safety requirements, and plant cost-effectiveness levels.

Saranga and Knezevic (2001) iterated that efficient maintenance on its own has economic objectives. As illustrated by Al-Najjar (1999) and Kothamasu and Huang (2007), the cost of maintenance accounts for significant amount of production costs. They mentioned that the expenses may increase substantially above the direct maintenance cost due to an inefficient maintenance policy. According to Peng et al. (2010), financial implication is borne by industries even though just a day of unscheduled stoppage may result in a significant amount of money. The majority of the expenses from production may be predetermined. However, maintenance is considered to be one of the main factors affecting cost and general performance enhancement (Al-Najjar and Alsyouf, 2003). The cost of production can be further reduced by minimising the cost of maintenance. In view of this, maintenance is regarded as an important aspect in the research focus.

As per the Rolls-Royce and Xerox examples, this study emphasises that maintenance services should be provided for products at customers' locations. It is therefore appropriate to draw attention to the latest capabilities of maintenance technologies which enhance product availability. A review of maintenance technology was undertaken by Lee and Wang (2008). According to them, maintenance technologies can be categorised as presented in Figure 1-1 below.

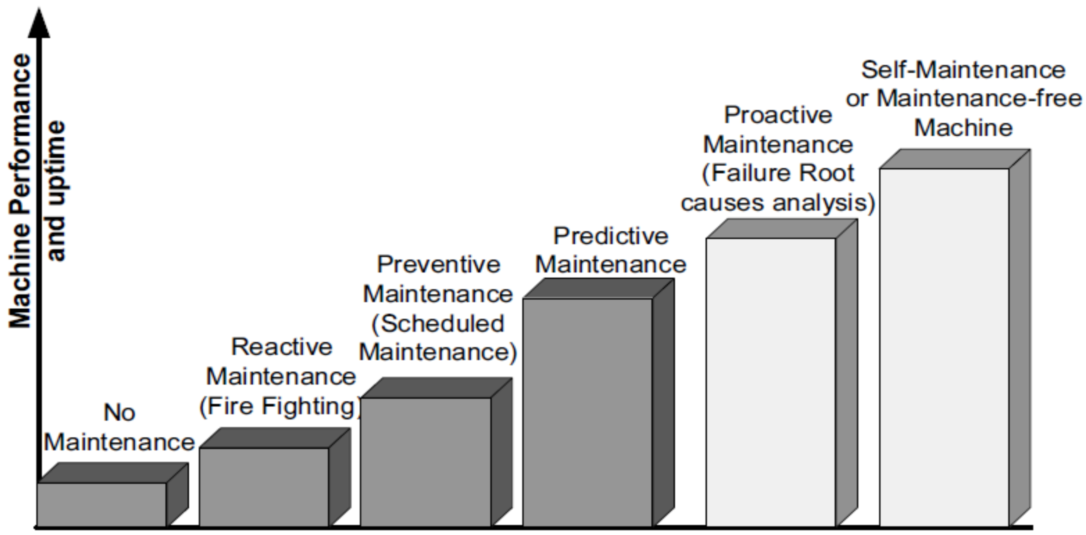


**Figure 1-1development of maintenance policies (from Lee and Wang, 2008)**

- **No Maintenance:** either it cannot be fixed or it is not economically viable to fix.

- **Reactive Maintenance:** This is the reaction to when the breakdown has occurred.
- **Preventive Maintenance (Planned maintenance):** to replace, service or even re-produce an article at a scheduled or adaptive period, not considering its state at that time.
- **Predictive Maintenance:** is a maintenance policy which is right-on-time. It depends on failure limit policy whereby maintenance is carried out only if the failure rate, or other reliability indicators of an article, reaches a pre-established level.
- **Proactive Maintenance:** entails any assignments that search for realising the seamless integration of judgment and prediction information and maintenance decision-making via wireless, Internet or satellite communication network.
- **Self-Maintenance:** it is anticipated that machines are capable of monitoring, diagnosing and repairing themselves in an effort to improve uptime.

The abovementioned advance maintenance policies analyse and consider the condition of the product upon failure through diagnostic sensors which is a successful application, or before failure through prognostics sensors that are able to warn about future failures; these are seen as the next frontier (Hess, 2002). However, according to Lee et al. (2006) such technology is inaccurate despite the effort being applied to improve these technologies.

Based upon the categorisation in Figure 1-1, Lee and Wang (2008) declared that improved machine performance and uptime is gained with sophisticated maintenance technology which, in turn, helps to reduce the related maintenance expenses (Greenough and Grubic, 2011). The reduction may well be from the perspective of equipment, for instance manpower, availability of spares and tools categorised under maintenance operation resources, all of which are presumably obtainable. The question is whether these technologies would have any significant consequences to the complex maintenance operation's performance, including the resources. In particular, the complexity of the maintenance operations would be aggravated in the case where the product itself is at the purchaser's site.

Maintenance operation is one of the main elements which affect the product's performance. Its operation is extremely difficult and complex, thus continuous assessment is vital to maintain the uptime and the availability of the product. Product performance is not limited to product reliability, but the wider system performance. Therefore, it is necessary for methods to dynamically capture and assess such a complex system. The assessment would include managing all the maintenance operations to include inventory and labour. As such, this operation ought to be simulated in order to have a broader understanding of how such an operation would behave. Simulation, in particular Discrete Event Simulation (DES), seems to be favourable in this respect as it has the ability to dynamically model such an operation with its resources.

Simulation is applied to demonstrate the behaviour and subsequent performance of systems over time (dynamically). Simulation has been used extensively in the modelling of manufacturing systems and it is being used increasingly for service systems. However, there is an absence of literature on the simulation of maintenance in service systems, especially maintaining products in use (where maintenance is carried out in remote places, i.e. the customer's site). Simulation models have been applied to maintenance (e.g. Altuger and Chassapis 2009; Ali et al., 2008) to increase production throughput in the manufacturing system's domain. There is, however, a gap in simulating maintenance for products in use where modelling maintenance activity and performance metrics are more complex, especially when implementing different levels of product monitoring (such as Diagnostics, and Proactive technologies) to ensure higher availability. But this raises the question of whether those technologies assure higher availability or better performance of maintenance operations?

It would seem intuitive that the more sophisticated the maintenance regime, the higher the product availability would be resulting in better performance against service contract metrics. As more is known about an product's performance, through increasing levels of product monitoring, it would be expected that the maintenance regime would enable better availability. However, initial investigations have shown this to not always be the case (Alabdulkarim et al., 2014). Products exist within a wider system and it is the performance of other parts of the system that influence availability as well (such as inventory, and labour availability). There has been little work carried out on the understanding of maintenance of products in a service system on the overall system's performance and even less on the use of simulation to support this analysis.

DES has been regarded as one of the most widely utilised methods in the field of operations management (Pannirselvam et al., 1999). The emphasis is to study how maintenance systems of products in use would behave with various stages of product monitoring from the operational perspective and not the product's view point. This would include the product itself, product location, labour, availability of spares, and comparison with various product monitoring levels etc. In evaluating the system's behaviour, DES is considered the most suitable instrument. Towards the later sections of this study, a discussion will be initiated on the various methods of analysis and the reasons for selecting DES against other methods.

## 1.2 Aim and Objectives

The aim of this research is to better understand and evaluate the complex maintenance operations of a product in use with different levels of product monitoring using discrete event simulation approach. Objectives are:

1- Establish current knowledge and practices in analysing the behaviour of complex maintenance operations for a product in use.

2- Assess the potential role discrete event simulation can play for such analysis.

3- Develop means of using discrete event simulation to understand the behaviour of complex maintenance operations.

4- Build and validate discrete event simulation models of complex maintenance operations of a product in use.

5- Compare different maintenance approaches (Reactive, Diagnostics, and Proactive) for complex maintenance operations for a product in use through simulation experimentation to better understand such systems.

## 1.3 Research Scope

This research focuses on evaluating the maintenance operations for products in scattered areas (remote customer locations), rather than maintenance in manufacturing systems where the production equipment is the focus.

After describing the maintenance technologies and discovering the question may arise, a decision has been made by the researcher to investigate the effects of remote product monitoring levels (namely Diagnostics, and Prognostics) on maintenance operations for products in scattered areas remote from the service provider (maintenance centre) over the traditional maintenance (Reactive). The product monitoring levels are defined as follows:

- **Reactive Maintenance (RM):** as described earlier, to react when the product has broken down, maintenance technician diagnose the product on site, check spares availability and then repair the product (traditional maintenance). This may require two visits from the technician, the first visit is to diagnose the product, and then another visit will be required when the technician gets the spare part if it is available, otherwise the technician will order a spare and when this becomes available he/she will make the second visit.
- **Diagnostics Maintenance (DM):** on failure the product diagnoses itself and sends feedback information to the maintenance centre. The technician will then travel to the product only when the spares are available so that he/she can repair the product (a type of proactive maintenance strategy).

- **Prognostics Maintenance (PM):** in this strategy the product predicts its failure before it happens. This minimises the downtime of the product (a type of proactive maintenance strategy).

This research will focus on simulating these maintenance strategies using a DES approach. The research will be looking at the wider system of complex maintenance operations which includes product number and location, technicians location, multiple failure modes, spare parts and their ordering policies, travel times, and product monitoring levels. The maintenance technologies will be restricted to RM, DM, and PM. DM and PM are types of condition monitoring strategies. The maintenance technician hereafter will be called “Labour” because this is the entity name in the simulation software representing maintenance technicians.

In specific cases, condition monitoring strategies can replace preventative maintenance regimes as the latter are more labour intensive, do not eliminate catastrophic failures, and cause unnecessary maintenance (Heng et al., 2009). It is now known that condition monitoring is more efficient than a preventative approach in maintenance, as the part will be changed according to its condition rather than the expected lifetime. This research seeks to understand the effects of different monitoring levels on the complex maintenance operations of products in use and consequently preventative maintenance will not be included in this study.

Predictive maintenance strategy is a part of proactive strategy (Swanson, 2001). As proactive maintenance represents different monitoring levels of diagnostics (the asset diagnoses itself) and prognostics (when the asset warns about future breakdown) then this will be included in the research investigation as a different monitoring level. This will be compared with RM where no monitoring is applied. The research is more about the maintenance operation’s performance and understanding the maintenance operation when different levels of monitoring technologies are applied rather than investigating the costs of the maintenance operation.

## 1.4 Thesis structure

This section aims to outline the structure of this thesis by illustrating the important issues in each chapter and showing how these are related to other chapters. Figure 1-2 maps the structure of the thesis. It also shows the inputs to the different stages of research, as well as the outputs (in terms of published work) of each phase.

Chapter 1 introduces the research motivation, point of departure, aim and objectives, and the thesis structure. This chapter seeks to introduce the reader to the topic area and describes why this research topic was chosen.

Chapter 2 makes the reader aware of the established previous knowledge. It starts with the methodology on how the literature review was conducted and then scopes the literature review. This chapter discusses the drivers to adopt product monitoring levels, and is followed by a discussion of maintenance approaches and definitions. A comparison is made of simulation techniques with other techniques and give reasons why simulation should be applied in such research. Finally, a systematic literature review is conducted of the application of simulation in maintenance research. From this, gaps in the current knowledge have been identified to formulate the research questions of this study.

Chapter 3 presents the research methodology and design in general. After this, methodological choices are made. It includes the selection of the research philosophy paradigm, as well as research methods, data collection techniques, and tools applied in the different phases of this research.

Chapter 4 develops the generic requirements to model a complex maintenance operations. This is initiated by discussing the methods of conducting a simulation study, followed by how to develop a conceptual model. Two approaches of gathering the generic requirements are applied; firstly, by analysing the peer reviewed papers, and secondly by conducting interviews with academic and industrial practitioners. As a result, this chapter outlines the generic inputs/outputs of such a complex maintenance operations that need to be simulated, and also shows how the generic conceptual design are developed and validated.

Chapter 5 discusses how the simulation modules are created to represent different product monitoring levels (Reactive, Diagnostics, and Prognostics). A description is then given of how and why an MS Excel interface is linked to Witness. This is followed by a presentation of a developed case study for the purpose of preliminarily testing the developed simulation tool.

Chapter 6 presents the testing and validation phase of the developed tool. A set of experimentation plans are defined followed by a description of three industrial case studies. An in-depth analysis and comparison of the experimentation on each case is made and discussed.

Chapter 7 presents the discussion of the entire thesis and provides  a cross case discussion. This chapter concludes by reviewing the research questions.

Chapter 8 where the conclusion of this research and the potential future work is presented. Follows by, contributions to the existing knowledge this study has added. as well as the lessons learned from this PhD.

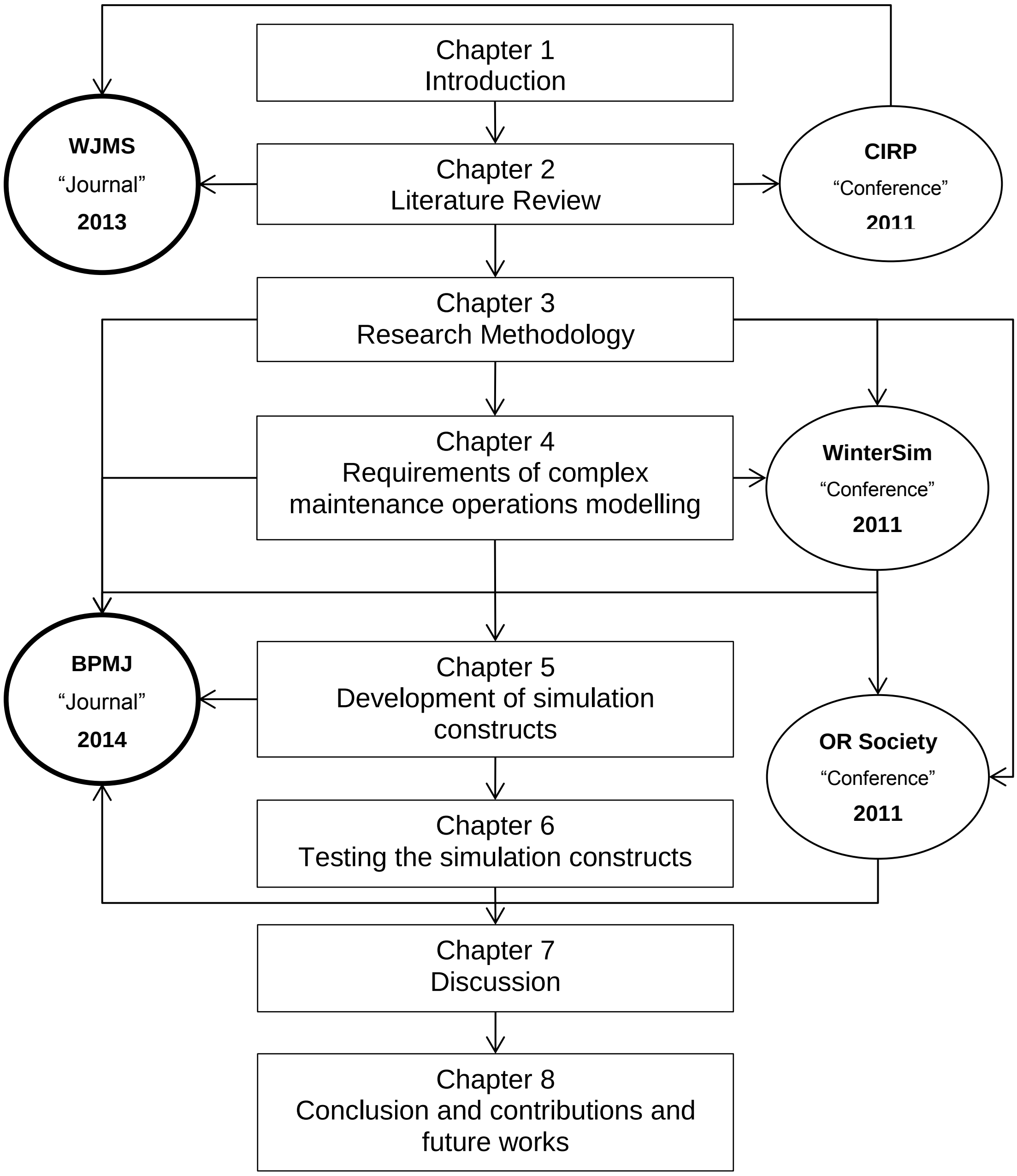


**Figure 1-2 Thesis structure and publication outputs**

# 2 LITERATURE REVIEW

## 2.1 Introduction

Undertaking a literature review is an important step in a research project. During the review “the researcher both maps and assesses the relevant intellectual territory in order to specify a research question which will further develop the knowledge base” (Tranfield et al., 2003). The literature review serves not only to give a background to the research, but also positions the research in a wider context and shows how the work relates to others.

To establish the generic scope of the literature review, few sections of this literature review followed key authors in PSS, maintenance, and simulation as well as familiar key words to establish the knowledge needed for the research. This step was to complement the systematic literature review which was carried out later in the specific area of simulation applications in maintenance research to determine the boundaries of the established work.

An organised procedure in the literature review was adopted to manage the number of papers published in this research area. The conventional method of narrative literature reviews could be affected by preconceived ideas or prejudices by the researcher (Mulrow, 1994; Denyer and Neely, 2004). The organised review theory, which was developed from medical research techniques, attracts interest and understanding in the area of management research (Tranfield et al., 2003; Denyer and Neely, 2004). Systematic reviews “bring together as many studies as possible that are relevant to the research being undertaken, irrespective of their published location, or even disciplinary background” (Thorpe et al., 2005). This has to be carried out in a manner that can enables clear decision-making during the review process, therefore, gives the opportunity for readers to assess the appropriateness of the studies included as well as the strength of the conclusion (Denyer and Neely, 2004).

This chapter will start by scoping the literature and the methodology used, followed by a detailed literature review description and comparison. After that, research questions were formed as a result of this comprehensive review.

### 2.1.1 Scoping the literature

The literature review for this research was selected in three broad domains: Simulation, maintenance approaches, and product monitoring levels. The fields have overlaps (e.g. simulation applications in maintenance) and these are also of interest to the research. Figure 2-1 shows the areas in which the main review was carried out.

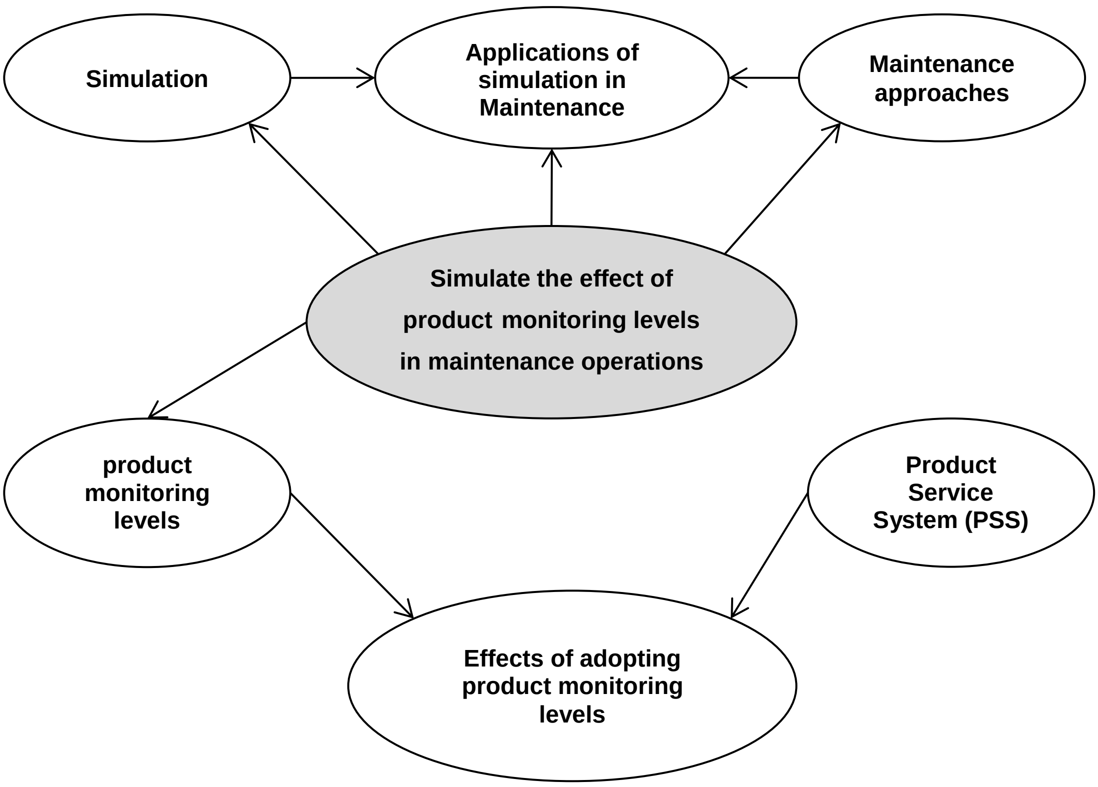


**Figure 2-1 Scope of literature review.**

The literature review is then scoped and structured as shown below:

- Monitoring levels: to address what the monitoring levels are, and determine why they are important to be adopted within products.
- Maintenance approaches: to address the approaches that organisations are applying to their maintenance operations.

- Simulation: determining simulation characteristics compared to other modelling techniques and thier application within maintenance research.

The literature review search included different keywords in various search engines to gain a wider collection of research papers. The keywords used were: simulation, maintenance, condition based maintenance, Product Service System, Prognostics, and Diagnostics. Search engines used were: Google Scholar, ABI (ProQuest), Scopus, Business Source Complete (EBSCO).

## 2.2 Background

Dealing with maintenance has been always regarded as a necessity in production to keep equipment in working order, safe to operate, and well configured to perform its task (Duffuaa et al., 2001). Simulation research has been always conducted to improve maintenance operations within a manufacturing context (Vineyard et al., 1999; Rezg et al., 2005; Gharbi and Kenné, 2005; Marquez et al., 2006; Savsar, 2006; Yang et al., 2007; Roux et al., 2008; Langer et al., 2010). Few authors have modelled maintenance using simulation outside a manufacturing systems context (Pruett and Lau, 1982; Agnihothri and Karmarkar, 1992; Deris et al., 1999; Cheu et al., 2004; Riberio et al., 2011).

Demands to integrate products and services have been rising recently as mentioned in the first chapter of this thesis. The rise of research in this area has led to new business models being developed that integrate the product and service such as the Product Service System (PSS), and the rise of capability and availability contracts.

In light of this, the need to evaluate maintenance operations outside a manufacturing systems context has been revealed. This is to ensure the performance of the products under such contracts is achieved, as well as to minimise the total operational maintenance cost. But, a question may arise to the reader regarding the key differences between maintaining manufacturing systems -production side- and maintaining products in availability and capability contracts. In manufacturing systems, maintenance is conducted in the same place where maintenance personnel maintain the production equipment of their organisation. In addition, access to the equipment is relatively easy, as in monitoring the users (production personnel). Breakdowns in such systems will affect production and the cost associated with it. Meanwhile, maintaining products under different maintenance contracts or business models that focus on product outcome or performance is different than the case of maintenance in manufacturing systems. First, the maintenance operation is more complex as it deals with different products at different locations with different customers. Access to the products for inspection is not easy. Product breakdowns affect the reputation of the product and the cost associated with breakdown as stated in their contracts.

In order to provide a higher product performance, there is a suggestion to implement monitoring technologies to monitor the current health of the product. The next subsection will discuss the drivers to implement such monitoring technologies on products.

### 2.2.1 The drivers to adopt product monitoring levels

The growth in the importance of services in traditional manufacturing organisations is reflected in the literature by a trend towards ‘integrated solutions’ or ‘PSS’ (Mont, 2002a; Cook et al., 2006; Davies et al., 2006). Various other terms have also been used to describe the increasing attention paid to developing service offerings, including ‘servicisation’ (Quinn et al., 1990), ‘servitization’ (van Looy et al., 1998), and ‘new manufacturing’ (Marceau et al., 2002). Product manufacturers have been urged to integrate services into their core product offerings if they are to maintain their competitiveness (Davies et al., 2006).

The literature also suggests several advantages of developing service strategies. Benefits for the provider are said to include services which are often more profitable than physical products (Cohen et al., 2006), as well as balancing the effects of economic cycles and in providing a more stable cash flow to organisations (Anderson et al., 1997). Companies such as IBM, GE and Siemens are often cited as examples of organisations which have attempted to capture attractive service revenues, and where services now account for the majority of the total revenues (Mathieu, 2001; Gebauer et al., 2004).

Nordin et al., (2011) mentioned that by offering such integrated solutions to customers, the risk of the maintenance cost is now being transferred to manufacturers/suppliers. As a result of providing customers with capable products, as in the case of PSS and availability contracts, maintenance operations is a key to the product’s performance. Researchers have suggested ways to reduce the maintenance cost or the cost incurred based on the down time of the equipment (Product) and have urged to a move towards e-maintenance. E-maintenance can be simply defined as a maintenance strategy where the tasks are managed electronically using real time equipment data obtained as a result of digital technologies (i.e. mobile devices, remote sensing, condition monitoring, knowledge engineering, telecommunications and Internet technologies) (Tsang 2002). From this point of view, e-maintenance is interpreted as a maintenance management process (Hausladen and Bechheim, 2004) which deals with the expansion of the volume of data available. This definition is refined by Moore and Starr (2006) in the following way: ‘‘E-maintenance is an asset information management network that integrates and synchronises the various maintenance and reliability applications to gather and deliver asset information where it is needed, when it is needed’’.

Lee et al., (2006) described the reactive and preventative strategies that are often implemented in maintenance as a waste. They urged toward using new sensing technologies, such as Prognostics, which monitors the actual health of the product. Banks and Merenich (2007) and Lightfoot et al., (2011) advised using product health monitoring technologies as this leads to improved maintenance actions which will in turn lead to a higher availability of products as well as feedback that could improve the design of the product (Lightfoot, 2011). Figure 2-2 illustrates the benefits of adopting product monitoring as it will help to improve maintenance decisions as well as feedback to design teams enabling improvement to the product design.

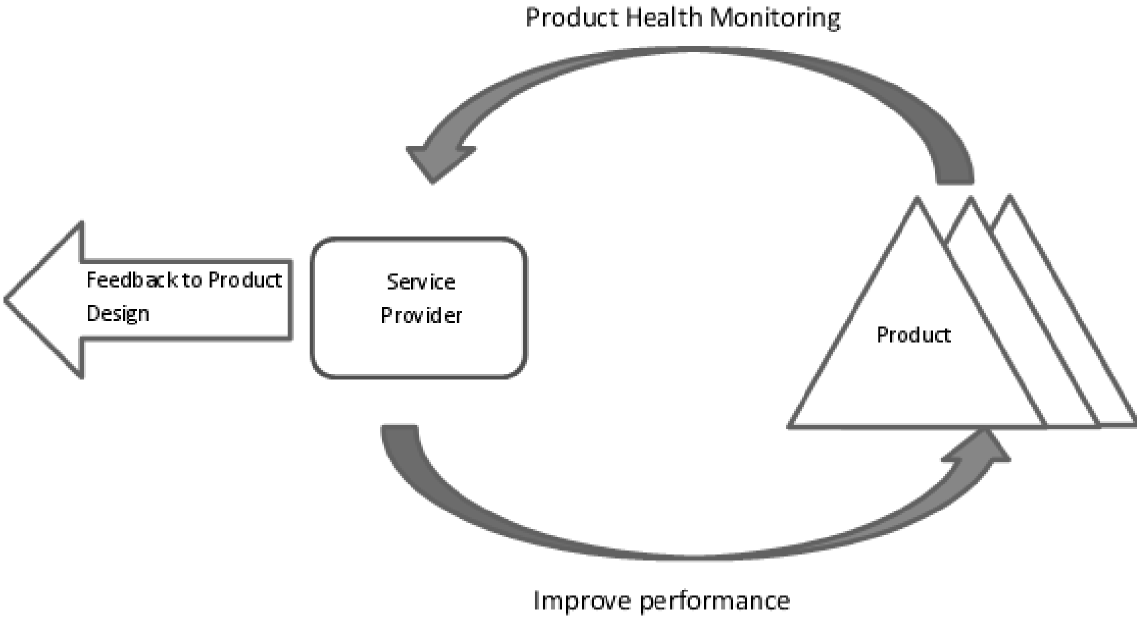


**Figure 2-2 Benefits of product monitoring**

Kothamasu et al., (2006) described system health monitoring as a set of activities performed on a system to maintain it in operable condition. Monitoring may be limited to the observation of the current system condition, with maintenance and repair actions prompted by these observations. Alternatively, monitoring the state of the current system is augmented with the prediction of future operating condition and predictive diagnosis of future failures. Such predictive diagnosis or prognosis is motivated by the need for manufacturers and other operators of complex systems to optimise equipment performance and reduce costs and unscheduled downtime. Prognosis is a difficult task requiring precise, adaptive and intuitive models which can predict the condition of the machines future health.

These above mentioned reasons were to show the importance of implementing such technologies to monitor the product remotely. Prognostics and Health Management (PHM) and Integrated Vehicle Health Management (IVHM) (Rajpathak et al., 2012; Esperon-Miguez et al., 2013) are examples of extensive technological research on how to apply such monitoring on existing products.

However, many studies has focused on the technological aspect of monitoring technologies rather than managerial ones (Saccani et al., 2013). Literature review lacks an assessment tool to enable decision makers to select the level of asset health monitoring suitable for their specific maintenance operation (Fan et al., 2013; Alabdulkarim et al., 2014).

## 2.3 Maintenance approaches

Maintenance plays an important role in product availability. A failure in equipment or facilities not only results in loss of productivity, but also in a loss of timely services to customers, and may even lead to safety and environmental problems which damage the company's image (Alsyouf, 2007). Choosing the right maintenance activity, or the right combination of activities, is significant in ensuring the product's availability and its overall performance.

Literature shows different categories of maintenance approaches that have been applied to different maintenance operations. This section will describe these approaches and clear the confusions that could occur due to the unclear definitions of some of these approaches. By reviewing different maintenance papers and books, the researcher can describe these approaches as follows:

1- Reactive maintenance: These maintenance activities take place only when a breakdown happens (Kothamasu et al, 2006; Lee and Wang, 2008). This is also called Failure-Driven Maintenance (FDM) (Moubray, 1997).

2- Proactive maintenance: as the name suggests, it does not wait for the equipment to fail. Therefore, it is a combination of Preventive and Predictive maintenance (Swanson, 2001; Lee and Wang, 2008). This approach can be divided into the following approaches as shown in figure 2-3:

    a. Preventive maintenance: this includes inspections and routine maintenance activity for equipment (such as lubricating, cleaning, changing of filters, etc.) as well as maintaining the equipment based on the Mean Time Between Failures (MTBF) to prevent expected breakdowns. However, this could incur unnecessary maintenance as it is based on historical data (Swanson, 2001; Kothamasu et al., 2006) this is called planned maintenance as the maintenance activities are planned in advance, also known as Time-Based Maintenance (TBM) (Gerëtìsbakh, 1977).

b. Predictive maintenance: this anticipates when a repair will need to take place and plans can be made to this effect using equipment monitoring technologies. Thus, the actual time of failure is predicted rather than expected based on MTBF (Niebel, 1994; Eade, 1997).

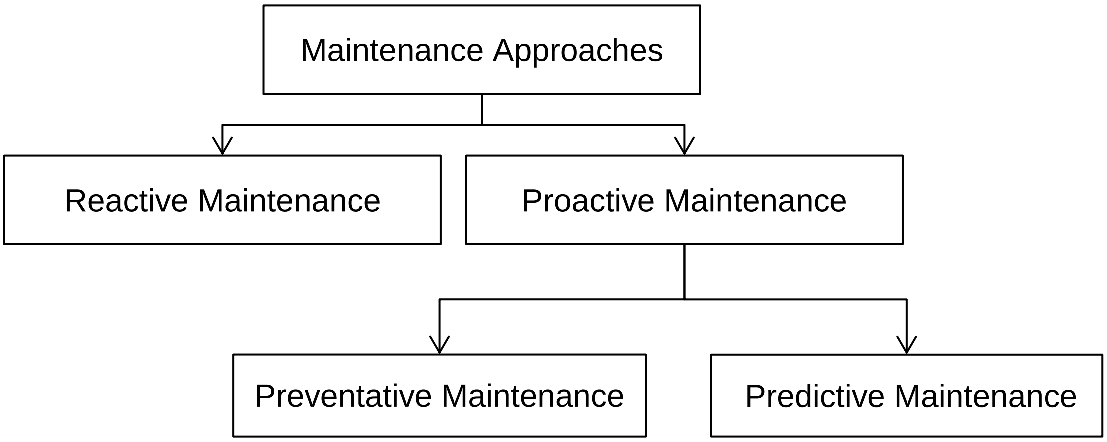


**Figure 2-3 Maintenance approaches adopted from (Kathamasu et al, 2006)**

As defined earlier, preventive maintenance includes routine inspection and also anticipates the repair based on Mean Time Between Failure (MTBF) data which is represented by statistical distributions of historical data without using sensing monitoring. Most models make an effort to apply distributions of historical data and assumed these will represent the system. This assumption is unconvincing as the whole data history is considered. In fact, systems could change modes due to various reasons, including unknown reasons, which are not directly related to the machines (Khalil et al., 2009). Predictive maintenance also known as Condition-Based Maintenance (CBM), which is a monitoring strategy based on the real time diagnosis of impeding failures and the prognosis of the future health of the equipment (Peng et al, 2010). The monitoring technologies are divided into two levels; Diagnostics and Prognostics (Banks and Merenich, 2007; Greenough and Grubic, 2011).

Diagnostic technologies enable service providers to quickly identify the cause of breakdown, whereas manual diagnosis takes up half of the maintenance time in some applications (Niebel, 1994). As this application is successful, researchers tend to build on this and apply prognostics technologies to enable the evaluation of the actual health of the asset and warn of future breakdowns (Greenough and Grubic, 2011).

In order to maintain equipment effectively and cost efficiently, a maintenance strategy should be selected to suit the need. Therefore, organisations tend to apply Reliability-Centred Maintenance (RCM) or Total Productive Maintenance (TPM) to formulate the most suitable maintenance approaches to best serve their businesses.

Maintenance communities have applied Reliability-Centred Maintenance (RCM) to allow the selection of an appropriate maintenance strategy for their equipment. Moubray (1997) defines it as “a process used to determine the maintenance requirements of any physical asset in its operating context”. Tsang (1995) added that RCM is a controlled methodology to determine the maintenance requirements of any physical asset in its operating context.

Smith (1993) stated that the core objective of RCM is to maintain system function. As a result, the random maintenance activities which are not cost effective should be eliminated (Anderson and Neri, 1990). The RCM process involves investigating the way equipment fails, and assesses the consequences of each failure while choosing the correct maintenance action to ensure that the desired overall level of the equipment’s performance (availability, reliability) is met (Smith, 1993). Therefore, it is a structured methodology and a unique process which is used to develop optimum equipment maintenance plans (Ochoa and Wendell, 1995).

RCM consists of two main tasks; one is to study and classify failure modes based on the effect of the failure on the system; and the other is to examine the maintenance schedule and reliability influence (Kothamasu et al., 2006). Applying RCM has benefits, as outlined by Moubray (1997), which are as follows:

- Improving the understanding of how assets work.
- Better understanding of how assets can fail.
- Greater safety and environmental protection.
- Improved operating performance (output, product quality, and customer service).
- Greater maintenance cost-effectiveness.
- Longer useful life of expensive item.
- A comprehensive maintenance database.
- Greater motivation of individuals.

TPM is a maintenance management philosophy which was established by Japanese manufacturers to back the just-in-time manufacturing implementation, to advance manufacturing technologies, and to support the efforts toward improving product quality (Swanson, 2001). It concentrates on eliminating; equipment failure, set-up and adjustment time, idling and minor stoppages, reduced speed, defects in process and reduced yield (Macaulay, 1988). TPM is described by Maggard and Rhyne (1992) as a partnership approach to maintenance. In TPM, small teams build a relationship based on cooperation between production and maintenance which supports the success of the maintenance work. Furthermore, production workers collaborate in carrying out maintenance activities which allows them to perform a role in monitoring and maintaining the production equipment and this improves their skills and allows them to be more active in maintenance (Swanson, 2001).

RCM and TPM formulise an important structure within maintenance management (Hipkin and De Cock, 2000), which is defined as “all activities of the management that determine the maintenance objectives, strategies, and responsibilities . . .” (Swedish Standards Institute, 2001). TPM was established for the manufacturing sector, while RCM was originally established for the aviation industry; both are now widely applied in different industries. TPM combines production operators within maintenance activities and enabled continuous improvement to maximise the overall equipment performance. The essential objective is robust processes that are free from disruption (Nakajima, 1989). However, TPM cannot be applied on complicated physical assets, RCM focuses more on technology and offers a sound basis for evaluating maintenance requirements in this context (Geraghty, 1996). RCM can be described as “a systematic approach for identifying effective and efficient preventive maintenance tasks, by means of function and risk analysis” (Hansson et al., 2003).

According to Alabdulkarim et al., (2014) RCM and TPM techniques can provide a deeper understanding of the technical aspects of maintenance activities; for example, identifying the cause of the failure modes and how to improve Mean Time Between Failure (MTBF) by selecting the appropriate maintenance strategy. In addition, the severity and consequences of a breakdown can be specified. Usually the decision is made on whether or not to adopt Condition Based Monitoring (CBM) technology based on the experience of maintenance personnel and managers as well as assessing the maintenance data gathered. TPM and RCM on their own are unable to provide a quantitative ‘what if’ analysis for decision making by taking a dynamic system level view rather than a local asset view. This being the case, simulation has the ability to do so, and is therefore suggested by the researcher as an appropriate approach for deciding upon a suitable monitoring level to be applied. The next section will highlight why simulation is the nominated technique to be applied.

## 2.4 Maintenance Simulation

### 2.4.1 Modelling and Simulation

Law and Kelton (2000) stated that in order to study a system, an experiment has to be carried out with the real system or by testing a model of the real system. This can be achieved by designing a physical model or by means of a mathematical model. Engineers in general, prefer to utilise mathematical models as these models can be broken up into analytical or simulation models (see Figure 2-4).

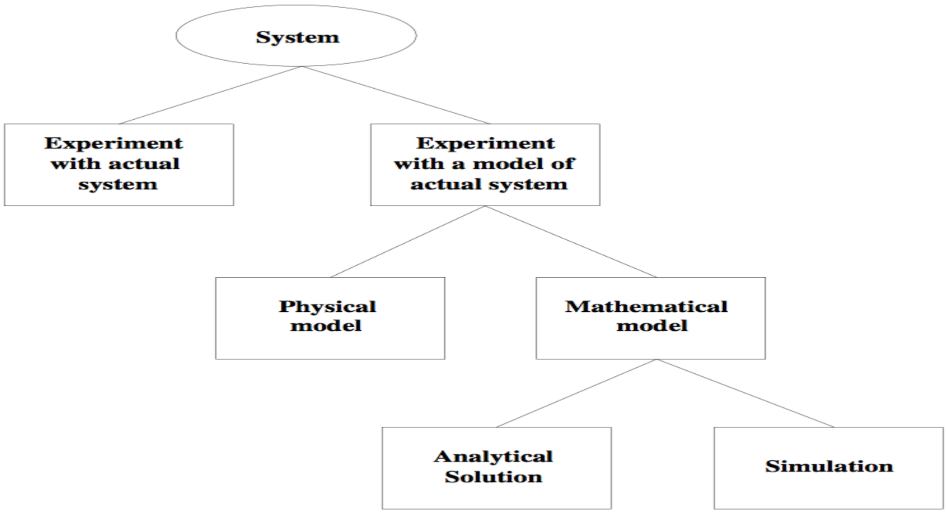


**Figure 2-4 How to study a system (Law and Kelton, 2000)**

In order to select the best modelling approach for this research, it would be appropriate to highlight a few different modelling approaches. Various mathematical modelling approaches have been widely utilised in academic researches. Techniques such as Queuing Theory have been employed as an analytical instrument for varieties of applications, e.g. telephone conversations, aircraft landing, repair of machines, and taxi stands (Gross and Harris, 1998). When humans are part of the system, Queuing Theory considers them to act in a definite way to satisfy the controlled queue assumptions, and the customers clearly understand the system they are in as well as its operation (Warwick, 2009). In addition, it always assumes that the arrival and service times have particular distributions (Robinson, 2004). Developing queuing systems for analytical models often turns out to be very difficult for various reasons such as input or characteristics of service mechanisms, complexity of the system design, nature of queuing discipline or a combination of all these factors. Furthermore, if the probability distribution varies with time, then it may be impossible to generate analytical solutions and for such problems, simulation appears to be the right tool (Gross and Harris, 1998).

The definition of simulation by Robinson (2004) is “Experimentation with a simplified imitation of an operations system as it progresses through time, for the purpose of better understanding and or improving that system”. Some other modelling methods vary from simple paper calculations, through spreadsheet models to more difficult mathematical programming and heuristic approaches (such as linear programming, dynamic programming, simulated annealing and genetic algorithms). Winston (1994) mentioned that queuing theory gives a specific class of model that looks at similar situations to those often represented by simulations, arrivals, queues and service processes. Furthermore, according to Robinson (2004) there are various reasons why simulation would be utilised in preference to these other models. These reasons are then explained as follows:

- **Modelling Variability**: simulations have the capability to model variability including its effects, which some other methods are unable to perform. (It is worth noting that some approaches in modelling may be adapted to take into consideration the variability, however, this will always increase the complexity.) If the modelled systems are exposed to many levels of variability, then simulation is usually the only method for an accurate performance prediction. It is impossible for some systems to be analytically modelled. Robinson and Higton (1995) contrasted the results from a ‘static’ analysis of alternative factory designs based on a simulation. The variability in the static analysis, caused mainly by the failures of the equipment, was taken into account by averaging their consequences into the process cycle times. The variability in the case of simulation was modelled in more detail. Though the static analysis forecasted that all designs would achieve the expected throughput, none of the designs were acceptable from the simulation aspect. It is therefore important to carefully consider the variability when attempting to forecast the performance.

- **Restrictive assumptions:** simulation requires some assumptions, if necessary. Alternatively, other techniques require certain assumptions. For example, queuing theory assumes certain distributions are to be used for arrival and service times whereas simulation allows any statistical distribution to be applied.

- **Transparency**: managers who have to resolve a set of mathematical equations or complex spreadsheets may face difficulties in understanding or trusting the outcome of the model. In this sense, simulation is more acceptable as animations of the system can be produced, thus making it easier for non-experts to understand the model and be more assured. As listed by Pidd (1998) and Robinson (2004), simulations have a few advantages, which are:

- Lesser risk and safer,
- Time, it can simulate weeks, months or even years within a few seconds of computer time,
- Cheaper than conducting real life experiments,
- Can be repeated,
- Experimental conditions can be easily controlled, in comparison to a real life scenario.

Simulation can be categorised into two different approaches namely; Continuous and Discrete, with each approach having different uses. In a continuous approach, the simulation simulates the values which gradually change and are not isolated and the values used are available all the time within the simulation (Pidd, 1998). This continuous simulation has been utilised in various applications, for instance, economics, i.e. during modelling the behaviour of economic systems using a few differential equations, as well as in the field of Engineering (Pidd, 1998; Robinson, 2004) and Biology (Robinson, 2004).

Sterman (2000) defines System Dynamics (SD) as a specific form of continuous simulation which represents a system as a set of stocks and flows. SD is applied at strategic levels where less operational details are required (Borshchev and Filippov, 2004).

There are many applications of this system; it is especially helpful for reviewing strategic matters within organisations (Robinson, 2004). There are instances where system dynamics could be utilised in place of a Discrete Event Simulation (DES), or vice versa. As an example, both are utilised to simulate a supply chain (Anderson et al., 2000; Jain et al., 2001) and matters pertaining to health care (Lane et al., 1998; Taylor et al., 1998).

Discrete Event Simulation (DES) is the term used for discrete simulation utilising a powerful computerised system based on the assumption that time only exists at determined points, and that events will only take place at these points which need to be previously scheduled (Pidd, 1998; Robinson, 2004). In order to simulate an operations system, DES is one of the most widely used approaches (Pannirselvam et al, 1999). However, if a system is required to be modelled in details, DES is more suitable than the system dynamics particularly if individual items have to be traced within the system (Robinson, 2004). DES is more effective for detailed modelling while SD is stronger with regard high level modelling. SD is abstract and does not capture individual transactions (machine breakdown, arrival of parts, etc.), and therefore detailed modelling cannot be achieved.

However, there is another simulation technique known as Agent-Based Simulation (ABS) defined by Shannon (1975) as the process of designing an ABS of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/ or evaluating various strategies for the operation of the system. In ABS, a complex system is represented by a collection of agents that are programmed to follow some (often very simple) behaviour rules. System properties emerge from its constituent agent interactions (Bonabeau, 2002). This technique has been always compared to DES and the questions raised was when to apply ABS or DES. The next table (Table 2-1) shows the comparison between the two approaches (DES and ABS).

**Table 2-1 Comparison between DES and ABS approaches (adapted from Siebers et al., 2010)**

| DES approach | ABS approach |
|---|---|
| Process oriented (top-down modelling approach); focus is on modelling the system in detail, not the entities. | Individual based (bottom-up modelling approach); focus is on modelling the entities and interactions between them. |
| Top-down modelling approach. | Bottom-up modelling approach. |
| One thread of control (centralised). | Each agent has its own thread of control (decentralised). |
| Passive entities, that is something is done to the entities while they move through the system; intelligence (e.g., decision making) is modelled as part in the system. | Active entities, that is the entities themselves can take on the initiative to do something; intelligence is represented within each individual entity. |
| Queues are a key element. | No concept of queues |
| Flow of entities through a system; macro behaviour is modelled. | No concept of flows; macro behaviour is not modelled, it emerges from the micro decisions of the individual agents. |
| Input distributions are often based on collect/measured (objective) data. | Input distributions are often based on theories or subjective data. |

According to the above comparison in table 2-1, ABS is more into social behaviour modelling rather than process modelling. In the area of this thesis modelling different product monitoring levels is a key requirement to be modelled with its different processes. Also, entities such as spare parts and tools (maintenance tools that are used during repair activities taking place) are a passive entities as they move through the system as they are modelled as a part of the system. Based on the above mentioned reasons, the decision was made by the researcher to apply DES approach.

### 2.4.2 Suitability of Simulation for Maintenance Operations

One of the main motivations for developing a simulation model or using any other modelling method is that it is an inexpensive way to gain greater understanding when the costs, risks or logistics of manipulating the real system of interest are prohibitive. Simulations are generally employed when the complexity of the system being modelled is beyond what static models or other techniques can usefully represent (Fishman, 2001; Kellner et al., 1999).

In order to discuss the need for simulation in the workplace there are a few concepts which need to be understood. First on the list is the need for variability. The variation could be predictable as in the call centre example, where the number of operators is changed to meet the changing demand of the callers throughout the day. The variation of the system could be unpredictable, such as the breakdown of equipment in a flexible manufacturing cell. These two types of variation exist in most operation systems.

Secondly is the concept of interconnectivity. Most operation systems are interconnected with the components used in the system and are not isolated from each other. but interconnected with their performance affecting one another. Changes which occur in one part of the system can lead to changes in other parts of the system. An example of where this can occur is when one machine is set to work faster than the others. This scenario can lead to a reduction of the work in progress upstream while at the same time can lead to a build-up of parts downstream.

However, it should be noted that there exists a degree of difficulty in predicting the effects of interconnectivity on any system, with the level of difficulty increasing as the level of variability increases. The third aspect of simulation which needs to be understood is that of complexity. In regard to simulation modelling there are two main types of complexity which need to be considered for any system and they are ‘combinatorial complexity’ and ‘dynamic complexity’. As the names suggest, combinatorial complexity can relate to the number of components which are present in the system or it can relate to the combination of all the system components. Combinatorial complexity can be present in some systems but not in all. A good example of where this type of complexity occurs in a traditional job shop environment where if the number of machines increase, so does the potential level of interconnections. Dynamic complexity, however, is not related to size and it occurs due to the interactions between system components over a given time period. This type of complexity can occur in small as well as large, systems and, furthermore, systems which possess a high level of interconnections are most likely to display this type of complexity.

“Most operations systems are interconnected and subject to both variability and complexity (combinatorial and dynamic)”. Many operations systems are interconnected and subject to both variability and complexity (combinatorial and dynamic). Because it is difficult to predict the performance of systems that are subject to any one of variability, interconnectedness and complexity, it is very difficult to predict the performance of operations systems that are potentially subject to all three. However, this is not the case with simulation. Simulation models are able to take into account any or all three conditions and as a result simulation can be used to accurately predict system performance, to compare alternative system designs and to determine the effects of alternative policies on system performance. Also, the combination of modelling variability and interconnectedness means that complexity in a system can be represented by a simulation model (Robinson 2004).

Maintenance operation is the type of operation system that contains variation, interconnectivity, and complexity. These can be represented in the research problem domain through machine locations and breakdown patterns and labour locations and their skills related to each type of failure. In addition, it deals with the spare parts related to each failure type and also spare part ordering policies (e.g. lead time, minimum order quantity, and safety stocks). All of this mixed interconnectivity makes this type of operation system a dynamic, complex one.

Several authors have reported the suitability of applying simulation, and have come to the conclusion that the main characteristics of simulation are as follows:

- Provides quantitative information for decision making,
- Analyses the dynamic interdependency of activities and entities within the process,
- Conduct ‘What-if’ experiments,

- Enhancement of corporate capabilities to achieve an in-depth understanding of the internal process performance and correct allocation of resources (Fathee et al., 1998),
- Simulation can be used to analyse process change or to design a completely new process and test the future behaviour of the real system (Alboras-Barajas, 2007),
- Incorporates the stochastic nature of business processes and the random behaviour of their resources (Irani et al., 2000),
- Allows the participation of non-technical staff since it gives a highly visual display of the process and its operation and hence can be used as a training tool (Robinson, 2004),
- Enables a detailed analysis before incurring the risk of making major changes to existing processes or implementing new processes (Jones, 1995),
- Allow a greater understanding of the key drivers in resource management and increased dependability in terms of the decisions made (Dennis et al., 2000).

The problem this research seeks to investigate is the complex processes of maintenance which need to be understood. DES offers a set of built-in entities that would help to model some of the requirements of the problem for example, labour, machines, and breakdowns which form of the main aspects of maintenance activities. However, combining the whole maintenance system to include different failure modes with their related spares and tools and locations needs to be developed. The breakdown which will be modelled is not a straight forward breakdown which is offered in most of the DES software. In a Reactive process, labour and tools need to be available to travel to the product in order to diagnose it and then the availability of a spare part related to that failure needs to be checked. Other monitoring levels (Diagnostics and Prognostics) would skip the diagnostic step and assume that the failure is known in advance. In this case, labour and tools would only travel to the product when the spare is available. In the Prognostics case, the model would need to trigger the labour, tools, and the spare part required in advance of the breakdown.

### 2.4.3 Reported Simulation application to Maintenance research

This section is dedicated to report simulation applications in maintenance research. According to Andijani and Duffuaa (2002) the purpose of simulation studies in maintenance systems has been classified, evaluated and categorised into: (1) Organisation and Staffing, (2) Evaluation of Maintenance Policies, (3) Maintenance Planning and Scheduling, (4) Spare Parts and Material Management, and (5) Shutdown Policies. These five categories are extended by this review. In their review category (5) has only one reference and this review retrieved more papers due to the passage of time and key words used. Therefore, a revised categorisation was developed by Alabdulkarim et al., (2013) incorporating (1) to (4) and adding four others. The new categories reflect a wider review and diversity of the research and were developed using keywords and objectives within the papers. The keywords were used to establish clusters and these were iteratively revised to ensure they were exclusive to one another and could capture all the areas of maintenance in a small number of categories. This section will highlight the most relevant applications of simulation in maintenance systems for each category (for the full list of papers and their categorisation please refer to Appendix A). There are two main types of simulation application in maintenance systems:

- The first application is the use of simulation without optimisation for comparison, evaluation, and validation purposes,
- The second application combines simulation models with optimisation techniques to optimise a given problem.

The definitions of each category given, as described by Alabdulkarim et al. (2013) are presented next.

#### 2.4.3.1 Maintenance Policies

Maintenance policies are defined as the components of the framework for maintenance, e.g. proactive, reactive, etc. Maintenance policies are identified as the main research focus. Two policies that are commonly considered by simulation are reactive/corrective maintenance and preventive maintenance (Wang, 2002).

The review shows a dominant focus on evaluating traditional maintenance policies, such as preventative and corrective maintenance, within the manufacturing boundaries. One such example is the development of a DES model to evaluate several performance measures in order to determine optimum operating policies given resource failure (Albino et al., 1992). Here different maintenance policies were assessed in order to better understand their impact on the overall system performance of a multi-stage manufacturing line. This work, and that of Finger and Meherez (1985), Banerjee and Burton (1990), Dekker and Smeitink (1991), Kaegi and Kröger (2009) and Boschian et al., (2009) focused on the preventative and corrective maintenance policies.

One of few examples which tackled non-traditional maintenance policies is Gong and Tang (1997) who evaluated the on-line monitoring of random breakdowns of a machine at a manufacturing plant. This and other papers lacked insight into the implication of such policies on maintenance operations.

Apart from manufacturing systems, few papers compared maintenance policies in different settings. Chasey et al. (2002) developed a simulation framework to understand and quantify the impact of deferred maintenance on highway systems while Crocker and Sheng (2008) developed a DES model to compare different maintenance policies applied to high value, repairable assets. As with other literature on maintenance, their comparison concentrated mainly on preventative and corrective policies.

One of the few cases of combining simulation with other techniques was Hennequin et al (2009) who proposed a method based upon fuzzy logic and simulation-based optimisation to optimise defective preventive maintenance and remedial steps carried out at single equipment level.

It is evident from the reviewed papers that the main focus of the research conducted on maintenance policies using simulation is within the manufacturing systems' boundaries. Maintenance policies associated to products are relatively disregarded using simulation. All of the policies were compared and evaluated in terms of their impact to resource allocations, performance, and cost. The emphasis of the policy evaluation was on traditional maintenance. No papers investigated the use of prognostics technology to warn of the next expected product breakdown or the organisational response to breakdown. In light of some businesses moving from selling products to services, there is a lack of understanding on how to evaluate different maintenance policies for products, such as after sales services, or maintenance contracts. The main focus is on the production side and whilst this is important, evaluating maintenance policies are neglected for products in service that significantly influence performance. Maintenance is important to ensure that production flows smoothly to avoid unexpected stoppages, however, evaluating maintenance policies for the products sold is essential as this will influence the reputation of the manufacturer/supplier.

#### 2.4.3.2 Maintenance Scheduling

Maintenance scheduling describes the timing of activities. It is not restricted to preventative maintenance, as it covers scheduling reactive maintenance and associated maintenance resources. Scheduling maintenance activities is an important area where organisations could save time and money. A number of authors have looked into maintenance scheduling using simulation for validation or comparison purposes such as Percy and Kobbacy (2000); Baek (2007); Aissani et al. (2009); and Celik et al. (2010). These papers range from looking into preventative maintenance scheduling to reactive scheduling and at times a combination of the two. The focus is generally on preventative maintenance scheduling.

Condition-Based Maintenance (CBM) and its implications to scheduling maintenance activities has been neglected except for the research conducted by Baek (2007) that examined how CBM could influence the reduction of unnecessary preventive maintenance activities to reduce time and cost. CBM assesses the product condition through real-time monitoring and this could have a significant impact on scheduling maintenance activities for reactive as well as preventative policies. His study shows that the intelligent maintenance scheduling approach proposed does not necessarily guarantee an optimal scheduling policy. However, from a mathematical point of view, it is verified through a simulation-based experiment that the intelligent maintenance scheduler is capable of providing a good scheduling policy that can be used in practice.

Cavory et al. (2001) optimised a preventative maintenance schedule for single line production using simulation. This is one of a few examples where simulation is combined with an optimisation technique. Apart from within the manufacturing boundaries, few papers have tackled this aspect. Cheung et al (2005) incorporated Genetic Algorithms (GA) to look into aircraft service scheduling by using simulation as a technique to verify their proposed method. Cheu et al. (2004) proposed a method to optimise the scheduling of highway maintenance in order to reduce the travel time of vehicles during lane closures. Their objective was to minimise the travel time incurred by these closures using GA for maintenance scheduling combined with traffic simulation.

Scheduling is an essential activity as it influences cost and time through reducing unnecessary preventative maintenance. The literature shows that significant research has been carried out in applying simulation to maintenance scheduling within manufacturing systems and how that would impact the stoppage of production lines, while research into the scheduling of maintenance activities beyond the production side has been very low. Manufacturers/suppliers are now focusing on enhancing their products' performance at customer locations through effective maintenance. CBM has the capability to influence scheduling activities as it predicts the future failure of an asset through diagnostic and prognostic technologies. There is an absence of literature regarding CBM’s influence on reactive/correction maintenance scheduling using simulation beyond reducing preventative activities within manufacturing systems. Scheduling plays an important role in reducing costs and enhancing product performance through maintenance response time.

#### 2.4.3.3 Condition-Based Maintenance

Condition-Based Maintenance (CBM) monitors the condition of a system based upon constant supervision or checking so as to ascertain necessary maintenance before any forecasted breakdown (Grall et al., 2002). Most papers published in this category simulated machine deteriorations, with the emphasis on machine reliability using continuous simulation (Barata et al., 2002; Marseguerra et al., 2002; Coolen-Schrijner et al., 2006; and Caesarendra et al., 2010). The core of the literature took a manufacturing system’s perspective and there was no wider discussion of CBM strategies to monitor products in use or enhancement beyond reactive strategies. Only Vardar et al. (2007) designed a queuing-location model to assess the adequacy of after sales service providers through information from remote diagnosis tools. While assuming the consequences of congestion, the model optimises the place, capability and the service centre category by means of a simulation optimisation based on genetic algorithms.

One research paper in the literature has looked into combining CBM as a maintenance policy and the spare part levels (de Smidt-Destombes et al., 2006). They stated that a maintenance policy, spare part levels, and repair capacity can control the system availability. They presented two analytical approaches to evaluate system availability. Their DES model showed the trade-off between inventory, repair capacity, and maintenance policies for the proposed approaches. This work is one of the few to combine different operational settings instead of the common research practice where each setting is modelled in isolation. Nevertheless, they have not covered all the operational settings, e.g. labour availability. As the complexity of the operational system increases the application of analytical models will be more problematic (de Smidt-Destombes et al., 2006).

There is potential to apply DES techniques to evaluate different maintenance strategies incorporating all the maintenance operational settings, such as product location, spare part levels, labour availability, travel time to asset, etc., rather than using hard analytical models. The DES approach will enable organisations to choose the appropriate maintenance policy (reactive, proactive: where CBM is introduced) which is suitable for their use from an operational point of view rather than a machine reliability view. The DES technique will enable researchers to have an understanding of the overall dynamic operation.

Research papers in this category commonly use analytical models. Simulation, was applied mainly as a comparison technique between different models. There are cases where a CBM simulation technique was utilised and recent situations which show the way prognostic technologies are employed in forecasting equipment breakdowns. This appears to be suitable as simulation is an operation performance assessment technique. There are gaps in identifying the performance of maintenance control systems in the move from reactive maintenance to CBM. Papers in this category investigated CBM from equipment and technical points of view. CBM enhancement in the context of maintenance operations using simulation, and in particular DES, is lacking.

There is potential to use DES as a tool to analyse the performance before and after implementing diagnostics and prognostic technologies. DES could evaluate the level of improvement that diagnostic/prognostic technologies can offer over reactive maintenance. This applies to manufacturing systems as well as instances where maintenance is carried out at a customer's site.

#### 2.4.3.4 Maintenance Cost

Whilst the papers across most maintenance categories used in this research are developed to reduce or optimise the maintenance cost in one way or another, papers falling under this category were those that focused primarily on cost or the assessment of cost.

Boussabaine and Kirkham (2004) presented an innovative simulation based technique utilising a maintenance cost model for a sports centre and argued that the building maintenance expenditure can account for a considerable proportion of the entire life span expenditure. Similarly, Dessouky and Bayer (2002) introduced a simulation designed with an experimental modelling approach in order to reduce buildings' maintenance costs. One of the few examples on warranty service was created by Rao (2011) who developed a Decision Support System (DSS) for repair/replace decisions using the criterion of the expected cost of servicing the remaining warranty. Rao then used simulation to verify the effectiveness of the proposed DSS. Others have looked into maintenance costs in terms of equipment reliability in manufacturing systems (e.g. Heidergott, 1999; Iwamoto and Kaio, 2008).

Maintenance costs were investigated through different maintenance categories. For example, Chang et al., (2007) applied simulation to investigate the trade-off between maintenance personnel levels and production line throughput, while da Silva et al., (2008) developed a simulation tool to calculate the cost associated with maintenance in a food plant.

As with other maintenance categories, the main focus of the literature is manufacturing systems. Nevertheless, Lanza and Raül (2009) developed a method to enable manufacturers to support their products through service. Their method enables manufacturers to calculate the costs of service contracts during the offer phase. Costs will be determined by Monte Carlo simulation in order to estimate the uncertain forecast. Their research is one of the few in the literature that has incorporated simulation to calculate maintenance contracting.

Most maintenance research aims to reduce costs by either reducing direct maintenance cost, or through improving machine performance to increase productivity as in da Silva et al (2008). Interestingly, with the introduction of CBM technologies where remote monitoring is possible, there are no apparent discussions on the cost of introducing such sensing technologies for products in use. A question must be raised on the cost efficiency of introducing such technologies for the service contracted product, such as the case in PSS.

Maintenance cost optimisation is being investigated through other tools such as linear and non-linear programming (Tam et al., 2006; Adeyefa and Luhandjula, 2011). It is perceived to be more suitable when dealing directly with cost but there appears to be limited simulation-based assessment. However, simulation techniques have the ability to model system complexity and the key variables that form the cost drivers in turn evaluate the overall system performance over time. Therefore, simulation is able to capture the complexity and dynamics to investigate the detail of the cost performance drivers rather than provide cost only as an output.

#### 2.4.3.5 Maintenance Reliability and Availability

According to Blank (2004) “the reliability of a process, product, or system is the probability that it will perform as specified, under specified conditions, for a specified period of time”. Also, he defined availability as “the percentage of time a product or process is ready for use without expenditure of additional effort or unplanned waiting”. Simulation covers evaluation and optimisation of reliability, with emphasis on the evaluation of the reliability and availability of an operating system. Several authors used simulation to assess reliability (for example, Greasley, 2000; Ciarallo et al., 2005; El Hayek et al., 2005; Ke and Lin, 2005; Basile et al., 2007; Chew et al., 2008).

Boulet et al. (2009) suggested a multi-objective representation which employs a corrective and preventive model to reduce maintenance expenditure whilst capitalising on the availability of the system. Most papers have applied simulation to support their proposed methodologies. Manufacturing system reliability dominates published papers in this category, except for one published by Greasley (2000) who assesses the reliability of a train depot maintenance facility to enable the service provider bidders to have a greater understanding.

Simulation modelling has an enabler role in proposed methodologies or analytical models of system reliability. There is potential for more research to be conducted on the application of simulation to be combined with optimisation techniques on reliability.

#### 2.4.3.6 Maintenance Staffing (Resource levels and allocation)

Deciding the number of staff required to conduct maintenance activities efficiently plays an important role. Differing skills between workers and the number of workers will impact on the maintenance costs and asset availability.

Researchers have focused on evaluating staffing configurations in isolation. Al-Zubaidi and Christer (1997) created a simulation model for a specific hospital complex to investigate the potential gain to be realised by using different manpower management and operational procedures. They argued that simulation modelling is a suitable tool for analysing complex manpower problems in the area of building maintenance. Mjema (2002) developed a simulation model to analyse the influences of the flexibility and exchangeability of personnel (i.e. location flexibility) in decentralised maintenance centres. The work focused on the effect of the skills and number of personnel on the throughput time, equipment downtime and capacity utilisation of personnel. Mjema argues that the location flexibility of personnel is the main factor which affects the capacity utilisation of the personnel, throughput of the work order and downtime of the equipment. Many published papers focus away from production systems where the staffing will be critical due to the complexity involved in travel time and skills (e.g. Agnihothri and Karmarkar, 1992; Duffuaa and Andijani, 1999; Antoniol et al., 2004; Agbulos et al., 2006).

Most of the authors did not consider the effect of spare part availability on manpower requirement or utilisation. In most cases, if the spares are not available then nothing can be done to repair the machine even if the personnel are available. One of the few papers who discussed staffing requirement and spares planning was Shenoy and Bhadury (1993). They looked into the effectiveness of manpower resources and spares requirement planning through an application for a subsystem of a thermal power unit using simulation. Literature is limited on manpower requirements for more complex maintenance operations where the maintenance centre deals with different customers in different locations. One of the few examples of studying the staff resources in very complex maintenance operations beyond the manufacturing systems is Ribeiro et al. (2011). They presented a simple simulating annealing algorithm to solve a scheduling problem for the workover rigs for onshore oil wells. Finally, Duffuaa and Andijani (1999) present a model to integrate all sub-systems in the maintenance operations for an airline company. Although their integration is complex, it was only created conceptually.

As can be seen from the literature review, staffing requirements have been investigated. The introduction of modern technologies of monitoring levels will have an impact on the staffing requirements but the literature is limited from this perspective.

#### 2.4.3.7 Maintenance Operations Performance

Evaluating and analysing the maintenance performance using simulation has focused mostly on the up-time and down-time of machines. Simulation has the ability to model such complex operations and evaluate their performance. This category, unlike other categories of maintenance, is focused outside manufacturing systems.

Pruett and Lau (1982) stated that DES is the right tool to understand and evaluate performance measures in complex systems, such as highway maintenance operations. They incorporated different dynamic interactions in the system (such as labour and trucks required) while they neglected the impact of inventory on such operations. Louit and Knight (2001) developed a simulation model to improve mine maintenance. The fundamentals of an integrated simulation model for SAUDIA airlines were illustrated by Duffuaa and Andijani (1999). In their study, they described planning and scheduling, organisation, supply, quality control and performance measurement modules that made up the integrated model. Along a similar vein, Bengü and Ortiz (1994) proposed a new integrated maintenance operation for a telecommunications system and compared this against the existing maintenance operation using simulation. However, the comparison was limited to manpower requirement and service level.

Agnihothri and Karmarkar (1992) developed a model to evaluate the performance of field maintenance and tested their proposal by employing simulation. From this review, it was noted that little research has been conducted in field maintenance. The objective of the maintenance provider may differ commercially from that of the asset operator. This could mean that different elements of the maintenance operation would be measured and optimised independently.

All of these examples tackle the evaluation of maintenance operation performance. Some focus either on the staffing requirements (Pruett and Lau, 1982; Bengu and Ortiz, 1994), scheduling (Hani et al., 2008), or understanding the system's behaviour (Mattila et al., 2008).

Implications of monitoring technologies on maintenance performance using simulation was generally ignored. Of the few papers published, Simeu-Abazi and Bouredji (2006) modelled the predictive maintenance of equipment in a manufacturing environment although they did not address a proactive approach which depends on the actual feedback from the equipment via wireless as in diagnostic/prognostic applications.

Papers in this category focus on field maintenance: There is a lack of research into the value that DES can provide to understand the behaviour of complex field maintenance operations with multiple combined components (such as asset location, asset utilisation, staff availability, and stock) and discern the influence on the performance of maintenance operations (especially in field maintenance) on scheduling, delays, location of parts, travel time, etc.

#### 2.4.3.8 Maintenance Inventory

Analysis of the inventory of spares for maintenance is the focus of many papers as the inventory is a sensitive area with regards to cost.

Authors used simulation to assess spare parts management. Dhakar et al. (1994) presented a stock level policy for high value, low demand parts and used simulation to determine the parameters of the replenishment policy. Additionally, Lau et al. (2006) studied a multi-echelon repairable item inventory system under the phenomenon of passivation (where serviceable items are ‘switched off’) upon system failure. They proposed an efficient approximation model to compute time-varying availability that is validated by Monte Carlo simulation. Other authors have looked into a maintenance inventory with a simulation and optimisation combination (e.g. Petrović et al., 1982; Kumar and Vrat, 1994; Lin and Chien, 1995; Rezg et al., 2005; Wang et al., 2009) but the instances of this application area were very few. In general, the control systems modelled were simplistic and confined to simple reorder point types.

Chua et al. (1993) formulated a mathematical model for batching policies for repairable (overhauling) spare parts and then examined these policies by simulation. In most cases the inventory system was open-loop except for Chua et al (1993), where the spares inventory was consumed and left the model on failure. Discussion of closed-loop inventory systems is lacking, where the failed part is repaired and returned to storage as would be the case in Maintenance, Repair and Overhaul (MRO) systems, typical in aerospace and defence sectors. More specifically, interaction is not covered of such policies with other system elements, e.g. labour and the introduction of CBM. Whilst there may be examples of modelling the MRO operation in isolation, there is a lack of understanding of stock modelling for the maintenance of assets where the spares stock is recharged using MRO functions.

## 2.5 Gap Analysis

In the light of the above literature review, there are intentions to move towards an emerging business model such as Product Service System (PSS) where availability and capability contracts are applied. This has led to the manufacturers/suppliers of the product facing enormous pressure in the maintenance of their product. Unlike before, maintenance is a revenue generator for the product suppliers. This motivates the researcher to look for tools to evaluate and improve maintenance operations for products which are located in different customer locations.

Products are used by customers and are provided by the suppliers who need to ensure that these products performed satisfactorily. The need for monitoring the health of these products has increased, thereby necessitating product suppliers to respond effectively towards product faults in order to reduce the breakdown time and achieve the contracted service level. Product monitoring is being applied in high value products, such as aircraft engines. Product health monitoring has different levels according to Kothamasu et al. (2006) and Greenough and Grubic (2011) namely Diagnostics and Prognostics. Diagnostics identify the product failure and sends feedback of the fault to the maintenance provider whereas Prognostics is an advanced level of monitoring where the sensing technologies predict the failure and send the feedback to the maintenance provider in order for them to act accordingly before a breakdown occurs.

It is often difficult for companies to decide whether product monitoring levels are required for their operations. And, if it is required, which level of product monitoring should be selected. Banks and Merenich (2007) and Lightfoot et al., (2011) have regarded that the higher the asset monitoring the higher product performance will be achieved. But evidence for this in practice is limited and no quantitative techniques have been applied to prove this. To maintain a product, different maintenance resources needs to be available such as labour, tools, spare parts, and means of travel to the product’s location. Based on these resources and their availability, different levels of product health monitoring will have different impacts on maintenance operations. In this case, quantitative tools need to be developed to integrate these maintenance resources with different levels of product health monitoring to enable suppliers to decide which level is applicable for their operations.

Maintenance operations to maintain a product in use is certainly a Business Process (BP) as sets of activities are performed to serve a customer. It has been argued in this chapter that Discrete Event Simulation (DES) is a suitable technique used to evaluate and improve BP. Also, according to Pannirselvam et al., (1999) DES is one of the most widely used techniques to evaluate and improve operations management. Organisations currently tend to decide on the level of health monitoring for their products depending on the severity of the breakdown consequences. DES can offer decision support for organisations to help them select what type of monitoring level is suitable for their particular needs taking into account all resources that are normally used in maintenance operations.

Looking at simulation applications in maintenance research in this chapter indicates that the focus is on maintenance within the manufacturing plant. Simulation to maintain products is rarely applied although simulation has been used in isolation in other subsystems of maintenance operation. The integration of labour and their skills, tools, spare parts in inventory and their ordering policies, plus the location of the product has not been addressed which forms the whole basis of the maintenance system. In addition, there is an absence in the literature of modelling different monitoring levels and their implications towards maintenance operations. In light of this, the researcher argues that DES can be used as a new approach to support organisational decisions when determining which level of product monitoring should be selected to particular maintenance operations. DES has the ability to capture the dynamic behaviour of such a complex maintenance system. Therefore, it is a suitable approach in supporting organisations in their selection of which level of monitoring to use for their products.

In order to develop a generic simulation decision tool which integrates the wider system of maintenance operations, a set of generic requirements needs to be known. The literature review shows a lack of knowledge on the conceptual requirements of maintenance operations of products in use.

In order to fill this gap, it has to be decided whether DES could be a decision support tool for organisational selection in determining which product monitoring level is suitable for their complex operational needs. Firstly, a set of requirements to simulate a maintenance system is required. Additionally, the level of detail to be modelled in such a simulation study needs to be determined in order to integrate all operational requirements that effect the decision. Secondly, build the generic simulation tool which represents these generic requirements. Subsequently, a set of experimentations will be conducted to test and validate the developed approach.

## 2.6 Research Questions

**RQ1-** How can the behaviour of a complex maintenance system for product monitoring levels be simulated? (Obj 2, Foundation for Obj3)

> ***SRQ1.1-*** *What are the generic requirements for modelling complex maintenance operations for products in use taking into account the wider system (equipment, labour, spare part, etc.)?*
>
> ***SRQ1.2-*** *What is the conceptual model of complex maintenance operations of product in use?*

**RQ2-** How can discrete event simulation models be created to capture the behaviour of complex maintenance operations? (Obj 3, Obj4)

**RQ3-** Can discrete event simulation identify differences in the product's dynamic performance in complex maintenance operations with different monitoring levels? (Obj 5)

The next chapter will address different research methodologies in general and then select the most suitable research methodology and endeavour to answer the research questions which have emerged.

# 3 RESEARCH METHODOLOGY

## 3.1 Research Methodology Overview

The present research is intended to appreciate and appraise the complex maintenance operation of a product currently in use. This is performed with various levels of processes to monitor the product by means of discrete event simulation. By adopting these processes and by developing a simulation tool, it will support decision makers in companies to select the most suitable monitoring level. As such, in this chapter the researcher will draw attention to the philosophical standpoint of the research and justify the methodology applied in this research.

In general, the research is divided into two categories; namely, basic or fundamental research and applied research. The latter is described as the study undertaken to address a known problem by applying the recommendations of that particular study. Basic research, on the other hand, is carried out merely to contribute towards certain knowledge (Sekaran and Bougie, 2010). Given that this PhD thesis takes into account the importance of its potential contribution towards knowledge, it can therefore be categorised into a basic (fundamental) type of research. The terms - Research Methodology and Research Design- tend to create a misunderstanding as some perceive these two terms to mean the same. The latter offers a system to collect and interpret the data whereas the former only deals with the way the data is collected (Bryman and Bell, 2007). Yin (1994) meanwhile offers a definition of Research Design as a sequence of logics which relate the data obtained empirically to a study's initial research questions and finally to the conclusion. Karlsson (2002) clarifies that the methodology is aimed to convince readers that the study has been properly planned and undertaken. From the empirical data collected, analysis of the data is done and conclusions are drawn in a way that ascertain the study's reliability and validity in order  to determine the quality of the study.

## 3.2 Research Philosophy

Research philosophy can be interpreted as the fundamental belief concerning the world around us. According to Burrell and Morgan (1979), two assumptions; namely, 'Ontology' and 'Epistemology' form the thinking pattern of these beliefs. Ontology relates to the real world or the natural world. The existence of the social phenomena, as perceived by the realist, is not dependent upon its social participants. As such, the subject of ontology will result in the appreciation of knowledge. On the contrary, the study of epistemology is considered as learning the knowledge and studying what is regarded as valid knowledge. The responses to questions about how things actually work and the most effective way to acquire knowledge lie with epistemology (Lincoln and Denzin, 1994).

It is important to appreciate the research philosophy so as to facilitate in the selection of the appropriate research design. It demonstrates the connection between the theory and the data and therefore aids in determining the research design (Easterby-Smith et al., 2012). According to Neuman and Kreuger (2003), the philosophical stance can be categorised into four key paradigms; namely, positivism, post-positivism, realism and lastly constructivism. The essential features of each type are tabulated in Table 3-1 below. Nevertheless, at one extreme, the positivist emphasises that only observable and measurable phenomena can be sensibly considered as knowledge. The substantiation that can be measured on which positivism depends has a high level of control over the phenomena. Conversely, constructivism endeavours to comprehend the phenomena from the participants' perspective that are directly related to the concerned phenomena (Collins and Hussey, 2003).

The results of this study will represent the truth behind the complex maintenance operations of products in operation. Since the collected data are historical and numerical in nature, the result of this research cannot be manipulated by human factors. Furthermore, the researcher is not related to the subject being examined and has no interaction whatsoever with the study.

Since the results from the study are considered objectively, this particular research is categorised under the Positivist paradigm.

**Table 3-1 Research philosophy paradigms (Lincoln and Denzin, 1994).**

| | Positivism | Post-positivism | Realism | Constructivism |
|---|---|---|---|---|
| **Ontology** | ‘Real’ reality but questionable | ‘Real’ Reality but only imperfectly | Virtual reality shaped by social, political, cultural, and economic values | Local and specific constructed values |
| **Epistemology** | Objective point of view | Findings probably objectively true | Both subjective and objective points of view | Subjective point of view |

In an effort to develop the research design for this particular study, the method as recommended by Blaxter et al. (2010) was adopted. Three principles have been identified under this method when constructing a proper design framework; namely, research family, research approach and data collection.

## 3.2.1 Research Family

As identified by Jankowicz (2000), the research approach is regarded as “a systematic and orderly approach taken towards the collection and analysis of the data so that information can be obtained from those data”. The three most renowned forms of approaches to research are qualitative, quantitative and a mixed method. The selection among these forms takes into consideration the research objectives and aim. The following section will discuss the key attributes and will endeavour to compare them.

### 3.2.1.1 Quantitative Approach

A quantitative method of research as explained by Nau (1995), is a method that inclines to evaluate ‘how much’ or ‘how often’. As claimed by Creswell (2013), this approach is most suitable in the case that the key issue is trying to identify factors that may affect the result and appreciate the best predictors of the result or the utility of an intervention. Furthermore, in carrying out tests in a quantitative approach, the technique has to be described in terms of ‘operations’, for example investigation, laboratory experiments and mathematical modelling. The data analysis will be influenced by the statistical principles. In the case where there is a limited amount of information obtained from previous studies on the subject under investigation, qualitative research is favourable as a better understanding is required.

#### 3.2.1.2 Qualitative Approach

The development of the qualitative research approach was first performed in the field of social science in an attempt to investigate a specific phenomenon in its own social and cultural context. This approach signifies the importance of descriptive data through recorded narration and is carried out through strong links with the field or real life scenario. The qualitative technique consists of various attributes but the key issue is that the data emphasis is on naturally occurring everyday events in natural settings. Data properly collected using a qualitative approach will be rich and holistic with a high probability to reveal complexity. This approach offers explanations to enrich the understanding of the subject and encourages opportunities of agreed decisions for social adoption. It also provides contributions towards concepts, policy making and social awareness (McMillan and Schumacher, 2001). According to Royce (1995), these attributes aid in achieving the aim of understanding instead of predicting the dependent variables. Furthermore, qualitative research is undertaken by means of thorough and extended contact with the field (Merriam, 1998), which makes it an essential method in analysing processes.

Nonetheless, there are some disadvantages to the qualitative approach. The collected data, which are highly complex and rich, can make the analysis process difficult. Most importantly, the data are left open to interpretation and the real concern is the fact that the interviewee and the researcher can be biased in their interpretations. Lastly, the entire situation is active as the environment and circumstances can constantly change which tends to influence the validity and verification of the study (Cornford and Smithson, 2006). The comparison between both research approaches is presented in Table 3-2 below.

**Table 3-2 Quantitative approach vs. Qualitative approach (Bernard, 2012)**

| Quantitative | Qualitative |
|---|---|
| The process is deductive using formal language. | The process is usually inductive and uses informal language. |
| The process can be comparatively slow and costlier than the qualitative method. | The process can be quicker and less expensive than the quantitative method. |
| The concepts are usually outlined as distinct variables. | The concepts usually appear as themes, motifs and taxonomies. |
| The analysis starts with statistics, tables and charts. | The analysis process starts by extracting themes or generalisations based on proof and preparing data to present a coherent representation. |
| Standard procedures are used with the assumption of duplication. | Procedures used are specific and the replication is not always easy. |

#### 3.2.1.3 Mixed Method

According to Fielding and Schreier (2001), it has been accepted that a combination of both approaches in real life is even complementary in certain cases. The perception is always open to debate on whether quantitative research is constantly objective, as opposed to qualitative research which tends to lead to significant analysis (Laurie and Sullivan, 1991).

Based upon the Hammersley (1992) argument, the difference between the quantitative and qualitative method is not as useful and “indeed, carries some danger”. Selecting one method over the other certainly tends to reduce the grounds for complementarity and care should be taken to prevent the likelihood of combining the two methods, in order to choose the main approach with a clear mind the chosen main approach.

Fielding and Schreier (2001) demonstrated that in view of the manner in which the research has been undertaken previously, and the weight of the qualitative approach in the advancement of science, qualitative researchers have limited choice but to use a quantitative approach in place of a qualitative approach. Laurie and Sullivan (1991) mentioned that “we believe that if an attempt is to be made at understanding, which is not completely relativist, then some way must be found to accommodate the findings of both quantitative and qualitative research”.

Within the scope of this research, a qualitative method has been employed in a minor way, as the researcher has adopted semi-structured interviews for the collection of common requisites of modelling complex maintenance operations of the product. In the following section, the reasons for adopting the semi-structured interview will be further detailed. As stated by Oakley (1999), if the purpose of the research is to be used for evaluation from emphasis of the result, then the appropriate method is the quantitative approach. The result of this research is deductive based upon numerical output steered by the designed simulation tool. As such, this particular research falls under the quantitative category.

### 3.2.2 Research Approach

A research approach will facilitate the design of a research project, by applying various activities, such as action research, experiments, case studies and surveys. Action research is appropriate to social science studies as it suits researchers who undertake their research at places of work, and who are geared to help improve the work of their colleagues as well as their own (Blaxter et al., 2010). An approach based on experiments is used when the main aim of the research is to purposely and actively establish some changes in the condition, circumstances or familiarity of participants aimed at creating a change in their performance. Meanwhile, case studies are utilised to build up a detailed, intensive knowledge concerning a single case, or limited associated cases (Robson, 2002). The survey process entails gathering the same data concerning all the cases within a sample, and involves posing questions to people (Aldridge and Levine, 2001).

Based on the above, action research means a social investigation aimed at comprehending a social behaviour in establishments in an effort to change it. Typically, the research findings' function is executed as an element of the research process. Action research is, therefore, irrelevant to this kind of research since historical data are employed and no observation of the influence of the changes to the real world will be sought. Considering the industrial perspective of this study, an experimental method will be adopted for this research. The experiment will investigate the consequences of varying product monitoring levels in the complex maintenance operations by employing the simulation technique. The experiments will be performed based upon samples from the industry.

Since no appropriate mechanism is available to undertake the experiments, a new tool is thus necessary. The needs for this particular tool ought to be initiated from the operations and maintenance departments. This method will collect the common requirements to model such maintenance operations from relevant experts (academic and industrial practitioners). In order to create a simulation tool that satisfies the common needs of a complex maintenance operation for the products under study, it is essential for interviews to be undertaken.

### 3.2.3 Data Collection

#### 3.2.3.1 Literature Review

The initial step in an academic research is to undertake literature reviews as it is a starting block to ascertain the most up-to-date knowledge available in the subject matter. In addition, it is also used as a platform from which to collate the relevant requirements from the literature.

Under the scope of this research, the analysis of the literature review was aimed to collate the common requirements in modelling the maintenance operations. Usually, the requirements are expressed in the form of model input, output, and the required level of model detail. A total of ten selected peer reviewed papers across the entire literature review were used to gather the generic requirements needed to be modelled. The selection of the papers was based on the availability of the requirements. In most cases, the journals within the literature review did not clearly state their model requirements.

#### 3.2.3.2 Interviews

In gathering relevant data, the most commonly utilised method in social research is to conduct interviews. Interviews are usually grouped into three categories; namely, unstructured, semi-structured and structured type interviews. The differences between the three categories in accordance with Robson (2002) are as listed below:

- Structured interviews: these are pre-determined questions ordered with preset text; the distinction between structured questionnaires and interviews is merely the utilisation of questions with open responses.

- Semi-structured interviews: the questions are pre-determined, however it is possible to change the order according to the perception of the interviewer upon what appears to be the most suitable. The question texts can be modified and explanation provided.

- Unstructured interviews: the interviewer usually has a broad subject of interest and concern, but allows interaction within this subject. It can be totally informal.

As mentioned by King (1994), qualitative interviews can be employed in case exploratory work is needed in quantitative type research. The constraints collected from the literature reviews were made available to the researcher prior to carrying out the interviews. The interviews then took place upon the analysis of the common requirements from the literature reviews. The interviews were conducted in an effort to ensure that the common requirements were captured to improve the limitation arising from the literature review. A total of nine interviews were conducted with experts from academic and industrial field. The academic interviewees were identified as European authors in the field of simulation or maintenance. The interviewees from industrial backgrounds were selected through attending conferences. The interviewees came from various fields such as simulation, maintenance, operations management, and business consultation.

For this particular research, the category of interviews performed is regarded as semi-structured in view of the fact that the researcher has common requirements based upon the literature review. However, the researcher is not fully assured that the requirements include all features vital in modelling the products' maintenance operations. A prompt approach which, according to Robson (2002) is generic in semi-structured interviews was utilised during the interview process. This is aimed to remind the interviewee of various requirements from the literature. Semi-structured interviews were selected primarily due to their flexibility in attending to issues that may surface during the interview, whilst at the same time maintaining the focus on the main subject matter. It was decided to omit structured interviews as the purpose of gathering these requirements is to gain more requirements rather than guiding the interviewees through a structured interview so as to prevent prejudice to the interviewees.

The interviews were performed face-to-face as far as possible with telephone interviews used in isolated cases. Over a span of several months, interviews were carried out consecutively and these came to an end when the received responses did not offer any new requirements, i.e. the state of saturation was reached. Within the following chapter, details of the conducted interviews will be presented and discussed together with the collated requirements.

### 3.2.4 Tools

#### 3.2.4.1 Simulation

Chapter 2 presented and discussed the appropriateness of the simulation used. It is utilised within the context of a quantitative method as the simulation is used mainly as a quantification tool. It is a technique commonly used in operations management mainly because of its ability to appreciate the difficult operation by attempting to perform various experiments that may affect the operation. In addition, it provides flexibility in modelling the needs of the operation.

The simulation tool, Discrete Event Simulation (DES), is available in various commercial software packages. For this particular study, the software package known as WITNESS (developed by Lanner Group) was used for the simulation. It was selected for the following reasons:

- Its availability to the research team.
- Its flexibility.
- Satisfies the common requirements of maintenance modelling.
- Researcher's familiarity with the software.

The approach developed by Robison (2004) was employed by the researcher based upon Landry et al. (1983). It is a renowned method and has resulted from a few approaches employed by simulation experts.

#### 3.2.4.2 Spread Sheet

The DES modelling is fairly complex and not many are well versed with the software. To allow the researcher to easily and effectively uses the developed simulation tool during the application of various testing and verification of the developed tool using industrial cases, it was decided to develop an interface for data entry feeding directly into the WITNESS model. In addition this allowed the results to be in an easy to use format. In view of this, an Excel spreadsheet (Microsoft Office) was selected because it is flexible, easy to use, easily available and the researcher is familiar with the software.

## 3.3 Summary of methodological selections

This particular research has adopted the quantitative method as substantiated above, in view of the nature of the numerical output of the simulation tool employed. The literature review was performed to further understand the subject matter and to identify any missing links. Interviews were arranged to stress the requirements needed to model complicated product's maintenance operations in addition to satisfying other needs that may be lacking from the literature review. The summary of the methodological selection is presented in Table 3-3 below.

**Table 3-3 Summary of methodological selection**

| **Philosophical choice** | **Positivism** |
|---|---|
| Research Family | Mainly Quantitative, with minor qualitative interviews |
| Research Approach | Experimentation based on industrial cases |
| Data Collection Techniques | Literature review, Semi Structured interviews. |
| Tools | WITNESS, Microsoft Excel |

The following chapter discusses the common requirements in the simulation of complex maintenance operations for the products.

# 4 REQUIREMENTS OF COMPLEX MAINTENANCE OPERATIONS MODELLING

## 4.1 Introduction

The researcher has identified a gap in the literature in addition to proposing the research methodology. This chapter serves as a continuous step towards this research. The aim of this research is to better understand and evaluate the complex maintenance operations of a product in use with different levels of product monitoring. Simulation, in particular a Discrete Event Simulation (DES) approach, has been the nominated approach in order to understand such complex systems, as mentioned in Chapter 2 of this thesis.

A decision has been made to follow Robinson's (2004) approach to conduct a simulation study. The approach consists of four key processes and they were based on Landry et al. (1983):

- A conceptual model: description of the model that is to be developed.
- A computer model: simulation model implementation on a computer.
- Solution and/or understanding: derived from the results and experimentations.
- An implementation in the real world: obtained from implementing the solutions and/or understanding gained.

First step, a conceptual model is an essential step when conducting a simulation study. It helps the modeller understand the nature of the problem and propose a model that is suitable for tackling it. Conceptual modelling consists of four sub-processes as follows:

- Develop an understanding of the problem situation,
- Determine the modelling objectives,
- Design the conceptual model: inputs, outputs, and model content,
- Collect and analyse the data required to develop the model.

This chapter, will discuss in details the understanding of the problem from identifying the modelling requirements through literature review followed by conducting interviews with experts in the area of maintenance and simulation. The computer model and the understanding step will be discussed in the next chapters.

## 4.2 Conceptual model

The purpose of a conceptual model is to develop an understanding of the problem as well as determining the model objectives. These steps were established in the literature review chapter and will be refined during the conducted interviews. After this, a collection of inputs, outputs, and model content were gathered in order to develop a DES tool to understand and assess the effect of different product monitoring levels on complex maintenance operations. The researcher has decided to apply two approaches when gathering these modelling requirements which are:

- First approach: Maintenance models that exist in the literature review.
- Second approach: Semi-structured interviews with experts.

These two approaches will ensure that the modelling requirements can be gathered to form a generic requirement for modelling a complex maintenance operation for products in use. The next section will highlight how those papers were selected and then give a full description of the semi-structured interviews.

### 4.2.1 Maintenance modelling requirements by literature review

The maintenance models in the literature have been reviewed in order to gather the modelling requirements. Firstly, papers that do not clearly state their input and output were excluded while papers that clearly state their modelling requirements were included. The researcher stopped exploring more papers when a saturation of the requirements had been reached (e.g. papers repeating the requirements that had already been gathered). Table 4-1 shows the ten papers that were analysed for their modelling requirements.

**Table 4-1 List of published papers from which some of the input/output requirements have been drawn.**

| Reference | Description |
|---|---|
| **Pruett and Lau (1982)** | They have used a simulation model to better understand the response of highway maintenance systems under various conditions. |
| **Burton et al. (1989)** | A simulation study to evaluate the performance of a job shop plant, where the equipment is subject to failure under different maintenance policies. |
| **Agnihorthri and Karmarkar (1992)** | To assist service managers in evaluating the performance of a given service territory, to minimise the total cost of maintenance. |
| **Albino et al. (1992)** | A simulation study to evaluate service performance measures when examining different maintenance policies in just-in-time manufacturing line. |
| **Seal (1995)** | Applied spreadsheet simulation technique to model a machine repair problem of a queue with arrivals from a finite population. |
| **Al-Zubaidi and Christer (1997)** | Developed a building maintenance manpower simulation model for a hospital complex to assess the potential to be realised using different manpower levels and operational procedures. |
| **Duffuaa and Andijani (1999)** | Described the integrated elements of a simulation model for (SAUDIA) airlines. |
| **Duffuaa et al. (2001)** | Developed a generic conceptual simulation model for maintenance. |
| **Andijani and Duffuaa (2002)** | A review paper which examines and evaluates simulation studies in maintenance. |
| **Antoniol et al. (2004)** | Assessing staff needs for a software maintenance project through queuing simulation. |

The requirements collection consists of input and output data that are of importance to the complex maintenance operations community. From literature, it is obvious that the most frequent input data that appears is, of course, the product reliability data, followed by the maintenance staff levels and their locations, and the number of products that need to be maintained. Other requirements that have been picked as least frequent are spare parts and inventory, service level required, and cost elements.

In terms of outputs, the most frequent are the number of failures and their total time, the number of maintenance tasks performed, staff utilisation, and maintenance operating costs. Other outputs were also picked, such as spare parts and service levels.

### 4.2.2 Maintenance modelling requirements by Interviews

As a continuous step towards gathering the requirements in order to model a complex maintenance operation, the researcher suggested to conduct interviews with experts. This decision was made to ensure that literature was not limited and the literature is not lagging the practice. These interviews were held with the field experts who are fully aware of current maintenance requirements. In addition, these interviews confirm the requirements gathered by the literature review as well as adding more.

The semi-structured interviews (Robson, 2002) were conducted with academics and industrial practitioners in the field of simulation, maintenance, and operations management. The Interviewees were not chosen from the authors in in Table 4-1. The interviewees were asked about the level of detail that is required as well as the input and output requirements. Interviews (nine) were conducted until saturation was reached. The interviews gathered additional requirements and served to confirm the earlier requirements gathered by the literature review. These interviews were carried out over several months in order to accommodate the interviewees’ availability. Table 4-2 below shows full details of the interviewees and describes how the interviews were conducted.

The interviews started by describing the research aim and its purpose to each interviewee. This was followed by asking the interviewees what their objectives would be on achieving such a simulation model. Questions were raised about inputs, outputs, and what level of details the model should include. During the last phase of the interview, the researcher applied a prompting technique to remind the interviewee of other requirements that were mentioned by other interviewees or literature. The prompting technique is applied as a way of confirmation. Finally, the maintenance process logic of each monitoring level was discussed during the interviews in order to grasp a generic maintenance processes representing the three monitoring levels of products in use.

**Table 4-2 Interview and interviewee details.**

| Interviewee | Field | Interview method | Date |
|---|---|---|---|
| **1** | Academic/Monitoring technology | Face to face | 15/10/2010 |
| **2** | Industry/Simulation consultant | Face to face | 21/10/2010 |
| **3** | Academic/Simulation researcher | Phone | 01/11/2010 |
| **4** | Academic/Service offering researcher | Face to face | 05/11/2010 |
| **5** | Academic/Simulation researcher | Face to face | 28/12/2010 |
| **6** | Academic/Maintenance researcher | Phone | 18/01/2011 |
| **7** | Academic/ Maintenance researcher | Face to face | 18/02/2011 |
| **8** | Academic/ Maintenance researcher | Phone | 22/02/2011 |
| **9** | Industry/Maintenance Operations Manager | Face to face | 09/03/2011 |

From these interviews, it became apparent that the input data most frequently mentioned was the product reliability data, followed by the maintenance staff levels and their locations, and then the number of products needing to be maintained. Other requirements have been picked such as spare parts and inventory, service level required, and cost elements.

In terms of outputs, the most frequent are the number of failures and their total time, product availability, travel time, and maintenance operating costs. Other outputs were also picked such as spare parts and service levels.

It can be noted that the most frequent inputs from the literature and interviews are closely correlated.

### 4.2.3 Generic requirements to model a complex maintenance operations

The previous two sections discussed how the requirements were obtained starting with how the decisions were made to include the requirements from the literature review. Secondly, information described who took part in the semi-structured interviews and how these were made. This section will bring together those requirements. The requirements of modelling complex maintenance operations for product in use serves as a first step towards developing a Discrete Event Simulation (DES) tool to compare different levels of product monitoring.

The objectives sought for such a model are mainly to: a) minimise operating costs, b) maximise product performance, and c) compare different product monitoring levels. A content analysis for inputs and outputs requirements has been performed on the generic requirements gathered. Table 4-3 compares the frequency of each input requirement from both the literature review and interviews. In terms of input requirements, it is clear that both the literature review and interviews focus on the information regarding people and equipment while interviews focus more on spare part inventory, service levels, and cost. This leads to the need for integrating the whole complex maintenance system.

**Table 4-3 Content analysis for input requirements gathered.**

| | | Frequency | |
|---|---|---|---|
| | | Literature (L) | Interviews (I) |
| | Input Requirements | (count = 10) | (count = 9) |
| People | Number, Location (L,I) | 7 | 8 |
| | Skill (L,I) | 6 | 2 |
| | Shifts (L,I) | 1 | 3 |
| | Travel time (L,I) | 3 | 5 |
| Equipment | Number, location (L,I) | 6 | 9 |
| | Cycle time (L,I) | 1 | 1 |
| | Job arrival rate (production) (L,I) | 3 | 1 |
| | Breakdown (MTBF,MTTR)(L,I) | 10 | 9 |
| | Failure modes (I) | - | 4 |
| | Repair Time (rate) (L,I) | 7 | 5 |
| | Diagnose time (L,I) | 2 | 2 |
| | Priorities (L,I) | 3 | 2 |
| | Planned maintenance time (L) | 4 | - |
| | Tooling number (L,I) | 1 | 2 |
| | Monitoring level (I) | - | 3 |
| | Failures with no need for spares (I) | - | 2 |
| | Inspection (L) | 1 | - |
| Spares inventory | Stock policy (safety, lot size, Req.)(L,I) | 3 | 7 |
| | Lead time (L,I) | 1 | 6 |
| | Stock location (I) | - | 3 |
| | Alternative Stock policy (I) | - | 1 |
| Service level | Demand Profile (arrival rate) (I) | - | 1 |
| | Contract KPIs (e.g. availability) (L,I) | 2 | 2 |
| Cost | Labour hourly rate (L,I) | 3 | 6 |
| | Asset cost (I) | - | 1 |
| | Monitoring (sensing cost) (I) | - | 2 |
| | Contract cost and penalties (L,I) | 1 | 1 |
| | Spares cost (L,I) | 3 | 5 |

On the other hand, Table 4-4 compares the frequency of output requirements obtained by both the literature review and interviews. In general, this table shows that most of the requirements are relatively equally balanced between literature and interviews. However, there tends to be more emphasis on the spares inventory, travel times, and tool utilisation by interviewees as opposed to indications in the literature.

**Table 4-4 Content analysis of output requirements gathered.**

| | | Frequency | |
|---|---|---|---|
| | | Literature (L) | Interviews (I) |
| | Output Reference No. | (count =10) | (count =9) |
| People | Utilisation (busy, Idle) (L,I) | 6 | 9 |
| | Total hours on jobs (L,I) | 2 | 3 |
| | Time by each labour on job (L,I) | 3 | 2 |
| | No of Jobs (L,I) | 1 | 1 |
| | Total travel time (L,I) | 1 | 5 |
| | Required number (L,I) | 3 | 3 |
| Equipment | Production (No., lost) (L,I) | 2 | 1 |
| | Utilisation (idle, run, …) (L,I) | 2 | 4 |
| | Tool utilisation (I) | - | 2 |
| | Failures (No., time) (L,I) | 7 | 6 |
| | Maintenance (Number) (L,I) | 7 | 2 |
| | Waiting for repair (L,I) | 2 | 4 |
| | Required assets | - | - |
| Spares inventory | Stock level, stock outs (L,I) | 1 | 1 |
| | Number used, time in used (I) | - | 2 |
| | Stock level required (I) | - | 2 |
| | Location of stock and labour (L,I) | - | 1 |
| Service level | Demand satisfied (L,I) | 2 | 1 |
| | Availability (average, point) (L,I) | 3 | 6 |
| | Measuring KPI's (L,I) | 2 | 1 |
| Cost | Labour cost (L,I) | 4 | 3 |
| | Spare cost (L,I) | 3 | 1 |
| | Penalty cost (L,I) | 1 | 3 |
| | Prod. Lost cost (I) | - | 2 |
| | Inventory cost (L,I) | 1 | 1 |
| | Operating cost (L,I) | 6 | 5 |

Figure 4-1 represents the level of detail that is required for modelling, whilst Figure 4-2 represents the inputs and outputs that were gathered. In Figure 4-2 the letters (L) or (I) or (L, I) are shown next to each requirement to indicate from where each requirement is captured, where (L) represents literature review, (I) represent interviews, and (L,I) means this requirement has been captured through both the literature review and interviews.

**Asset**
**Monitoring Technology**
**Maintenance staff**
**Scheduling**
**Parts and tooling**
**Product Locations**
**Policies**
**Overhaul**

**Figure 4-1 Level of details of modelling product's complex maintenance operations (adapted from Alabdulkarim et al., 2011)**

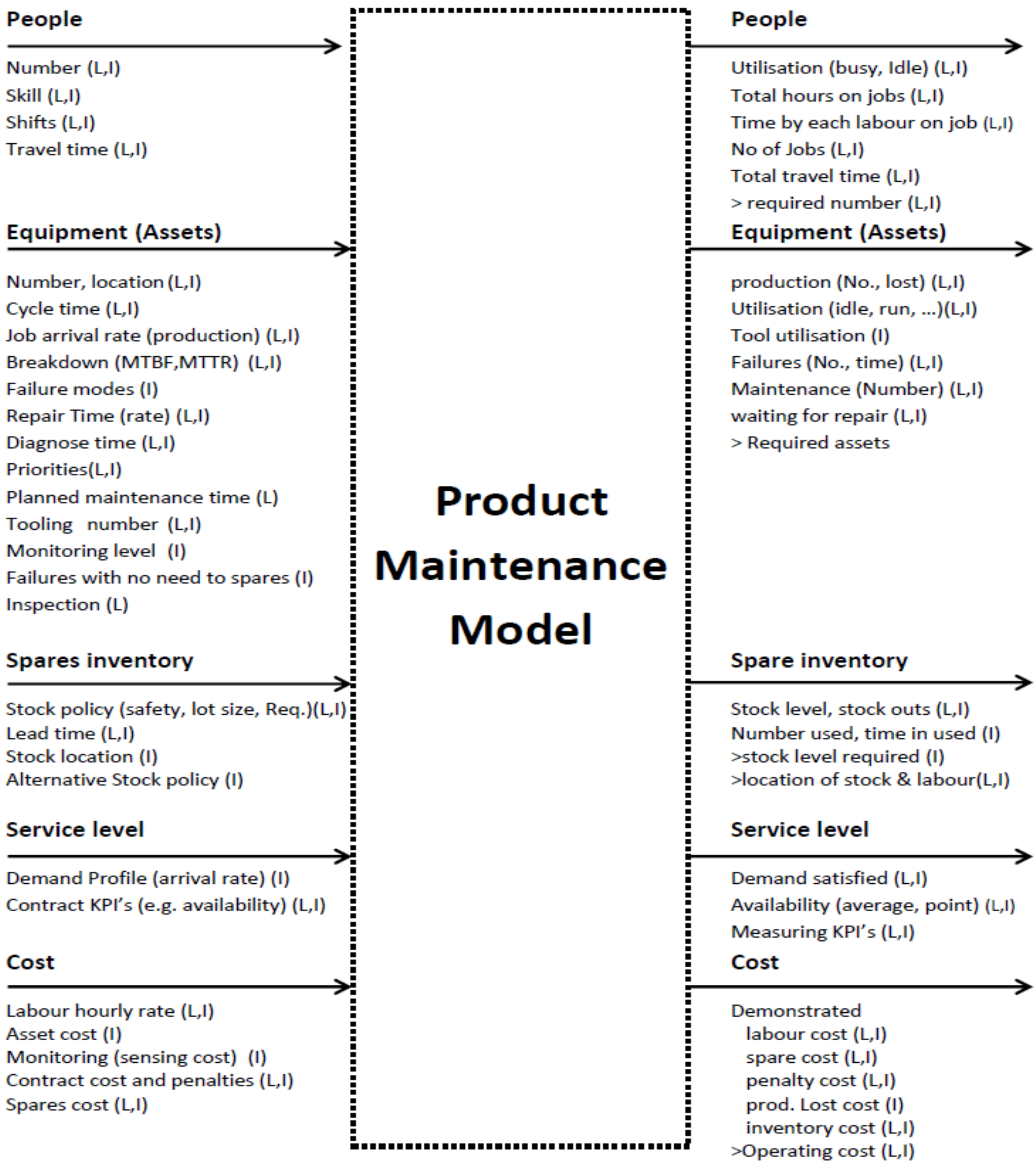


**Figure 4-2 Input/Output table for generic requirements of modelling complex maintenance operations (adopted from Alabdulkarim et al., 2011)**

### 4.2.4 Maintenance processes of different product monitoring levels

The researcher developed a conceptual model representing the three product monitoring levels. Each monitoring level has different complex maintenance processes which deal with the product failure. These processes have been obtained and discussed with the interviewees in order to generate a generic maintenance process for each monitoring level of a product.

By looking into the requirements gathered by the semi-structured interviews, it can be noted that these processes should include the following:

- Allocate a maintenance centre to each customer (Interviewee 1).
- Labour to diagnose or repair the equipment (Interviewees 1,2,3,4,6,7,8 and 9).
- Travel time (Interviewees 1,2,4, and 9).
- Tools to be used on diagnosing or repairing the equipment (Interviewee 4).
- Stock ordering (Interviewees 1,2,5,6,7,8,and 9).

Subsequently, a diagram was developed combining what was discussed in the interviews to represent the Reactive, Diagnostic, and Prognostic generic processes as shown in Figure 4-3.

Reactive level process, described as when a product failure occurs, maintenance centre will be informed then a labour and/or a tool will be scheduled (when available) to visit to travel to the product and perform diagnosing task. If the product can be fixed on the diagnosing visit then it will be fixed otherwise another travel to the product will be scheduled when the spare part is available. When the spare part is on stock then other visit will be made to repair the faulty product and then the resources (labour and/or tool) will travel back to maintenance centre.

Diagnostics level process, described as when a product failure occurs, maintenance centre will be notified in addition a diagnostics of the failure will be provided. In this case, the resources (labour and/or tool) will travel to the product location only when the required spare part is available. Then product will be repaired and the resources will travel back to the maintenance centre. In the process the resources only travel once to the product.

While Prognostics process, described as predicting the future failure of the product. In this case, the resources (labour and/or tool) will travel to the product once the spare part is available with the hope to repair the product before the actual failure occurs.

The generic processes generated were then sent back to Interviewees 1 and 4 for validation. A meeting with Interviewee 1 was arranged to discuss the conceptual model generated by the researcher due to the outcome of the interviews. The interviewee agreed on these processes as a generic form and made a suggestion to include a Prognostics Window (PW) in the case of the Prognostics level. PW simply means how much time in advance should be known about a failure. According to the interviewee, this is an important issue and needs to be investigated in order to understand the effect of PW when modelling the Prognostic level. Meanwhile, Interviewee 4 agreed on the conceptual model in its current form as a generic maintenance process.

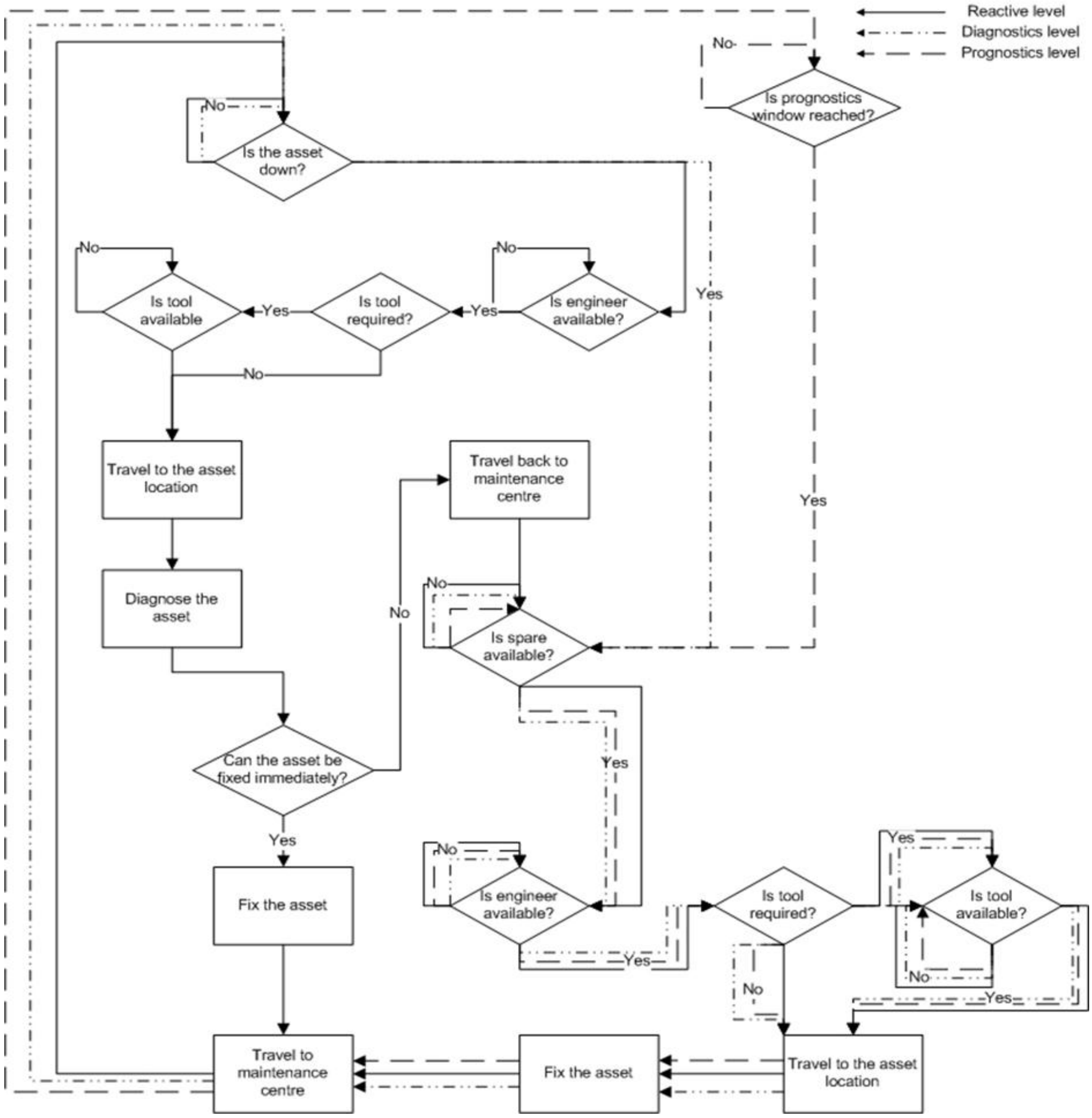


**Figure 4-3 Conceptual models represented by different processes for Reactive, Diagnostic, and Prognostic levels**

## 4.3 summary

This chapter has answered the first research question as well as the two sub questions. It discussed how the modelling requirements of such complex maintenance operations were gathered. In addition, it examined what these requirements are (objectives, level of detail in the model, input, output). Finally, a conceptual model was developed and validated to represent different maintenance processes. This conceptual model will assist in creating the computer model with Witness software.

# 5 DEVELOPMENT OF PRODUCT MONITORING LEVELS SIMULATION (PMLS) TOOL

## 5.1 Introduction

This chapter serves as the second phase in conducting a simulation study based on the four key processes, as described by Robinson (2004). This follows the gathering of generic requirements to simulate such complex maintenance operations of products where the generic conceptual model has been developed.

The aim of this chapter is to represent the developed conceptual model (Figure 4-3) into a computer model. The built-in functionalities which are provided by Witness software are explored first (Lanner Group, 2013). Following this, the functionalities that need to be developed by the researcher in Witness are identified in order to fulfil the conceptual model design into a computer model.

Discrete Event Simulation (DES) modules have been developed to represent the three different product monitoring levels (Reactive, Diagnostics, and Prognostics). A full description of building such modules will be provided. This is followed by creating an Excel interface with Witness for ease of use of the developed Product Monitoring Levels Simulation (PMLS) tool. This also rapidly mimics the wider maintenance system of any operation as the developed PMLS tool is generic.

To conclude this chapter, a pilot case study has been formed to demonstrate the developed PMLS tool. The purpose of such a pilot case is to ensure that all the generic requirements, which were provided in Chapter 4, can be captured by the PMLS tool and it also assesses the developed tool and ensures that the tool logic is implemented properly. An explanation of the case study, as well as the results analysis, will be provided.

## 5.2 Tool development process

Witness is a commercial DES software tool which is developed by the Lanner Group. It is well-known software that has been utilised within simulation communities around the world. Witness has been chosen by the researcher to be the platform for this research tool development. It has been nominated by the researcher for several reasons. In addition, it satisfies the common requirements of maintenance modelling. Also, it is readily available to members of the research group.

It will be necessary to explore the general built-in functionalities that Witness has to offer in order to identify which functionalities need to be developed. This is in order to develop a generic DES tool to compare the effects of different product monitoring levels on complex maintenance operations. Logical and structured steps have been followed in order to build a generic DES tool, as shown in Figure 5-1.

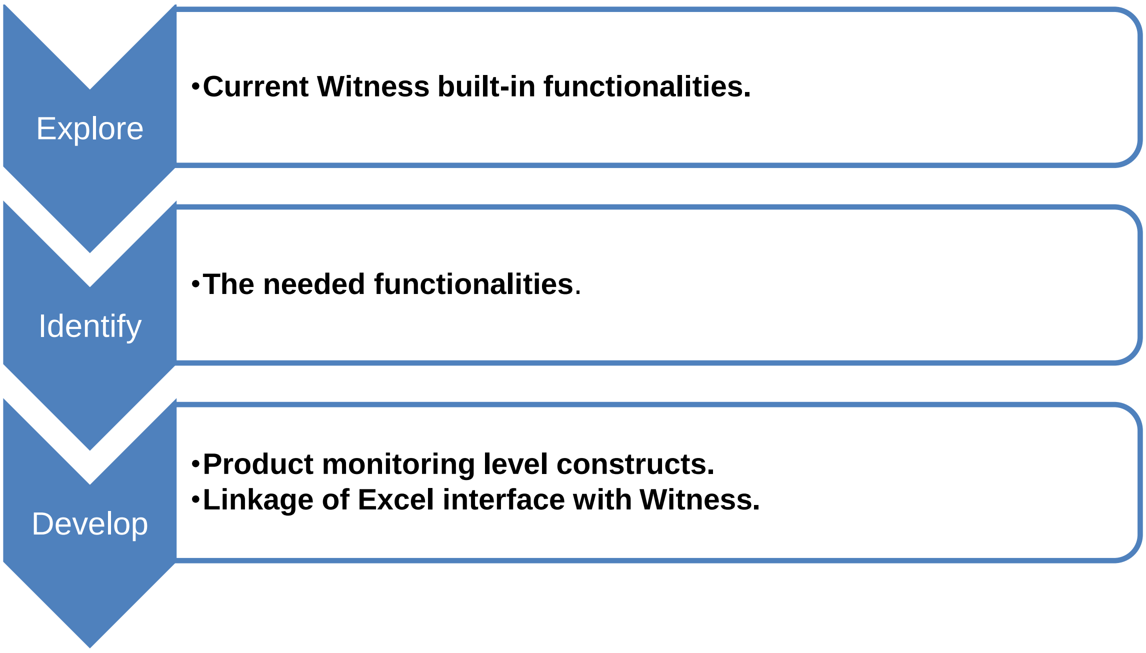


**Figure 5-1 Tool development process**

To explore the current Witness functionality and to identify which functionalities need to be developed, it would be useful to discuss the problem domain and features which need to be incorporated in the PMLS tool.

- ***Domain/ Context***

The aim of the tool is to compare the effect of different product monitoring levels (Reactive, Diagnostics, and Prognostics) on maintenance operations. This research focuses on the maintenance activitiy 'processes' depending on the monitoring level applied. Thus, different failure modes need to be represented by different logic depending on the monitoring level. These were presented in the development of the conceptual design in Chapter 4.

The logic for the monitoring levels which captures the decision points and the flow of information between stages has been presented previously. The conceptual design shows the common as well as unique elements, for example, travel to product and diagnosis are unique to reactive levels whilst checking for spares availability is common to all levels.

The product monitoring level logic starts at the top of the conceptual model (Figure 4-3) with either a breakdown occurring or the suggestion that a breakdown could occur. When a breakdown occurs in the reactive scenario then a check should be made in the model logic to ascertain the availability of labour to travel to, diagnose, and potentially fix the product. If the product cannot be fixed then labour needs to wait until spares are available before returning. For the diagnostic logic, the product self-diagnoses and communicates the fault and staff wait until spares are available before travelling. With the prognostic logic the failure is predicted and a service request is made. Once stock is available for all three scenarios, staff travel to repair or service the product. Checks are made throughout for tool availability if relevant.

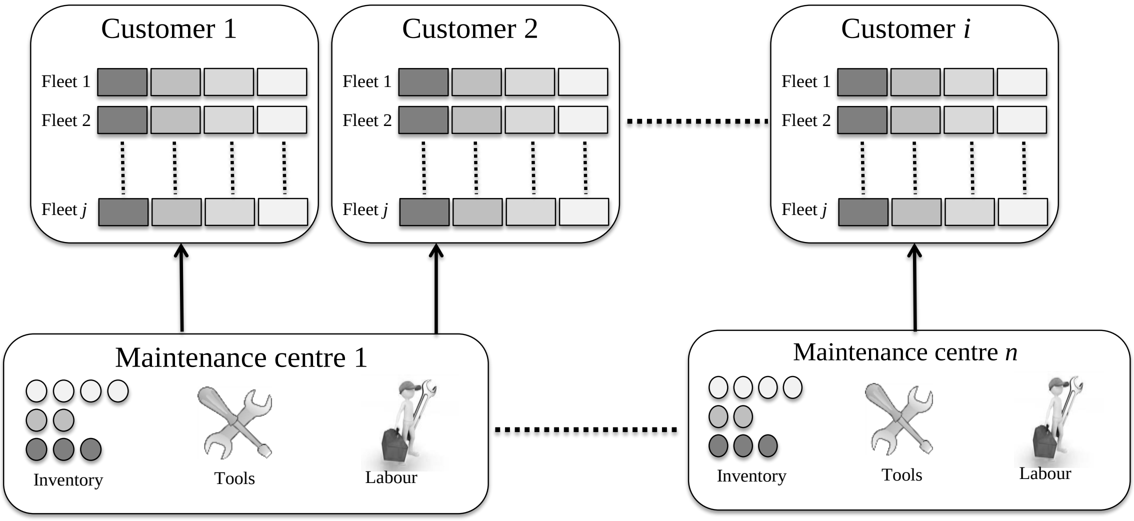


**Figure 5-2 Maintenance operational complexity for products**

Figure 5-2 represents how the complex maintenance operations for products can be modelled. The schematic shows a view on the models created that will need to be formed, each having the multiple instances of common elements of fleets of products, inventory, tools and labour. The differences between the three monitoring levels is not discernible in this view as the variants are dependent only on the control strategies, as shown in Figure 4-3. The next section highlights the features that need to be recognised and taken into consideration when building such a tool.

- ***Features***

The features of the PMLS tool have been captured from the generic requirements (Figure 4-2), the conceptual model (Figure 4-3), and maintenance operational complexity for products (Figure 5-2). These features all need to be considered when developing such a tool, and are described as follows:

- **<u>Equipment 'Product':</u>** it is the main feature in the maintenance operation. Without the product the maintenance operation would not exist. Within the product itself there is a need to model different failure modes which consequently affect the number of items produced by the product, and availability. For example, if the product is a washing machine it would be useful to know how many washing loads have been processed.

- **Monitoring level 'Processes':** deals with the failure according to the monitoring level applied. The researcher seeks to develop a tool that is able to compare the effect of the different product monitoring levels on maintenance operations. Different processes will need to be modelled to deal with the failure according to the monitoring level processes (Reactive, Diagnostics, and Prognostics). Additionally, all resources needed e.g. labour, tools, spare parts, travel time, etc. should be taken into account.
- **Customers:** multiple customers scattered in different areas with a fleet of products and in some cases different fleets of different products. This will add to the complexity of the tool in terms of modelling, but at the same time such a tool will add flexibility for the users.
- **Maintenance centres:** multiple centres should be created to capture the entire system of maintenance operations. The purpose of the maintenance centre would be to hold the labour, tools (if any), and spares inventory. In addition each maintenance centre would be assigned to serve a number of customers.
- **Service level:** these are performance metrics on which the maintenance operations would be assessed. For example, the number of product operations, availability, labour utilisation, spares used, etc.

In the next section, the built-in functionality which are available in Witness will be explored.

### 5.2.1 Witness built-in functionalities

The Witness software package offers various functionalities as it is a commercial platform which serves to model several applications in both the manufacturing and service sectors. In this section, the focus of Witness built-in functionalities will be limited to those that are within the scope of the problem domain which includes stationary products in use (such as washing machines, photocopiers, etc.). This section will highlight the elements that the PMLS tool should consist of and explore their functionalities to identify the functionalities (logics) that need to be developed.

- ***Elements***

What is meant here by elements is which entities the tool consists of. In this section, the main entities that would be included in the tool will be described here:

- **Machine:** this entity would represent the 'product' in the case of this thesis. Witness offers straightforward pull and push parts to and from the machine to be processed. The machines in Witness offer a straightforward breakdown where it will occur when the Mean Time Between Failure (MTBF) is reached and it will be fixed automatically when the repair time that is defined in the machine is consumed. It also gives the modeller the ability to add labour if needed as a resource to conduct the repair activity.

  Defining different failure modes can be easily created. In accordance with the conceptual model Reactive, Diagnostic, and Prognostic processes are not straightforward breakdowns as offered by Witness. Breakdowns in Witness lack the integration of all resources needed to resolve a breakdown (labour, spares, tools, travel time to and from the product).

  In the scenario of a Reactive maintenance, a diagnose time is needed as the product diagnose is done manually by the labour who will then travel back to the maintenance centre to collect the spare part needed (if available). Otherwise labour will do other maintenance activities until the spares arrive and then further travel will be needed to install the spare in order to resolve the repair activity.

  In the case of Diagnostics, the breakdown manual diagnostics should be discarded as the product should be able to diagnose itself and the labour will only travel once to do the repair if, and only if, the spare is available.

Prognostics maintenance requires predicting the future breakdown which requires a trigger to gather the resources needed to accomplish the maintenance activity before the actual failure happens. Therefore, there is a need to develop a maintenance trigger that can read the intended maintenance time based on the MTBF statistical distribution entered in the tool. In addition to this, it would be intuitive to specify the time in advance when the trigger needs to be activated, which hereafter in this research will be called the Prognostics Window (PW).

It would be of importance to the service providers to know how many parts the product has produced and lost in terms of production, number of failures occurring, and time of breakdown (diagnose time, repair time).

- **Labour:** is a resource that can be used to operate or maintain the product if needed. In the case of this research labour is an important factor in the maintenance activities. There is a need to model the labour to diagnose in the case of reactive maintenance as well as repairing the product in all of the three monitoring levels. Additionally the travel time from the maintenance centre to the product should be modelled and vice versa. Labour should pursue the maintenance activities if the other resources are available (e.g. tools, spare parts) if needed. It would be important to know the utilisation of the labour, the number of jobs achieved by labour, the average time spent on the job, and the travel time spent.
- **Tools:** will be used as a resource (if needed) to be part of the diagnosing or repairing activity. Tools utilisation and the number of times they are used need to be known. This is needed in certain industries where tools is a constrain in achieving maintenance activities (e.g. aviation industry).
- **Parts:** is an entity used by a machine to process it. This will be equivalent to the washing loads or printed papers if the product considered is a washing machine or photocopier.

  This will be used to represent two aspects in the model. Firstly, it will represent the items which are processed by the products. In addition, it will be used to represent the spare part stocks.

The number of items produced by the product and the lost item, the average time the spare spent in inventory, and the number of spares used all need to be captured as output information.

### 5.2.2 Developed Functionalities

Three monitoring level logic flowcharts were used as the basis of the PMLS tool. As discussed earlier, simulation software packages, in general, and Witness software have a simple built-in breakdown modelling capability for modelling failure and repair. However, according to the requirements gathered, more detail and complexity is required to represent what happens when a product fails and how it is repaired. For example, each monitoring level treats the breakdown and subsequent repair differently. Each failure mode needs particular labour skills, tools and, more importantly, the required spare part.

It would be intuitive to build a simulation module for each of the product monitoring levels independently to adopt all the process requirements for each monitoring level. Therefore, three modules should be built representing Reactive, Diagnostics, and Prognostics maintenance levels. By reviewing the processes for each monitoring level, a similarity between Diagnostics and Prognostics has been detected. The difference between Diagnostics and Prognostics levels in terms of maintenance processes are only in the Prognostics Window (PW). In other words, the Prognostics level needs a PW which is the time in advance that a maintenance activity should be triggered before the actual breakdown occurs whereas in Diagnostics the maintenance activity will be triggered at the time of failure, not before. Figure 5-3 shows the difference between the Diagnostics and Prognostics levels and what is meant by the PW.

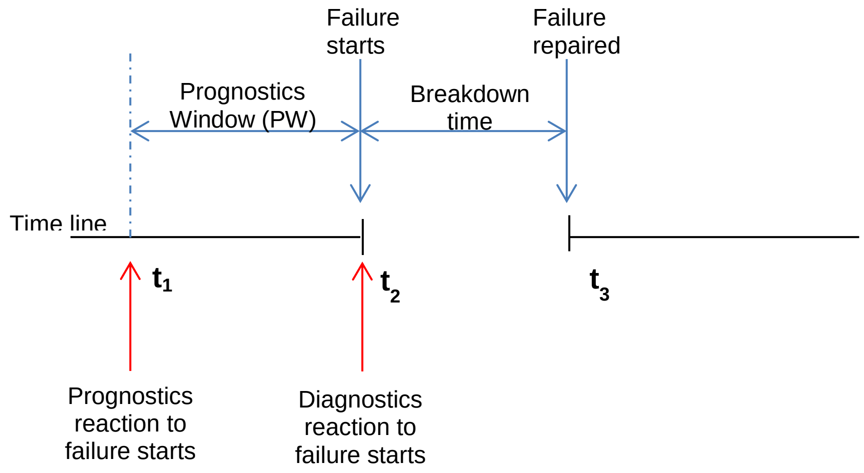


**Figure 5-3 Difference between Diagnostics and Prognostics levels**

According to Figure 5-3 the failure starts at $t_2$ in the Diagnostics level; the reaction towards the failure will start on failure at $t_2$. Checking for the availability of labour, spares, and maybe tools will start immediately after $t_2$. In the Prognostics level - as this level is to predict failures - there must be a known time in advance that allows maintenance providers to carry out the maintenance activity before the actual failure occurs. This time is defined in this research by the Prognostics Window (PW). In Figure 5-3, when the Prognostics level is applied, the maintenance provider will start to react from time $t_1$ for an expected failure that would occur at $t_2$. While $t_3$ represents the time when the failure is repaired.

It can be concluded that the difference between Diagnostics and Prognostics is the PW. The PW is an important aspect that needs to be studied in order to understand the effect of how much in advance a maintenance provider should react to a future failure. In the Prognostics level, the PW needs to be defined and it is certainly > 0 whereas in the Diagnostics level the PW should be set to zero. Other than the PW, the process of reacting to a failure in Diagnostics and Prognostics is identical and that is clear in the conceptual model in Chapter 4. Thus, when considering building a simulation module for Diagnostics and Prognostics, it can be combined in one module representing both levels given that the PW can be entered in the tool. The next sub-sections will discuss how these two modules were built using Witness software.

#### 5.2.2.1 Development of Reactive module

It was clear from the conceptual model that the Reactive level differs from the other two monitoring levels. Therefore, a module to represent the Reactive level needs to be developed by the researcher. Before starting to describe how the module was built in Witness, it would be intuitive to review the process flow of the Reactive level, as shown in Figure 5-4.

In order to describe how the Reactive module was built in Witness, a screenshot of the built module needs to be shown. Figure 5-5 shows a screenshot of the Reactive module that the researcher has developed in Witness. From this screenshot a full description of all the entities of the Reactive level module will be given. In addition, the purpose of each entity is demonstrated and how it serves towards achieving the process needed for the Reactive level.

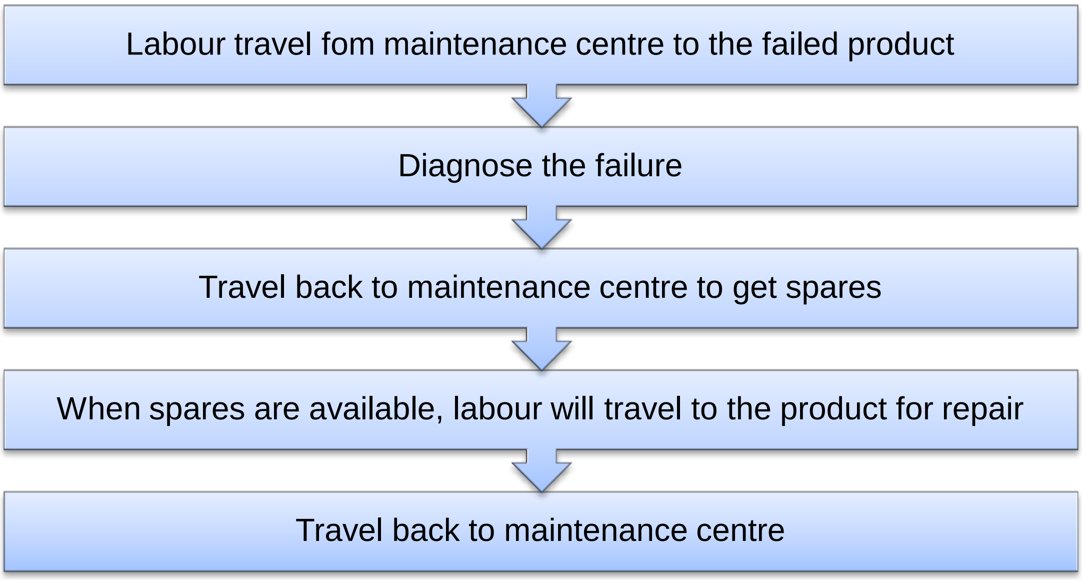


**Figure 5-4 Reactive maintenance process**

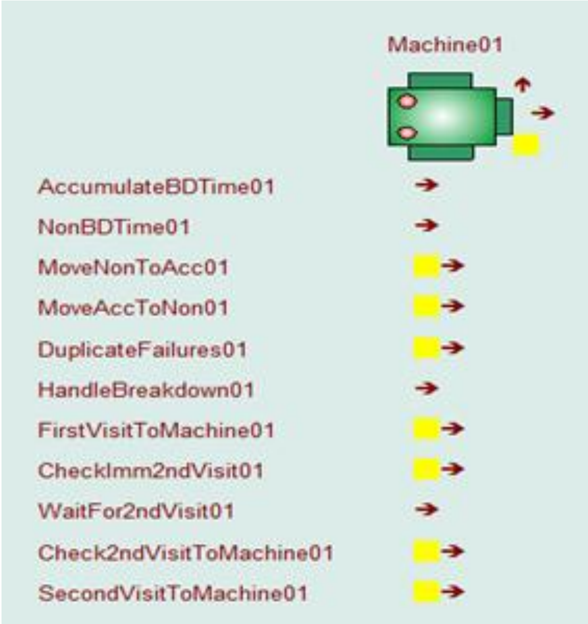


**Figure 5-5 Reactive level module**

Figure 5-5 shows the Reactive module contains of Machine01 which represent the 'product' needing to be maintained. It can simply pull and then push the parts after they are processed.

A dummy machine was created and named as DuplicateFailures01. Its mission is to create a part called Failure in the beginning of the model run. Depending on the number of failure modes for the Machine01, the DuplicateFailures01 will create a Failure part for each failure mode. Generally, the MTBF for each of the failure modes needs to be specified if it is based on machine 'product' available time or busy time.

If the failure mode is based on the busy time of the machine 'product', the part Failure is then pushed to the NonBDTime01 buffer by MoveAccToNon01 when the Machine01 is idle. When Machine01 is busy, then MoveNonToAcc01 will move the Failure part from NonBDTime01 buffer to AccumulateBDTime01 buffer by MoveNonToAcc01. On the other hand, if the failure mode is based on the available time of the machine 'product', then the Failure part will be always in the AccumulateBDTime01 buffer whether Machine01 is busy or idle. The

AccumulateBDTime01 buffer is responsible for accumulating the time for the Machine01 depending on the MTBF if it is based on busy or available time.

When a breakdown is due (based on the MTBF) for Machine01 the Failure part will be pushed from AccumulateBDTime01 to the HandleBreakdown01 buffer. At this instant, the Machine01 is broken down and will be waiting for the labour and the tool (if required) for manual diagnosing purposes. When the labour and tool (if required) are available, then they will be attached to the Failure part which will be pulled by the FirstVisitToMachine01 machine. The FirstVisitToMachine01 is a multi-cycle machine with defined four cycles.

The four cycles of this machine are travel time to Machin01, Diagnose time, fixing the breakdown if no spares are required, and the last cycle would be the travel time back from Machine01 to the maintenance centre. If the machine is repaired at this stage the Failure part is returned to accumulate the next breakdown. If not then the Failure part is pushed to CheckImm2ndVisit01. If spares, labour, and tools (if required) are available then these will be attached with the Failure part to be pushed to SecondVisitToMachine01. CheckImm2ndVisit01 is to check the imminent second visit if all resources needed are available. Otherwise, the Failure part is pushed to the WaitFor2ndVisit01 buffer.

The Failure part is then pulled from the WaitFor2ndVisit01 buffer by Check2ndVisitToMachine01 when all resources needed become available. The machine SecondVisitToMachine01 consists of three cycles. These cycles are travel to Machine01, repair of the machine, and then travelling back to the maintenance centre where labour and tools are freed for other maintenance activities.

### 5.2.2.2 Development of Diagnostics and Prognostics module

As discussed earlier, the Diagnostics and Prognostics levels are similar in terms of maintenance activities processes. The only difference was PW; in the case of the Diagnostics level, the PW is set to zero whereas the Prognostics level PW will be >0, as explained in Figure 5-3. Therefore, a module to represent both levels needed to be developed by the researcher.

It is important to emphasise that in the case of Diagnostics, the maintenance reaction to the failure will start after the product failure occurs whereas in Prognostics a reaction might start when the PW is reached. But it is not necessary that all the resources needed to carry out the maintenance activity will be available immediately when the PW is reached. In some cases of the Prognostics level when the resources are not available as soon as PW is reached, the product may fail on the time of failing then the maintenance activity will take place. This has been taken into account when building this module. Before starting to describe how the module was built in Witness, it would be intuitive to review the process flow of the Diagnostics and Prognostics levels, as shown in Figure 5-6.

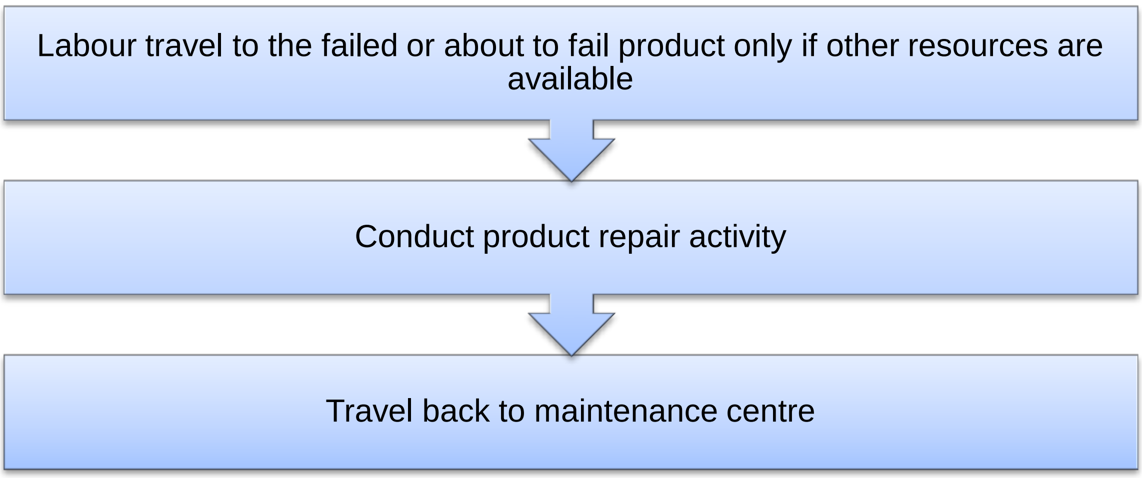


**Figure 5-6 Diagnostic/Prognostics maintenance process**

In order to describe how the Diagnostic and Prognostics module was built in Witness, a screenshot of the built module needs to be shown. Figure 5-7 shows a screenshot of the Diagnostic and Prognostics module that the researcher has developed. From this screenshot a full description of all the entities of the Diagnostics and Prognostics levels module will be given. In addition, the purpose of each entity is demonstrated and how it serves towards achieving the process needed for those levels.

As mentioned in the Reactive module, a dummy machine was created and named as DuplicateFailures01. Its mission is to create a part called Failure in the beginning of the model run. Depending on the number of failure modes for the Machine01, the DuplicateFailures01 will create a Failure part for each failure mode. Generally, the MTBF for each of the failure modes needs to be specified if it is based on machine ‘product’ available time or busy time.

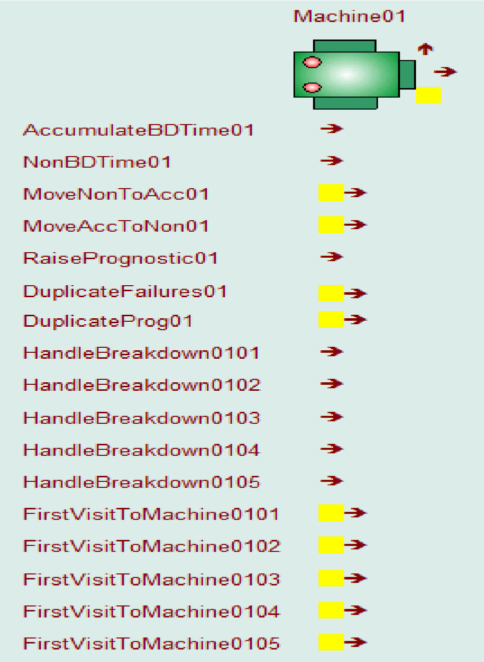


**Figure 5-7 Diagnostic and Prognostics level module**

The handling of the Failure part is the same as in the initial stages of the Reactive module in terms of how to calculate the time if the MTBF is based on the busy or available time. When a breakdown occurs, the Failure part is pushed by AccumulateBDTime01 to the RaisePrognostic01 buffer at the time specified by the PW value. The PW would be set to zero in the case of the Diagnostics level. If the Prognostics level has been applied then the PW value needs to be specified.

As soon as the Failure part is in the RaisePrognostic01 it will be pushed to DuplicateProg01 machine. In this case, it will divide the Failure part into two parts. One will be pushed to one of the HandleBrakedown01 buffers; depending on the failure mode it will be pushed to HandleBreakdown0101 if it is failure mode one. If it is failure mode two then it will be pushed to

HandleBreakdown0102 and so on. The current tool is capable of having five failure modes. This can be expanded easily if more than five failure modes were needed. The other Failure part will be pushed back to AccumulateBDTime01 or NonBDTime01 to accumulate the breakdown time.

When the Failure part is pushed to the HandleBreakdown01 buffer, the machine FirstVisitMachine01 will call the resources needed (labour, tools, and spare part) to process the Failure part which is waiting at the HandleBreakdown01. Again, the FirstVisitMachine01 is created for each failure mode, in the case of the tool it will be five for each machine ‘product’. FirstVisitMachine01 is a multiple cycle machine which consists of three cycles. These consist of the travelling time to the machine, fixing the machine (during this cycle if the machine has not yet broken down, it will be forced to break down so the repair activity can take place), and then travelling back to the maintenance centre.

The reader may raise the question of why the HandleBreakdown buffer and FirstVisitMachine need to be duplicated for each failure mode. The reason for this is that in the Prognostic case there may be multiple repairs in the queue for repair at the same time. With a PW > 0, more than one prognostic prediction may happen in this same timeframe. The PMLS tool here includes each repair process separately. More than one repair may even be in progress at the same time. It is recognised that this might be a simplification of reality in some cases.

This section has discussed how the Diagnostics and Prognostics module was built in Witness. The next section will explain the functions used to link the modules with the wider maintenance system.

#### 5.2.2.3 Linkage with wider maintenance system

Main resources such as labour, tools, spares have been added to Witness. The tool offers 99 different types of labours, tools, and spares. Each type can be replicated to different quantities. The entities of labour and tools used were the labour entity while spares were applied as part entities in Witness. The researcher has decided to limit the tool to 99, as this is already an extensive number. However, the PMLS tool can be expanded to more than that by cloning the entities if needed.

Some functions were created in Witness to develop a linkage of the modules built with the wider maintenance operation. For example, how a machine 'product' is assigned to a customer and maintenance centre which will be responsible to provide the maintenance. This section will explain how these functions were used.

AllowFirstVisit - this function is designed to check when all the needed resources are available to commence a first visit to the product according to each monitoring level applied. It is the product diagnosing process in the case of the Reactive level or, if the spares are not needed, it means the product will be fixed as well in the first visit.

In the case of the Diagnostics or Prognostics levels, another function has been introduced called AllowPrognosticVisit which is responsible for triggering the resources when available once the PW is reached.

The function of AllowSecondVisit is developed to check whether a second visit in the case of the Reactive maintenance is needed. If this is the case then it will check all the needed resources to despatch them when available.

OrderMaintCentres - this function is responsible to assign each machine 'product' to a customer ID. This customer ID is basically to determine to which customer this machine 'product' belongs. Also, it defines the travel times between each customer and the assigned maintenance centre. Furthermore, this function is designed to read the needed data from the Excel interface which will be explained in section 5.2.3 of this chapter.

CheckSafetyStock is a function used to check the safety stock in each maintenance centre for each spare part type. Orders of spares will then be made when the safety stock is reached. Order lead time will be taken into account.

These sections provide the reader with the general logic of how the module of different monitoring levels were built. In addition, they show how the linkage of those modules were made with the wider system.

### 5.2.3 Interface

An Excel interface was introduced and linked to the simulation model in order to allow rapid configuration of the tool and to avoid the need to work with Witness directly for the users who are not familiar with simulation software. Figure 5-8 shows the interface linkage between Excel and Witness.

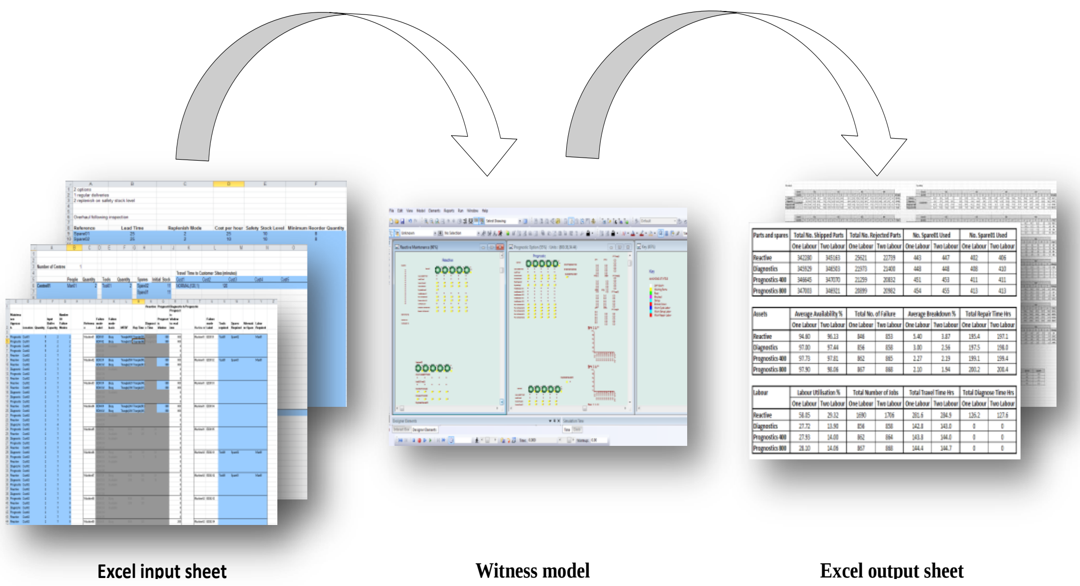


**Figure 5-8 Excel interface with Witness**

The interface was created in an Excel spreadsheet. Seven worksheets were developed to represent each type of input data as well as resulted outputs as follows:

1. <u>Maintenance Centre</u>:
   - Number of maintenance centres and customers.
   - Travel time from each maintenance centre to each customer.
   - Labour, tools, and spare parts located in each centre.

2. People: assignment of labour to shifts and skills.
3. Shifts: configuration of the number of shifts and durations.
4. Orders: creation of spares, arrival rate and assignment to particular product.
5. Product:
    - Breakdown priority for each product; the higher the number the higher the priority.
    - Monitoring level of Reactive, Diagnostics, or Prognostics by product.
    - Assignment of products to customers, their quantity and the number of failure modes.
    - Failure mode detail including failure according to available or busy time, the Mean Time Between Failures (MTBF), the diagnosis time (Reactive only), repair time, and in the Prognostics case the time in advance that a product will send feedback information about an upcoming failure.
    - Resources requirement for each specific failure mode: labour skill, tools and spares.
6. Spares: the lead time, safety stock and reorder quantity.
7. Results: the tool is able to measure the following results:
    - Product: Utilisation (Idle, Busy, Down), Downtime is broken down into full details (waiting for resources per product, actual diagnosis and repair time, travel time per product ... etc.), Number of failures per product, Number of product operations, Production (successful and lost), Availability percentage per product.
    - Labour: Utilisation (Idle, Busy), Quantity, Number of jobs, Average job time.
    - Inventory: Spare parts minimum and maximum quantity in the inventory during the model run time, number of each spare used, average time each spare spent in the inventory during model run time.

- Cost: all cost calculations can be calculated and obtained by the above results. The tool can offer different types of results on machine availability, breakdown percentage, inventory and labour information and statistics. These then can be easily calculated if the cost is known for each element.

Appendix B shows the figures of each of these input sheets. The reader may notice that the researcher has applied triangular distribution, that was done to the ease of the estimation of the distribution. A triangular distribution consists of three numbers: minimum, mode, and maximum. The WITNESS software will provide a random number according to this distribution. The random number will be assigned often between minimum number and the mode if the mode is more skewed to the minimum number. If the mode is skewed to the maximum number then the random number assigned will be often between the mode and the maximum number.

## 5.3 PMLS Tool testing

When the tool is built, important questions will be raised. Is the tool logic right? Does it represent the different processes? Would it compare those different processes as stated in the conceptual design? Pidd (2004) has suggested in this case to apply code testing. The author has applied code testing of the tool in two main steps. Firstly, self-checking the code as well as small test runs were made with proposed data to ensure that the logic is behaving in a correct manner.

The second step was to have the codes and tool logic reviewed by an independent external simulation expert. This step will add confidence on the built tool. The outcome of the review was that the model codes and logic represented the conceptual design despite some typographical errors in the codes due to the complexity of the codes used. These typographical errors have since been corrected.

## 5.4 PMLS tool assumptions

Any tool developed by simulation must have certain assumptions. There is a need to understand the assumptions made in the tool, as these assumptions might explain certain results gained when applying the tool on a specific case study.

This section will address these assumptions made when building this tool and are as follows:

- All monitoring levels are working 100% correctly:
  - No fault found not modelled
  - Diagnostics is correct.
- After each visit, the labour returns to the maintenance centre.
- Each maintenance centre is independent.
- Each customer’s need to be assigned to a particular maintenance centre.
- Each failure mode is independent.

## 5.5 Pilot case study

A pilot case study was applied in order to demonstrate and test the developed PMLS tool. The purpose of this hypothetical case was to test how the implementation of the generic requirements for modelling complex maintenance operations can be captured by the tool. The case is based on a company providing its service support for products used by different customers through a maintenance centre. The features of the case make it appropriate for testing: the incorporation of the areas of potential constraint of products, inventory and labour; the use of multiple products and labour; multiple failure modes; the requirement for specific spares to complete a repair. Figure 5-9 shows how one maintenance centre (which consists of maintenance labour, tools and spare parts) provides maintenance support to two customers, each of whom is located in a different location. Each customer has two different products; each product has a quantity of five. The failure modes of each product are stochastic MTBF. Each failure has its own required spare part (Spare01 for the first failure mode, Spare02 for the second failure mode). By using such a case it is possible to test both the capabilities of simulation in general, as well as the monitoring level logic specifically, to analyse operational set up and the effect on performance. Table 5-1 shows the input data used in this case.

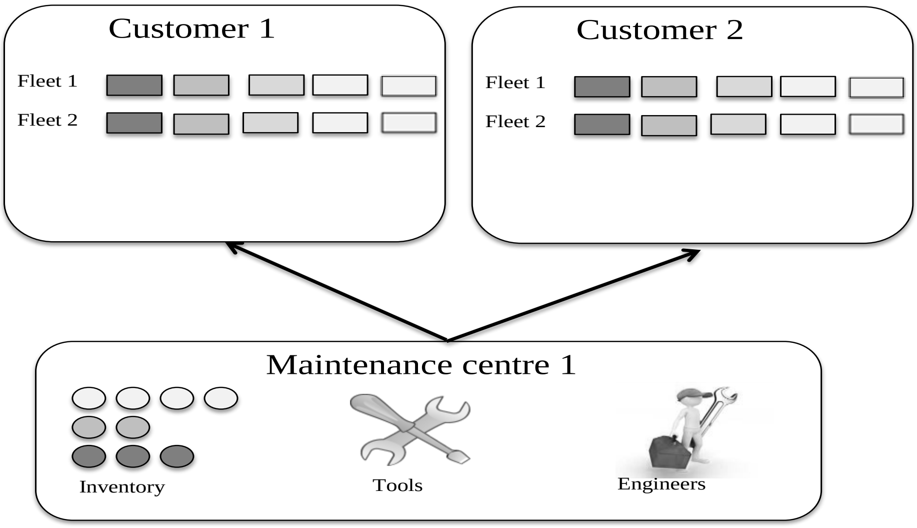


**Figure 5-9 Pilot case study description**

**Table 5-1 Pilot case study input data**

| Parameters | Data |
|---|---|
| **No. of Product** | 20 product (each customer has 2 types of products with quantity of 5 each). |
| **Breakdown patterns** | 2 Failure Modes (FM) for each product. |
| **Average MTBF (1st fleet of 1st customer)** | FM1: 53000 minutes, FM2: 45000 minutes |
| **Average MTBF (2nd fleet of 1st customer)** | FM1: 56000 minutes, FM2: 89000 minutes |
| **Average MTBF (1st fleet of 2nd customer)** | FM1: 78000 minutes, FM2: 52000 minutes |
| **Average MTBF (2nd fleet of 2nd customer)** | FM1: 27000 minutes, FM2: 37000 minutes |
| **No. of Spare parts** | Spare1 is used for FM1, Spare2 is used for FM2 |
| **No. of Engineers** | 1 engineer and then 2 engineers were applied. |
| **Travel time** | 120 minutes on average. |

The case study data were input into the Excel interface sheet used to generate the Witness model. For the prognostics case scenario, a prognostics window (PW) variable was used to model the time in advance that an expected breakdown is predicted. Two variants were used for the PW, initially 400 minutes and later on 800 minutes. The numbers of labour were also varied to enable the maintenance operations decision makers to compare between monitoring levels.

### 5.5.1 Results and Analysis

This section presents and compares the results of the case study described earlier across different product monitoring levels. It also serves to check that the output requirements gathered by the interviews and literature review analysis were captured and shows which monitoring level is more appropriate for this particular case. Figure 5-10 shows a sample of the results obtained from the PMLS tool (showing results for customer 01 only due to the length of results obtained) to show the details that can be grasped from such a tool. The results capture all the required output. As a rule of thumb, suggested by Robinson (2004), the researcher has applied a warm-up period of one year, three years run length, and three replications.

| One Labour | | | | | Custmer01 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Machine01 | | | | | Machine02 | | |
| Machine ID | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5 |
| % Idle | 15.86 | 15.86 | 15.85 | 15.85 | 15.86 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| % Busy | 78.4 | 79.91 | 79.04 | 77.85 | 77.65 | 95.22 | 93.73 | 95.01 | 94.48 | 93.12 |
| Average Wait Resource First Visit % per machine | | | 2.1 | | | | | 1.6 | | |
| Average First Visit % per machine (Travel+Work) | | | 1.3 | | | | | 1 | | |
| Average Wait Resource Second Visit % per machine | | | 1.5 | | | | | 2.2 | | |
| Average Second Visit % per machine (Travel+Work) | | | 1 | | | | | 1.1 | | |
| Diagnose Time per machine | 7.2 | 7.4 | 7.4 | 6.9 | 7.1 | 4.2 | 4.3 | 4.5 | 4.4 | 4.4 |
| Repair Time per machine | 8.6 | 9 | 8.7 | 8.4 | 8.5 | 9.8 | 10.2 | 10.6 | 9.9 | 9.9 |
| Number of Failures per machine | 41 | 42 | 43 | 39 | 40 | 41 | 43 | 45 | 42 | 42 |
| Travel time per machine | 13.7 | 14 | 14 | 13 | 13.3 | 13.7 | 14.3 | 15 | 14 | 14 |
| % Broken Down | 5.74 | 4.22 | 5.1 | 6.3 | 6.49 | 4.78 | 6.26 | 4.98 | 5.51 | 6.88 |
| No. Of Operations | 20603 | 21001 | 20772 | 20459 | 20407 | 16681 | 16421 | 16646 | 16552 | 16313 |
| | | | 103242 | | | | | 82613 | | |
| Availability% | 94.26 | 95.77 | 94.89 | 93.7 | 93.51 | 95.23 | 93.74 | 95.02 | 94.49 | 93.13 |
| No. of Broken down machine at the end of the run | 1 | | | | | | | | | |
| | Shipped | Rejected | | | | | | | | |
| Part01 | 103242 | 1873 | | | | | | | | |
| Part02 | 82613 | 22500 | | | | | | | | |
| Part03 | 78259 | 578 | | | | | | | | |
| Part04 | 78166 | 670 | | | | | | | | |
| | | | | | | | | | | |
| | Labour | | | Tool | | | | | | |
| % Busy | 58.05 | | Busy% | 46.15 | | | | | | |
| % Idle | 48.18 | | Idle% | 53.85 | | | | | | |
| Quantity | 1 | | Quantity | 1 | | | | | | |
| No. Of Jobs Started | 1690 | | No. Of Jobs Started | 1690 | | | | | | |
| No. Of Jobs Ended | 1690 | | No. Of Jobs Ended | 1690 | | | | | | |
| No. Of Jobs Now | 1 | | No. Of Jobs Now | 1 | | | | | | |
| Avg Job Time | 0.55 | | Avg Job Time | 0.55 | | | | | | |
| | | | | | | | | | | |
| | Spare01 | Spare02 | total | | | | | | | |
| Min | 0 | 0 | 0 | | | | | | | |
| Max | 13 | 14 | 27 | | | | | | | |
| Spare used | 443 | 402 | 845 | | | | | | | |
| Average time in inventory | 4.36 | 5.23 | | | | | | | | |

**Figure 5-10 Sample of Reactive level results of the pilot case study**

The simulation runs carried out sought to establish model variants from a single based model. The variants tested the effects of changes in isolation relating to the key areas of the model, namely product, inventory and staffing. By changing the parameters for each area it would be possible to establish how changes effect on the overall performance. Where constraints existed in the model it was likely that changes to parameters relating those constraints would have an impact on the overall performance and where there was excess capacity then there would be a low impact on the overall performance. For example, if there was a significant product capacity constraint it would be likely that product monitoring would impact on the overall performance. The experiments therefore, would test if the PMLS tool can identify where constraints existed and detect the impact on the overall performance.

Figure 5-11 shows the model outputs for two different labour levels and includes product availability, product output, breakdown percentage, breakdown frequency, labour travel time and spares used. It can be noted (Figure 5-11) that the higher the level of monitoring is applied the better performance is gained. However, the question that matters to decision makers is how significant are the improvements? In a low product value, usually a small increase of percentage of availability will not be of importance, whereas in a high product value, any increase in performance metrics would be significant. As can be expected, the travel time is halved when moving from Reactive to Diagnostics or Prognostics where self-diagnosis removes the need for initial staff attendance.

Repair time is practically the same throughout all monitoring levels as the actual repair is done by the labour and almost consumes the same amount of time regardless of the monitoring level. A slight increase in the repair time when moving towards higher a monitoring level is due to the increase in the number of failures when moving to advance monitoring, as the availability increases. This availability increase raises the number of parts shipped and also increases in the number of spare parts used.

The product production is one of the important metrics in some businesses. For example, in the photocopying industry the customers are usually charged according to the number of pages they print or copy rather than the availability of the photocopying machine. In light of this, the developed tool can capture the production number that can be performed by the product as this can be significant in terms of cost and profit. As shown in Figure 5-11 the number of production would increase when moving to a higher monitoring level, as well as when increasing the PW. The PMLS tool caters for lost production and this can be seen in Figure 5-11 in the total number of rejected parts.

In Figure 5-12 important metrics have been selected which are represented by graphs to show the effects of moving from the Reactive to the more advanced monitoring levels. The availability percentage has risen on average with the increased product monitoring level, however, the increase from the Diagnostics to the Prognostics level has been low. Increasing the labour helped more in the Reactive level as the availability increased by 1.5%, whereas in the Diagnostics level, the effect was approximately 0.44%. The Prognostics Window (PW) shows little impact; in this particular case between 400 minutes, and 800 minutes in the case of product availability.

| Parts and spares | Total No. Shipped Parts | | Total No. Rejected Parts | | No. Spare01 Used | | No. Spare02 Used | |
|---|---|---|---|---|---|---|---|---|
| | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour |
| Reactive | 342280 | 345163 | 25621 | 22739 | 443 | 447 | 402 | 406 |
| Diagnostics | 345929 | 346503 | 21973 | 21400 | 448 | 448 | 408 | 410 |
| Prognostics 400 | 346645 | 347070 | 21259 | 20832 | 451 | 453 | 411 | 411 |
| Prognostics 800 | 347003 | 346921 | 20899 | 20982 | 454 | 455 | 413 | 413 |

| Assets | Average Availability % | | Total No. of Failure | | Average Breakdown % | | Total Repair Time (Days) | |
|---|---|---|---|---|---|---|---|---|
| | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour |
| Reactive | 94.60 | 96.13 | 846 | 853 | 5.40 | 3.87 | 195.4 | 197.1 |
| Diagnostics | 97.00 | 97.44 | 856 | 858 | 3.00 | 2.56 | 197.5 | 198.0 |
| Prognostics 400 | 97.73 | 97.81 | 862 | 865 | 2.27 | 2.19 | 199.1 | 199.4 |
| Prognostics 800 | 97.90 | 98.06 | 867 | 868 | 2.10 | 1.94 | 200.2 | 200.4 |

| Labour | Labour Utilisation % | | Total Number of Jobs | | Total Travel Time (Days) | | Total Diagnose Time (Days) | |
|---|---|---|---|---|---|---|---|---|
| | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour | One Labour | Two Labour |
| Reactive | 58.05 | 29.32 | 1690 | 1706 | 281.6 | 284.9 | 126.2 | 127.6 |
| Diagnostics | 27.72 | 13.90 | 856 | 858 | 142.8 | 143.0 | 0 | 0 |
| Prognostics 400 | 27.93 | 14.00 | 862 | 864 | 143.8 | 144.0 | 0 | 0 |
| Prognostics 800 | 28.10 | 14.06 | 867 | 868 | 144.4 | 144.7 | 0 | 0 |

**Figure 5-11 Pilot case average results**

In terms of spare parts, it can be noted that when a higher monitoring level is applied, the number of spares used increases. This is due to increasing the availability which will lead to a rise in the number of failures occurring. This is also true when moving from 1 labour to 2 labours in the same monitoring level because by increasing the number of labours, the maintenance activities can be done faster which will lead to an increase of the availability.

Breakdown percentages show an inverse relationship with availability. The number of failures grows with the increase in the level of monitoring as the availability percentage increases, therefore, the probability of more failures will occur. It is more apparent that when labour is increased from one to two then the number of failures increases.

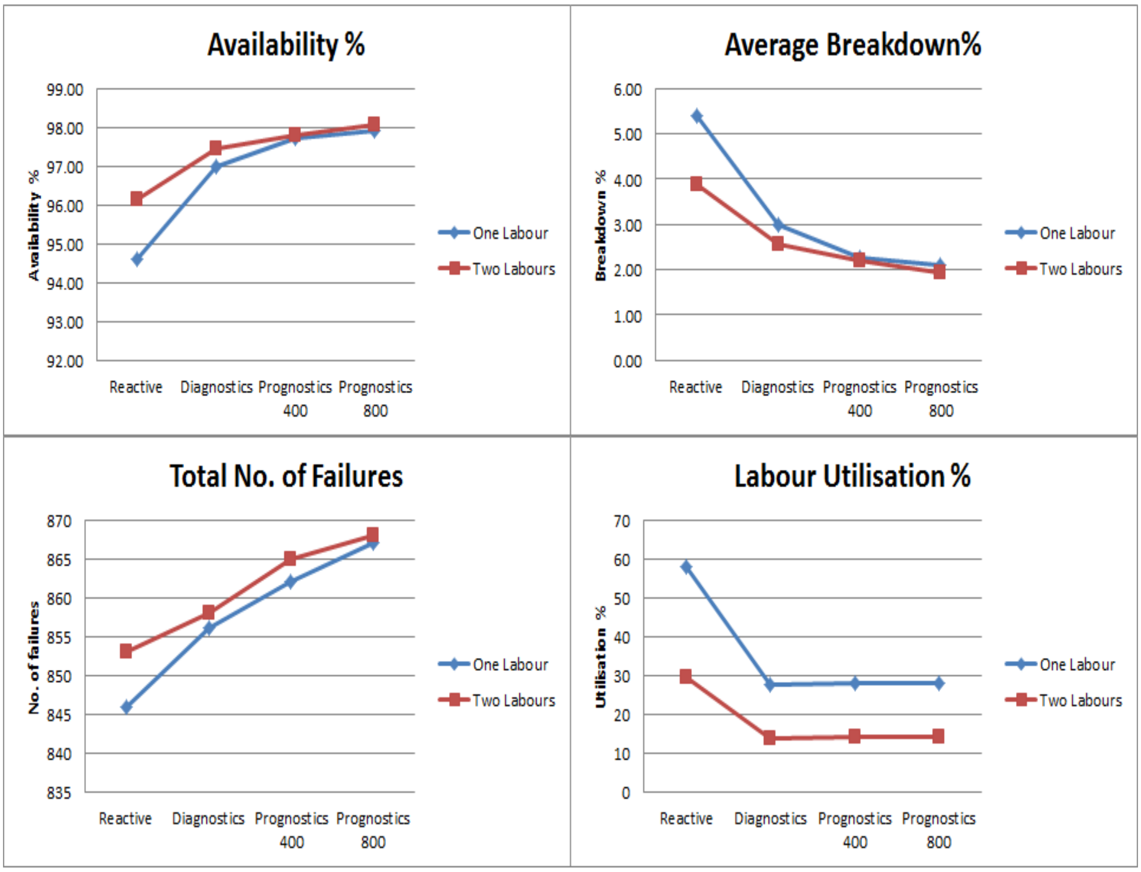


**Figure 5-12 Graphs representing important performance metrics for the pilot case**

### 5.5.2 Pilot case verification

Before moving forward to discuss the simulation output of the pilot case study, it is important to test the credibility of the results obtained. The model in hand needs to go through a verification process by which the researcher can be convinced that the model is properly realised in the computer program. To verify a model, Pidd (2004) recommended that the computer codes be checked by an independent third party if possible. In addition, he suggested to check its input/output relationship.

The first recommendation was applied when the whole tool was built and this has been discussed in section 5.3 of this thesis. Secondly, this pilot case study is presented to check that the tool built is logical and representing reasonable outputs and to check the input/output relationship. In order to do that, the output of the pilot case study was sense checked. This was covered in two main steps; firstly to sense check the output results and compare them with other related models' outputs. An example for sense checking would be to check the total number of spare parts used against the total number of failures as they should match. Secondly, to apply different experimentations to the pilot case study to check if the tool is able to detect the experimental changes. The latter has been discussed in the previous results and analysis section while the output relationship to the input will be discussed here.

To sense check the outputs, a few questions would arise such as: does the number of failures match the number of spares used? Does the number of jobs completed by the labour match the number of failures? Does the availability % with the Breakdown % accumulate to 100%? Does the number of product operations match the number of parts produced? These questions were asked and answers were checked in every experiment made. In this section, the author will illustrate answering these questions for the Reactive model only to show the concept of sense checking. Other experiment's sense checking were not shown here due to similarity.

In the Reactive model, the total number of failures (all failure modes are included) for all the products is 845. When checking the number of spares used, Spare01 has been used 443 times, while Spare02 is used 402 times. Thus, the total number of spare parts used is (443+402)=845 which matches the number of failures. The number of jobs that were done by labour were 1690 which is double the number of failures. In the Reactive scenario, this is due to the labour having to make two visits for the same failure. The average availability % for all the products for all customers was 94.60%, while the average Breakdown % for all the products for all customers was 5.39% which makes their cumulative total ≈100%.

Henceforth when checking the number of operations for each machine, it should match the number of parts produced by the product. The total number of operations was 342,280 which matches the total number of parts produced. At this point, the author has compared the total or the average numbers to simplify it for the reader. In actual fact checks were done to each product separately in all the experimentation to ensure that the logic worked in the correct manner.

## 5.6 Summary

This chapter has explained how the PMLS tool was developed taking into account the requirements that were gathered in Chapter 4. Firstly by exploring the built-in functionality that Witness can offer. Then, explaining how the functionality to build the PMLS tool was developed followed by introducing the Excel interface that was built to ease the use of such a tool.

In addition, the tool testing and assumption were presented. A pilot case study was applied to ensure that the tool logics are working reasonably and verification of the case model was discussed. This chapter has satisfied and answered the second question of this research which was: How can discrete event simulation models be created to capture the behaviour of complex maintenance operations?

The next chapter will discuss the industrial case studies and the experimentations that were performed to gain more insight in applying different monitoring levels in complex maintenance operations using a Discrete Event Simulation approach.

# 6 PMLS TOOL VERIFICTION BY INDUSTRIAL CASE STUDIES

## 6.1 Introduction

After gathering the requirements for modelling complex product maintenance systems, and building the Product Monitoring Levels Simulation (PMLS) tool the researcher applies industrial cases to test and demonstrate the proposed tool. In this chapter, the researcher will present three industrial cases that were applied to the developed PMLS tool. In addition, experiments with those cases have been carried out to gain further insight and understanding of such complex systems. The experiments are the fundamental essence of research as they discover something about a particular process or system. Montgomery (2008) has defined experimentations as “a test or series of tests in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response”.

In this chapter, the researcher will start by stating the purpose of the experimentation conducted and explain the experimentation approach applied. Then, each industrial case will be introduced and the experiments set up for each case will be discussed. This is followed by a discussion on the results obtained and the validation process used.

## 6.2 Experimentation approach

The purpose of the experiments carried out are firstly to ensure that the developed tool can mimic the current (As-Is) complex maintenance operations and the effect of different monitoring levels on the current situation. Other experiments have been carried out and the purpose of these is to assess if the tool can absorb the changes of some factors as well as to gain more insight and understanding of how these factors affect the complex maintenance operations.

Experimentation approaches are usually classified into two: Factorial Experiment (FE) and One Factor At a Time (OFAT) (Pidd, 2004). FE can be made to investigate the interactions between the factors and how that would affect the responses (Czitrom, 1999). Usually this approach is applied when best solutions to improve the system are being sought. In addition, when conducting simulation experiments dealing with multiple factors on different levels, there is a need to replicate each experiment which makes it a very time consuming task (Robinson, 2004). Furthermore, if the purpose of the study is to gain more understanding of the system being simulated, FE is less likely to be applied (Andijani and Duffuaa, 2002).

This research aims to better understand such complex maintenance operations with different product monitoring levels. To gain more insight, it would be interesting to investigate the effect of a single factor on the system outputs to explore how this affects the system behaviour. This research is not about studying the factors mixture to evaluate their effect on each other. In addition, industrial cases were applied as the tool testing method while the OFAT approach is applied more frequently in practice (Montgomery,2008). It studies the effect of individual factors (input) on the responses (output) of the system (Wu and Hamada, 2000). The OFAT approach satisfies the simulation experimentation in this research as it provides an insight on each factor being changed and its effect on the responses. Furthermore, the experimentation was to assess if the developed tool can discern the different scenarios used to ensure the tool is behaving in the intended manner.

From the earlier requirements gathered in Chapter 4 it can be identified that there are broadly three main factors; equipment ‘product’, labour, and inventory. Based on these factors some questions have been raised. These questions were raised before contacting the potential case companies and were based on the generic requirements gathered as follows:

1. What would be the impact of improving or decreasing the product MTBF?
2. What would be the impact of different Prognostics Windows (PW)?

3. What would be the impact of increasing or decreasing the labour count?
4. What would be the impact of increasing or decreasing the travel time?
5. What would be the impact of increasing or decreasing the spare parts lead time and minimum reorder quantity?

These are common starting questions for each case. However, they may be refined to take account of case specific features. Before explaining each industrial case, it will be intuitive to give the reader a summary of the industrial cases, as shown in Table 6-1.

**Table 6-1 Summary of industrial cases**

| Company ID | Case 01 | Case 02 | Case 03 |
|---|---|---|---|
| **Location** | Saudi Arabia | United Kingdom | United Arab Emirates |
| **Field** | Refrigeration | Water pumps | Utility station |
| **Monitoring level applied** | Reactive | Reactive | Diagnostics |
| **No. of locations** | 4 | 1 | 4 |
| **Total No. of Product** | 6 | 100 | 98 |
| **Data obtained by** | Company estimation | Company estimation | Computer system |
| **Willingness to adopt monitoring levels?** | No | Yes | Yes |
| **How they assess the move to other monitoring levels?** | N/A | Unknown to them | Based on comparison between the cost and severity of the breakdown |

The industrial cases shown in Table 6-1 are fundamentally different. Their differences are: representative of different industries, applying different monitoring levels, different number of customers (locations), and different number of products.

A description of the industrial cases and the results obtained are presented next.

## 6.3 Industrial case 01

This case company is a large perishable food importer into Saudi Arabia. It distributes the food (e.g. cheese, vegetables, and chicken, etc.) across Saudi

Arabia which will be stored in main hub areas ready to be distributed to nearby cities and villages. This company has four main distribution hubs which hold huge refrigerating systems in order to store the perishable food. These refrigerators are huge and their capacities are measured in tons. Refrigeration systems are significant to this company. A breakdown of a few hours in these refrigerators will result in massive losses. Therefore, maintaining these refrigerators is essential for its business.

This company has two large hubs and two smaller hubs. Each of the large hubs have two refrigeration systems while the other two hubs own only one each. The maintenance activities in this company are done in-house. All of the refrigerating systems installed in each of the hubs are similar. Each system installed has four failure modes and each one needs a specific spare part in order to repair it. It is worth mentioning that these refrigerating systems are working continuously. Figure 6-1 shows the schematic diagram of the case study details.

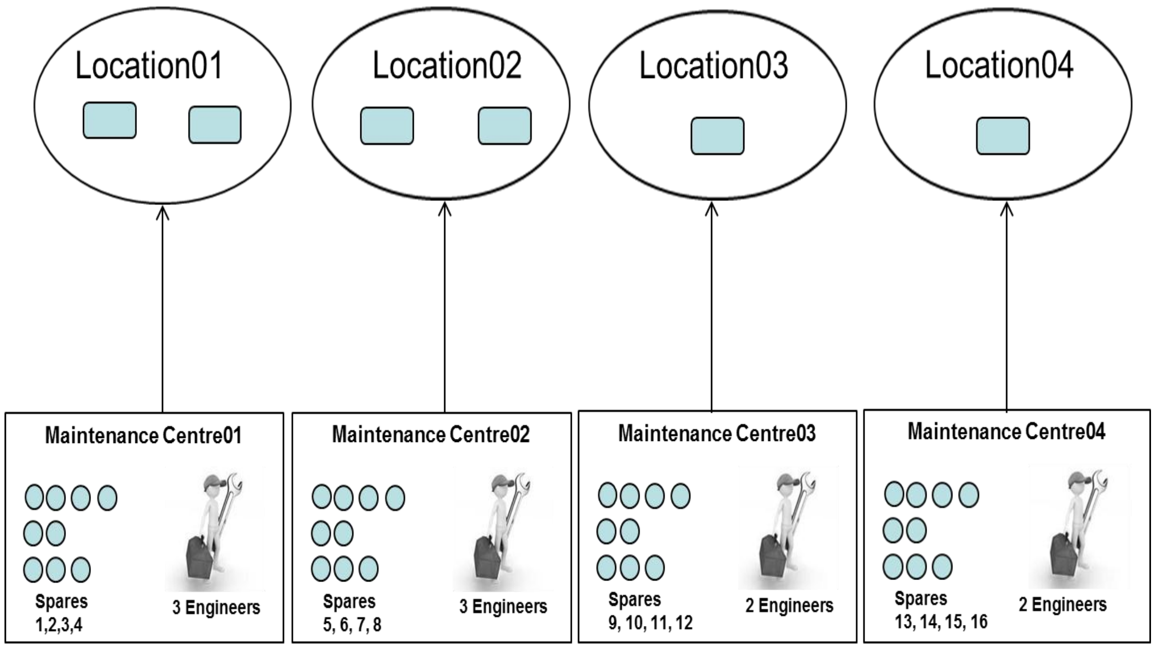


**Figure 6-1 Schematic diagram of case 01**

Location01 and location02 are the major distribution hubs of the company which have two refrigerating systems with three dedicated maintenance engineers each. Location03 and location04 are identical and have one refrigerator with two engineers on each location on standby for maintenance. The engineers will immediately diagnose and repair the refrigerating system once it fails (Reactive Maintenance). MTBF is relatively high which is typical in refrigerating systems. All data required has been obtained through a face to face interview with the maintenance manager of the company who is a maintenance engineer with experience in the field of refrigerating systems of more than 20 years. Triangular distribution has been chosen to represent MTBF, Diagnose, and repair times for ease of estimation.

All the refrigerating systems installed at all the hubs are by different manufacturers but similar in their failure modes and their associated MTBF. The only difference among these systems are the spare parts related to each failure mode. In this case, this company has 12 different spare parts. Table 6-2 shows case study information obtained from the case company.

**Table 6-2 Case 01 input data**

| Location | Location01 | Location02 | Location03 | Location04 |
|---|---|---|---|---|
| **No. of refrigerating units** | 2 | 2 | 1 | 1 |
| **No. of engineers** | 3 | 3 | 2 | 2 |
| **No. of failure modes** | 4 | 4 | 4 | 4 |
| **Spare parts** | Spare01,02,03, 04 | Spare05,06,07, 08 | Spare09,10,11, 12 | Spare13,14,15, 16 |
| **Failure mode01** | MTBF (mins):Triangular Distribution (86400,259200,518400) | | | |
| | Diagnose time (min):Triangular Distribution (60,120,840) | | | |
| | Repair time (min):Triangular Distribution (720,1080,1440) | | | |
| **Failure mode02** | MTBF (mins):Triangular Distribution (86400,129600,259200) | | | |
| | Diagnose time (min):Triangular Distribution (60,120,840) | | | |
| | Repair time (min):Triangular Distribution (720,1080,1440) | | | |
| **Failure mode03** | MTBF (mins):Triangular Distribution (518400,864000,1036800) | | | |
| | Diagnose time (min):Triangular Distribution (60,120,840) | | | |
| | Repair time (min):Triangular Distribution (20,25,30) | | | |
| **Failure mode04** | MTBF (mins):Triangular Distribution (86400,172800,259200) | | | |
| | Diagnose time (min):Triangular Distribution (60,120,840) | | | |
| | Repair time (min):Triangular Distribution (60,150,720) | | | |
| **Lead time** | 20 days | | | |
| **Reorder quantity** | 3 each except for Spare03,07,11,15 are 1 each | | | |
| **Safety stock** | 1 for all spares | | | |

The next section will discuss the experimentation set-ups (run length, warm-up period, and number of replications). In addition, it will list the number of experimentations conducted in this case.

### 6.3.1 Case 01 experiment setup

When a simulation experiment is about to be conducted, a setup for the experiment needs to be made. Experiment setups in simulation are often simulation run length, warm-up period, and number of replication needed.

According to Robinson (2004) there are two different types of simulation models: terminating and non-terminating models. A model will be considered terminating when there is a natural end point to terminate the run length of the model (e.g. bank closes at the end of the day, end of the busy lunch period at a supermarket), whereas the model would be considered as non-terminating when no natural end point exists and the model would only end when the simulation run would be terminated by the user.

The nature of the models to be simulated in this research are non-terminated models. For non-terminated simulation the model output often reaches a steady-state. To reach a steady-state output, the output will gradually go through an initial transient period. Usually, in the beginning of the simulation run, the model is not stable and it builds up until it reaches the steady-state output.

To obtain accurate output results for non-terminated simulations, the user needs to determine the warm-up period. In addition, the user needs to either have a long run or multiple replications. By performing multiple replications and taking the mean of the results, a better estimate of model performance is gained. Performing multiple replications is equivalent to taking multiple samples in statistics. Meanwhile, performing one long run is equivalent to taking one large sample.

In this industrial case, the run length was decided to be for five years. This decision was agreed by the case company and the researcher as a sufficient number of breakdowns will occur during such a period for each product. while, the warm-up period was decided to be for one year (one year warm up, five years run length). This was based Time-series inspection suggested by Robinson (2004). He stated that one of the model output should be measured through the model running time and the modeller can decide visually where the steady-state of the system starts. By doing so, the warm-up period needed can be decided. For this research, the researcher decided to use labour utilisation as an output measure to decide the warm-up period as the labour utilisation is associated with the product breakdown which is the main concern for this research. Time-series charts for warm-up can be is shown in appendix D.

The number of replications was decided based on a rule of thumb (three to five replications) suggested by Pidd (2004) and Robinson (2004). In addition, the researcher has calculated the required number of replications based on a confidence interval method. Table 6-3 confirms that two replications are sufficient as the deviation is less than 1%. The calculations were based on the (As-Is) model, and the output measure used for this calculation was the average availability percentage of the refrigerators. Combining the rule of thumb and the confidence interval method, the researcher decided to select three replications to be used in this case.

**Table 6-3 No. of replications calculation based on the confidence interval method for case 01**

| | | | | **Significance level** | **5.0%** | |
|---|---|---|---|---|---|---|
| | | | | **Confidence interval** | | |
| **Replication** | Result-Availability % | Cum. mean average | Standard deviation | Lower interval | Upper interval | % deviation |
| **1** | 98.32 | 98.32 | n/a | n/a | n/a | n/a |
| **2** | 98.29 | 98.31 | 0.021 | 98.11 | 98.50 | 0.19% |
| **3** | 98.23 | 98.28 | 0.046 | 98.17 | 98.39 | 0.12% |

A set of experiments have been conducted for this case. These experiments were based on the questions raised in section 6.2 and are shown in Table 6-4.

**Table 6-4 Experiments conducted for case 01**

| No. | Experiment description |
|---|---|
| 1 | As-Is |
| 2 | Labour reduction to one at all locations |
| 3 | Travel time 240 (mins) |
| 4 | Travel time 720 (mins) |
| 5 | Increase the MTBF by 50% |
| 6 | Decrease the MTBF by 50% |
| 7 | Increase spares lead time and decrease Min. reorder quantity |

Three scenarios (Reactive, Diagnostics, and Prognostics) were compared for each of the experiments. Furthermore, different Prognostics Windows (PW) were applied.

Seven different experiments were applied with three monitoring levels, while the Prognostics level has been applied with three different PWs which are (PW=400 min, PW=1000 min, and PW=86400 min). These different PWs were to assess different levels of PW on maintenance operations. In addition, a significant PW value (PW=86400 min) was decided to assess the scenario when PW > spares lead time (this was only applied when experimenting with the spare lead time). Bearing in mind that three replications for each scenario were decided, this makes the total number of the simulation runs for this case come to 84 runs. Following this, the analysis of the results obtained will be presented and followed by a validation process.

### 6.3.2 Industrial case 01 results and discussion

In this section, the results of the different experimentations for case 01 will be analysed and discussed. The researcher will show the standard results obtained from an experiment as guidance in showing the reader what type of results can be obtained.

Figure 6-2 shows the average results obtained for the As-Is scenario applied to the Reactive level only. (results tables of case 01 can be found in appendix C, while appendix E provides PMLS tool snap shot for case01).

| Avg | Location01 | | Location02 | | Location03 | Location04 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Machine01 | | Machine02 | | Machine03 | Machine04 | | | | | | | | | | | |
| Machine ID | 1 | 2 | 1 | 2 | 1 | 1 | | | | | | | | | | | |
| Idle% | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | |
| Busy% | 98.30 | 98.33 | 98.24 | 98.28 | 98.30 | 98.22 | | | | | | | | | | | |
| Average Wait Resource First Visit % per machine | 0.00 | | 0.00 | | 0.00 | 0.00 | | | | | | | | | | | |
| Average First Visit % per machine (Travel+Work) | 0.56 | | 0.54 | | 0.50 | 0.58 | | | | | | | | | | | |
| Average Wait Resource Second Visit % per machine | 0.00 | | 0.00 | | 0.00 | 0.00 | | | | | | | | | | | |
| Average Second Visit % per machine (Travel+Work) | 1.20 | | 1.17 | | 1.17 | 1.20 | | | | | | | | | | | |
| Diagnose Time per location (days) | 10.28 | | 9.92 | | 9.19 | 10.59 | 9.99 | Avg | | | | | | | | | |
| Repair Time per location (days) | 21.90 | | 21.29 | | 21.29 | 21.90 | 21.60 | Avg | | | | | | | | | |
| Number of Failures per machine | 42 | 41 | 42 | 41 | 42 | 43 | 250 | Total | | | | | | | | | |
| Travel time per machine (days) | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | | | | | | | | | | |
| Broken Down% | 1.7 | 1.67 | 1.76 | 1.72 | 1.70 | 1.78 | 1.72 | Avg | | | | | | | | | |
| No. Of Operations | N/A | N/A | N/A | N/A | N/A | N/A | avg | | | | | | | | | | |
| Availability% | 98.30 | 98.33 | 98.24 | 98.28 | 98.30 | 98.22 | 98.28 | | | | | | | | | | |
| No. of Broken down machine at the end of the run | 0 | | | | | | | | | | | | | | | | |
| | Man01 | Man02 | Man03 | Man04 | Totals | | | | | | | | | | | | |
| Busy% | 1.16 | 1.12 | 0.85 | 0.89 | | | | | | | | | | | | | |
| Idle% | 98.84 | 98.88 | 99.15 | 99.11 | | | | | | | | | | | | | |
| Quantity | 3.00 | 3.00 | 2.00 | 2.00 | | | | | | | | | | | | | |
| No. Of Jobs Started | 83.00 | 82.67 | 42.00 | 42.67 | 250.33 | | | | | | | | | | | | |
| No. Of Jobs Ended | 83.00 | 82.67 | 42.00 | 42.67 | 250.33 | | | | | | | | | | | | |
| No. Of Jobs Now | 0.00 | 0.00 | 0.00 | 0.00 | | | | | | | | | | | | | |
| Avg Job Time (days) | 0.76 | 0.74 | 0.73 | 0.76 | | | | | | | | | | | | | |
| | Spare01 | Spare02 | Spare03 | Spare04 | Spare05 | Spare06 | Spare07 | Spare08 | Spare09 | Spare10 | Spare11 | Spare12 | Spare13 | Spare14 | Spare15 | Spare16 | |
| Spare used | 18.00 | 31.00 | 5.67 | 28.33 | 16.33 | 32.33 | 5.33 | 28.67 | 9.33 | 15.67 | 2.67 | 14.33 | 9.00 | 16.00 | 2.67 | 15.00 | 250 |
| Average quantity in inventory | 2.68 | 2.63 | 1.94 | 2.61 | 2.68 | 2.56 | 1.94 | 2.67 | 2.85 | 2.80 | 1.97 | 2.83 | 2.85 | 2.79 | 1.97 | 2.84 | |
| Maximum spares in inventory | 4.00 | 4.00 | 2.00 | 4.00 | 4.00 | 4.00 | 2.00 | 4.00 | 4.00 | 4.00 | 2.00 | 4.00 | 4.00 | 4.00 | 2.00 | 4.00 | |
| Minimum spares in inventory | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| total spare used per location | | | | 83 | | | | 83 | | | | 42 | | | | 43 | |

**Figure 6-2 Example of case01 average results for (As-Is) Reactive level**

A comparison between experiments conducted in all the three monitoring levels will be presented and discussed here. Due to the length of the results obtained, the researcher will focus on applying the comparisons of different monitoring levels based on the main measures of availability percentages, breakdown percentages, number of failures and labour utilisation percentages. Other metrics such as idle percentages, busy percentages for refrigerators and labour are collectively reported in these main metrics.

Figures 6-3, 6-4 and 6-5 show the comparisons of availability percentages, breakdown percentages, and number of failures on different experiments. A discussion of each experiment will be presented as follows:

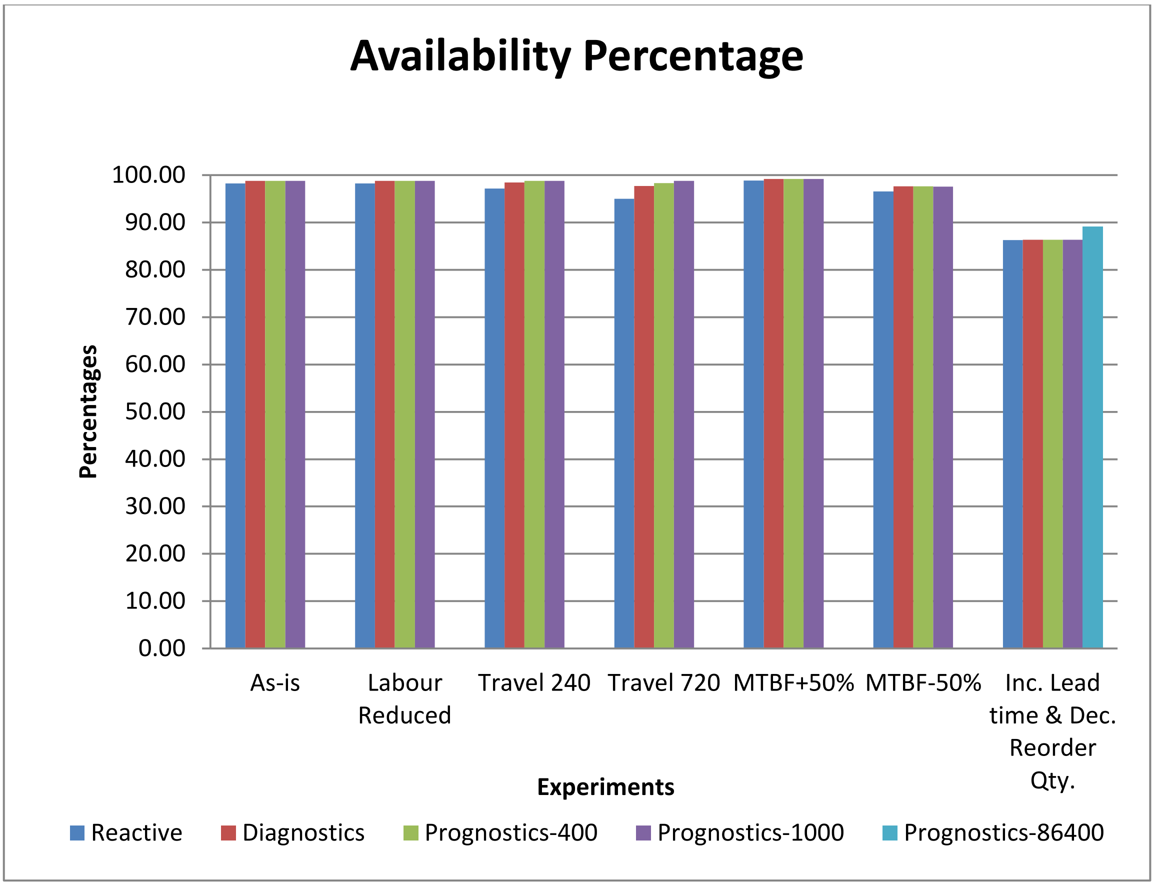


**Figure 6-3 Case 01 availability percentages across different experiments**

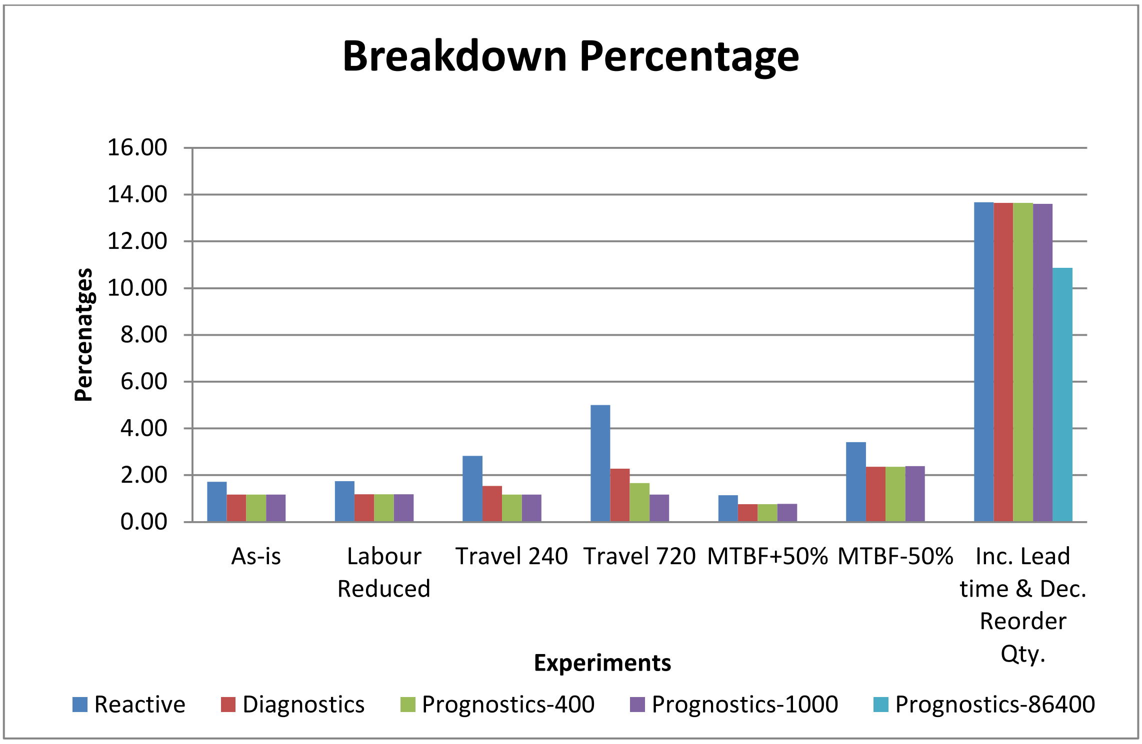


**Figure 6-4 Case01 breakdown percentages across different experiments**

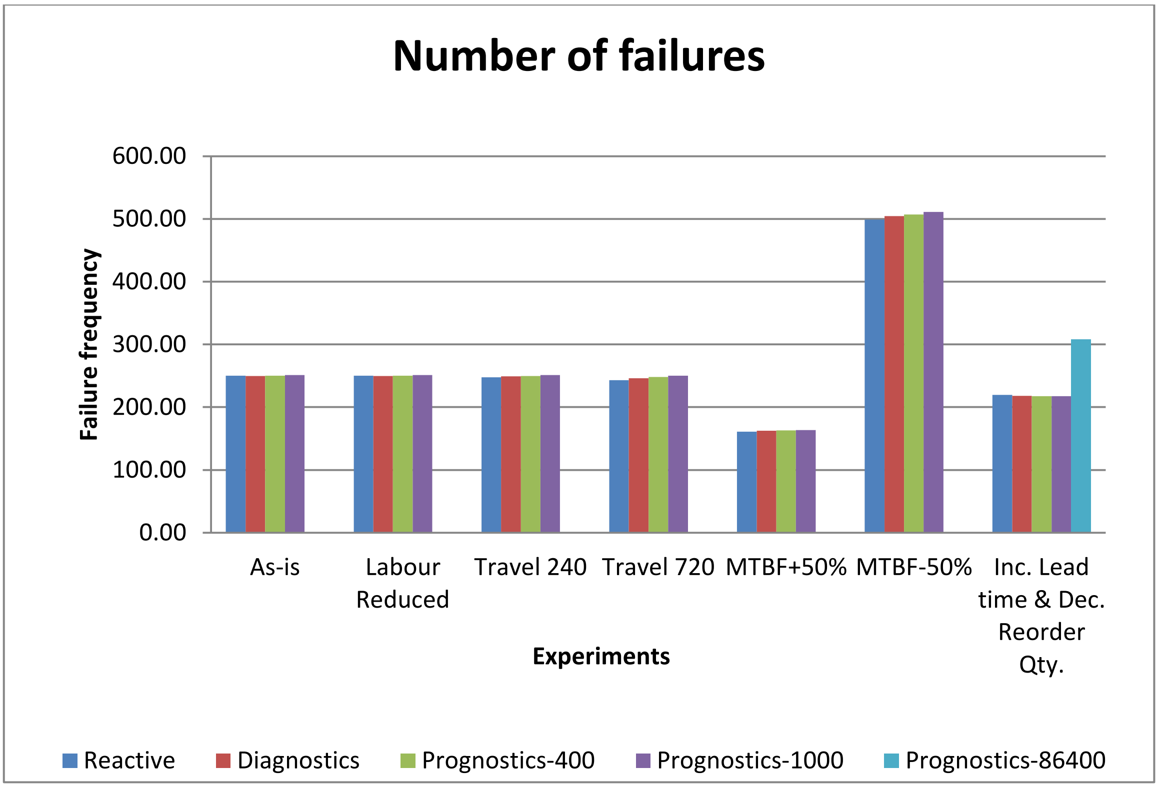


**Figure 6-5 Case01 number of failures across different experiments**

- **As-Is scenario and Labour reduction**

As this case is about maintaining the refrigerating system and taking into account the high MTBF for such systems, this explains the high availability already obtained. As-Is and labour reduction scenarios were combined in the discussion here as they provide the same results. The number of labour in the As-Is scenario is clearly more than the company actually needs. When this was raised to the case company, the reply was that having more labour is preferable compared to losing perishable food which is worth millions of Saudi Riyals (SR) due to a breakdown. In addition, the labour costs are low. Consequently, the researcher decided to conduct another experiment with the minimum number of labours (one labour) at each maintenance centre. The results of the As-Is and the labour reduction are the same.

In the As-Is and labour reduction scenarios, it can be noted that Diagnostics and Prognostics in general give slightly better availability than Reactive. This improvement of 0.55% is small compared to that of the Reactive level which in this case is already achieving high availability. The reader might be surprised to discover why the Diagnostics and Prognostics levels in these scenarios provide exactly the same results. Figures 6-6 and 6-7 explain the reason behind this, particularly as there is no travel time and that all the resources needed, such as labour and spares, are always available.

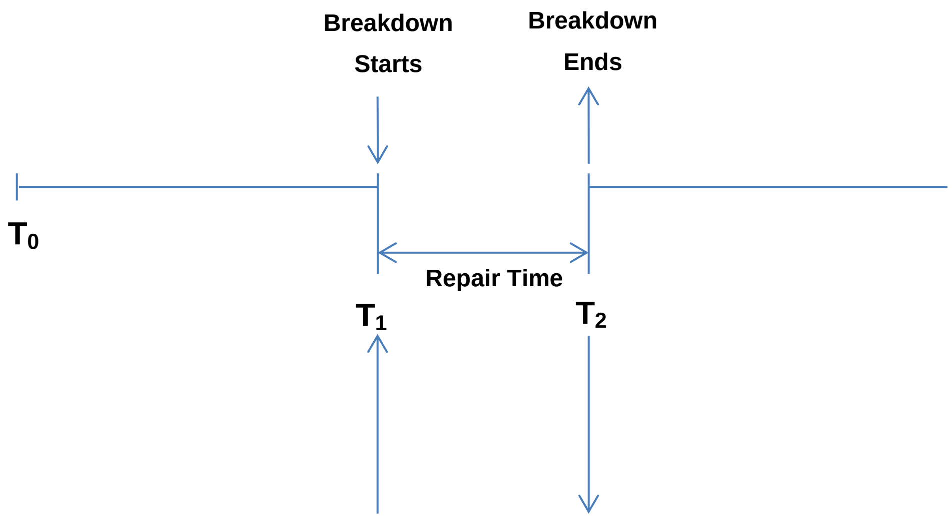


**Figure 6-6 Diagnostics level case when no travel time and all resources available**

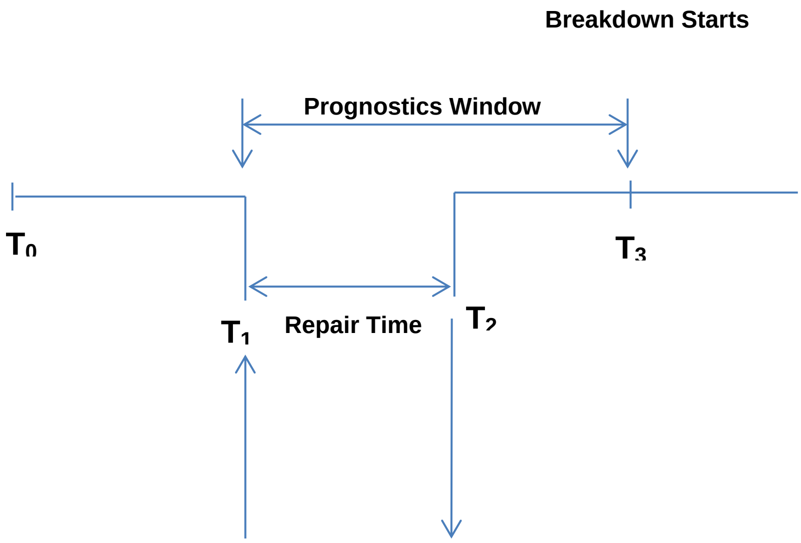


**Figure 6-7 Prognostics level case when no travel time and all resources available**

Figure 6-6 shows that in the case of the Diagnostics level applied, where all resources are available and there is no travel time to the product, then the failure is supposed to happen at $T_1$. As there is no travel time and resources are all available then the repair will start at $T_1$ until $T_2$ as there will be no waiting for resources at all.

Figure 6-7 explains what happens when the Prognostics level has been applied where all resources are available and there is no travel time to the product. Failure is expected to happen at time $T_3$ but as the Prognostics Window (PW) is applied, the resources should be triggered at $T_1$. Repair activity will take place immediately at $T_1$ by stopping the product and carrying out the repair activity. Downtime for both Diagnostics and Prognostics in this particular case will be the same. The only difference is that in the case of Prognostics the repair time will be shifted earlier but the magnitude of repair time will be the same. This explains the reason why Diagnostics and Prognostics give the same results in the first two experiments (As-Is and Labour reduction). Breakdown percentages reflect the opposite direction of availability percentages which is correct as the sum of both the availability and breakdown percentages comes to 100%.

The number of failures, as seen in Figure 6-5, increase as the higher monitoring levels are applied. This is as the availability increases which logically increases the number of failures occurring.

**Table 6-5 Labour utilisation percentages for As-Is and labour reduction experiments for case01**

| | As-is | | | | Labour Reduced | | | |
|---|---|---|---|---|---|---|---|---|
| Monitoring levels/Labour | Location01 | Location02 | Location03 | Location04 | Location01 | Location02 | Location03 | Location04 |
| Reactive | 1.16 | 1.12 | 0.85 | 0.89 | 3.48 | 3.37 | 1.70 | 1.78 |
| Diagnostics | 0.78 | 0.77 | 0.57 | 0.63 | 2.32 | 2.30 | 1.15 | 1.25 |
| Prognostics-400 | 0.78 | 0.77 | 0.57 | 0.63 | 2.35 | 2.30 | 1.15 | 1.25 |
| Prognostics-1000 | 0.79 | 0.78 | 0.57 | 0.63 | 2.36 | 2.32 | 1.15 | 1.25 |

Table 6-5 shows the labour utilisation percentages in both experiments. Location01 to Location04 represent the labour utilisation percentages at each maintenance location of case 01. As can be seen, utilisation percentages are very low; however, this was expected due to the nature of the maintenance activities and the high number of labour utilised. The labour are used during the job time to carry out other non-maintenance activities. These activities were not modelled as the priority was always for the maintenance of the refrigerating systems.

The Reactive shows higher utilisation percentages as expected due to the labour diagnosing and repairing the product, whereas in other levels the diagnosing activities are carried out by the monitoring technologies installed. Labour utilisation increased when the number of labour was reduced to one at all locations.

- **Travel time 240 (min) and travel time 720 (min)**

In these experiments two levels of travel times (240 minutes and 720 minutes) were applied from the As-Is model. The reason behind the choice of these travel levels was to have one travel time (240 minutes) below all the Prognostics Windows applied in these experiments (P-400, P-1000) and the other travel time (720 minutes) to be between the PW applied in order to assess the effect of travel times on the PW.

In the case of the 240 minutes travel time, it can be noted that the higher the monitoring level is applied then the higher availability is gained. However, in the Prognostics level as the travel time is below all of the PWs, it can be seen from Figure 6-3 that there is no improvement in the availability which will be gained among the different PWs applied. In contrast, when the 720 minutes travel time is applied it is clear that when the PW is more than the travel time (P-1000) then more availability is achieved, whereas when the PW is less than the travel time then the availability decreases. Travel time has a clear effect on the product availability performance and the developed tool has enabled a better understanding of this effect. As discussed earlier in other experiments, breakdowns reflect the opposite percentages to the availability which is reasonable.

The number of failures increases slightly when higher monitoring levels are applied. However, in the case where the travel time is 240 minutes, the number of failures is the same between P-400 and P-1000. In the case of 720 minutes travel time, the number of failures has increased a little between P-400 and P-1000.

Table 6-6 shows the labour utilisation when travel time is applied. It is obvious that the utilisation percentages increased as the travel times were included with the Reactive level giving a higher utilisation than other levels due to manual diagnosing activities. As the number of failures increases slightly towards higher monitoring levels, the utilisation percentages increase as well. When the travel time is longer (travel 720 minutes) an obvious increase in the utilisation is noticed.

**Table 6-6 Labour utilisation percentages for travel time experiments of case01**

| | Travel 240 minutes | | | | Travel 720 minutes | | | |
|---|---|---|---|---|---|---|---|---|
| Monitoring levels/Labour | Location01 | Location02 | Location03 | Location04 | Location01 | Location02 | Location03 | Location04 |
| Reactive | 2.14 | 2.10 | 1.61 | 1.64 | 4.06 | 4.04 | 3.07 | 3.10 |
| Diagnostics | 1.27 | 1.27 | 0.94 | 1.01 | 2.27 | 2.24 | 1.67 | 1.78 |
| Prognostics-400 | 1.28 | 1.27 | 0.94 | 1.01 | 2.28 | 2.27 | 1.69 | 1.79 |
| Prognostics-1000 | 1.29 | 1.28 | 0.94 | 1.01 | 2.31 | 2.28 | 1.70 | 1.79 |

- **MTBF+50% and MTBF-50%**

These experiments were conducted to assess whether the developed tool is also able to grasp the changes in the MTBFs as it would be of interest to the research to assess the effect of MTBF on different monitoring levels. Firstly MTBFs in this case study have been increased by 50%. Then, another experiment was done when the MTBF is decreased by 50% from the As-Is model.

In the MTBF+50% experiments, a slight performance improvement has been achieved in terms of availability percentage from the As-Is model. In the Reactive level this has increased the availability by 0.57% from the As-Is model while the improvements were 0.41% for the rest of monitoring levels. These improvements were only slight due to the fact that the base model (As-Is) is already achieving a very high availability. Still higher monitoring levels give slightly better availability than the Reactive level. Diagnostics and Prognostics levels achieved the same availability levels for the same reasons that were discussed in the As-Is model when both levels gave identical availability results.

When the MTBF-50% experiment was conducted it shows a drop in the availability in general from the As-Is model. The Reactive level in MTBF-50% availability dropped by 1.70% from the Reactive in the As-Is with other levels dropping from the As-Is model by almost 1.20%. Again, with the MTBF-50% experiment, Diagnostics and Prognostics levels show that they achieve a slight increase of 1.04% in availability than the Reactive level.

**Table 6-7 Labour utilisation percentages for MTBF+50% and MTBF-50% experiments**

| | MTBF+50% | | | | MTBF-50% | | | |
|---|---|---|---|---|---|---|---|---|
| **Monitoring levels/Labour** | **Location01** | **Location02** | **Location03** | **Location04** | **Location01** | **Location02** | **Location03** | **Location04** |
| **Reactive** | 0.79 | 0.74 | 0.56 | 0.60 | 2.28 | 2.26 | 1.72 | 1.72 |
| **Diagnostics** | 0.51 | 0.50 | 0.38 | 0.40 | 1.59 | 1.56 | 1.15 | 1.21 |
| **Prognostics-400** | 0.51 | 0.50 | 0.38 | 0.40 | 1.59 | 1.57 | 1.15 | 1.22 |
| **Prognostics-1000** | 0.51 | 0.51 | 0.39 | 0.40 | 1.60 | 1.59 | 1.16 | 1.23 |

Table 6-7 shows the labour utilisation when experimenting with MTBF. Obviously more labour utilisation will be shown for the case of MTBF-50% as more failures occur. Generally, the Reactive gives higher utilisation, while the utilisation in the case of Diagnostics and Prognostics gives a very slight increase of 0.01% in some cases as the number of failures increases.

- **Increasing spares lead time and decreasing minimum reorder quantity**

In the base model the spares lead time was 20 days on average. With this lead time in the As-Is model, high availability has been achieved due to the reason that MTBF obtained from the company is relatively high as well as the spares always being available every time a failure occurs. Thus, the researcher has decided to examine the effect of increasing the spares lead time to 60 days. Also, the minimum reorder quantity of the spares has been set to one to establish a starving inventory situation.

A new PW of 86400 minutes (60 days) is added to this experiment (P-86400) to test if the PW > spares lead time would be reflected on the product performance.

A significant drop in availability was seen from the As-Is model which was about 98% to 86% at all monitoring levels when the lead time of spares was increased. However, setting the PW to 86400 minutes in this experiment gives a higher availability among all levels of monitoring as it increased from 86% to 89%. Diagnostics shows a very slight increase over the Reactive level by 0.03%. Diagnostics and P-400 gives the same availability, while P-1000 has increased the availability from P-400 by 0.04%. The spares lead time has shown its effect on setting the PW.

The number of failures has also increased slightly when moving to higher monitoring levels. However, it shows a sharp increase when P-86400 has been applied which is associated with the availability increase.

**Table 6-8 Labour utilisation percentages for increasing lead time and decreasing reorder quantity experiments**

| | Inc. Lead time & Dec. Reorder Qty. | | | |
|---|---|---|---|---|
| **Monitoring levels/Labour** | **Location01** | **Location02** | **Location03** | **Location04** |
| **Reactive** | 0.96 | 0.91 | 0.85 | 0.89 |
| **Diagnostics** | 0.63 | 0.60 | 0.57 | 0.63 |
| **Prognostics-400** | 0.63 | 0.60 | 0.57 | 0.63 |
| **Prognostics-1000** | 0.63 | 0.60 | 0.57 | 0.63 |
| **Prognostics-86400** | 0.78 | 0.80 | 0.93 | 0.98 |

Table 6-8 shows the labour utilisations for this experiment. It is evident that the utilisation percentages in general have dropped compared to the As-Is model. This was based on the shortages in the spares inventory due to the lengthy lead time. A higher utilisation was achieved when the PW was set to 86400 minutes as the resources were triggered in advance to match the spares lead time. This was obvious due to the higher availability achieved.

After analysing and discussing the results obtained from the developed tool for the industrial case01, a better understanding of this particular complex maintenance operation has been developed using the proposed tool. Travel time and spares lead time play important roles in deciding the PW as their effects were assessed in this industrial case study.

Also this case has provided a better understanding for the product monitoring levels when travel times are not involved, and other maintenance resources are available (labour and spares) as in this case Prognostics levels will not have any more advantages than the Diagnostics level. In the next section, the validation of these results will be explained.

### 6.3.3 Case 01 validation

A web meeting was held with the maintenance manager of the case company to discuss the output obtained from the tool. The meeting started by asking the maintenance manager about his estimates of the average availabilities of the refrigerators and the labour utilisations in the current maintenance operations. The reply was 96% as an average refrigerating availability with about 70%

labour utilisation. After this the result graphs were presented to discuss the reliability of these outputs obtained from the tool according to his experience from reality.

The differences of the manager's estimates and what was obtained from the tool were discussed. Both the researcher and the manager agreed that the difference of about 2% on the availability was acceptable and that it was due to several reasons. These reasons are that the manager's estimate was based on experience and was not based on actual calculations. Also, the input data was based on the manager's experience and was not obtained from a computerised system due to the simple fact that they do not currently have a computerised system to log all their maintenance activities. It is worth mentioning that, in the data collection stage, the researcher asked the case company to use their paper records to obtain accurate data rather than expert estimation, but the request was refused due to internal reasons.

A significant difference was observed on the labour utilisation between the manager's estimate and what was obtained from the tool. This issue was discussed, and the outcome of these discussions was that according to the maintenance manager they are assigned to other maintenance and non-maintenance activities during their working hours and that is why the maintenance manager gave an estimate of 70%. The manager agreed with the current utilisation obtained by the tool as these utilisations were calculated according to the maintenance of refrigerators only. When asked about why more labour is used than needed in each station, the reply was those labour costs are very low compared to the significant cost of the perishable goods that might be lost if a breakdown occurred. The manager mentioned that the case company is satisfied with its current maintenance strategies and that it is not willing to adopt the monitoring technologies.

All other experiments were shown and discussed with the manager during the web meeting. The manager was not an expert in monitoring technologies but states that all the results obtained are sensible, logical and explainable. Following this, the second industrial case is presented, analysed and discussed.

## 6.4 Industrial case 02

This case presents a large water pumping manufacturer in the United Kingdom. It produces several types of water pumps used in primary, secondary and tertiary water treatment. Alongside its manufacturing activities it offers customers service support to maintain their water pumps.

An initial meeting was set at the case company's headquarters with the maintenance director. The director was introduced to the developed simulation tool by a short tool demonstration. The suitability of the tool to analyse the company's maintenance operations was discussed. The director has shown an interest to move towards a higher level of pump monitoring as the company currently applies Reactive maintenance in its operations. Moreover, the company is unsure on whether to move to a higher monitoring level as it lacks approaches to assess the decision. The demonstrated simulation tool has the potential to assess the company's maintenance operations.

One of the highest profile customers was selected as a suitable focus for evaluation. Objectives of the simulation experiments were discussed, as well as the potential data requirements and expected output. This customer has many pumps that are all located at the customer's site. However, the case company decided to limit the data that will be under study here to only 100 identical pumps rather than providing the researcher with full data due to an internal reason of the case company.

The data was obtained by estimation as maintenance activities are manually logged and it is a very time consuming task for the case company to provide exact maintenance data. Triangular distribution has been chosen to represent MTBF, Diagnose, and repair times for ease of estimation. The estimations were discussed and agreed by both the maintenance director and the maintenance scheduler. The pumps were identical and have four failure modes each. As this is a high profile customer, the case company has two maintenance engineers who are located at the customer's site. Each failure mode has an associated spare part needed for repair. For this case spare01, spare02, spare03, and spare04 are respectively associated to failure modes 1 to 4. Figure 6-8 is a schematic diagram to represent the case details while Table 6-9 represents the case 02 input data obtained.

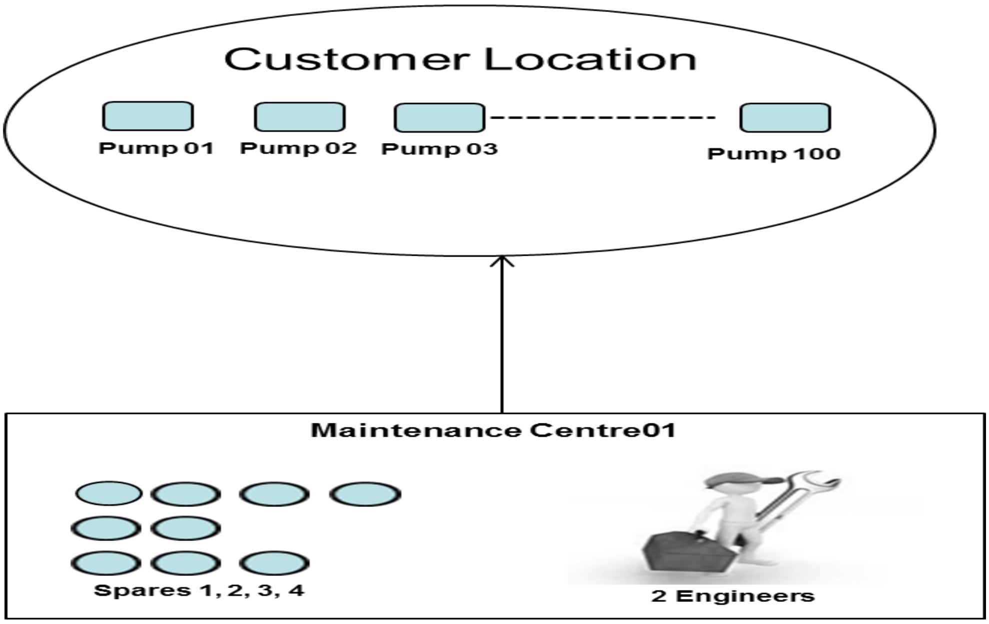


**Figure 6-8 Schematic diagram of case 02**

**Table 6-9 Case 02 input data**

| Location | Location 01 |
|---|---|
| **No. of pumps** | 100 |
| **No. of engineers** | 2 |
| **No. of failure modes** | 4 |
| **Spare parts** | Spare1,2,3,4 |
| **Failure mode01** | MTBF (mins):Triangular Distribution (1036800,1555200,2073600) |
| | Diagnose time (mins):Triangular Distribution (30,54,60) |
| | Repair time (mins):Triangular Distribution (360,420,480) |
| **Failure mode02** | MTBF (mins):Triangular Distribution (1036800,1555200,2073600) |
| | Diagnose time (mins):Triangular Distribution (30,54,60) |
| | Repair time (mins):Triangular Distribution (420,480,540) |
| **Failure mode03** | MTBF (mins):Triangular Distribution (518400,1555200,2073600) |
| | Diagnose time (mins):Triangular Distribution (10,15,20) |
| | Repair time (mins):Triangular Distribution (120,126,150) |
| **Failure mode04** | MTBF (mins):Triangular Distribution (1,1036800,2592000) |
| | Diagnose time (mins):Triangular Distribution (10,15,20) |
| | Repair time (mins):Triangular Distribution (120,126,150) |
| **Lead time** | 4 days |
| **Reorder quantity** | 1 for each spare |
| **Safety stock** | 1 |

### 6.4.1 Case 02 experiment setup

The setup of the experiments for case 02 were done in the same method as case 01. The run length was decided to be for ten years as multiple failures of each failure mode will occur during this run length. Moreover, the case company would like to assess its maintenance operation in such a long run. The warm-up period was decided to be three years (three year warm up, ten years run length). Warm-up period were decided by a Time-series method suggested by Robinson (2004) and the output measure is the labour utilisation as explained in the case01. The Time-series graph is shown in appendix D.

The number of replications has been decided based on a combination of a rule of thumb and the confidence interval method. Table 6-10 confirms that two replications are sufficient as the deviation is less than 1%. The calculations were based on the (As-Is) model, and the output measure used for this calculation was the average availability percentage of the pump. Combining the rule of thumb and the confidence interval method, the researcher decided to select three replications to be used in this case.

**Table 6-10 No. of replications calculation based on the confidence interval method for case 02**

| | | | | **Significance level** | **5.0%** | |
|---|---|---|---|---|---|---|
| | | | | **Confidence interval** | | |
| **Replication** | Result-Availability % | Cum. mean average | Standard deviation | Lower interval | Upper interval | % deviation |
| **1** | 97.21 | 97.21 | n/a | n/a | n/a | n/a |
| **2** | 97.18 | 97.20 | 0.021 | 97.00 | 97.39 | 0.20% |
| **3** | 97.21 | 97.20 | 0.017 | 97.16 | 97.24 | 0.04% |

A set of experiments has been conducted for this case. These experiments were based on the questions raised in section 6.2 and are shown in Table 6-11.

**Table 6-11 Experiments conducted for case 02**

| No. | Experiment description |
|---|---|
| **1** | As-Is |
| **2** | Labour reduction |
| **3** | Travel time 400 (mins) |
| **4** | Travel time 1200 (mins) |
| **5** | Increase the MTBF by 50% |
| **6** | Decrease the MTBF by 50% |
| **7** | Increase spares lead time |
| **8** | Increase spares Min. Reorder Quantity (MRQ) |
| **9** | Safety stock Reduction |
| **10** | Increase diagnose time to by 100 times |

Three scenarios (Reactive, Diagnostics, and Prognostics) were compared for each of the experiments. Furthermore, different Prognostics Windows (PW) were applied.

Ten different experiments were applied with three monitoring levels. The Prognostics level has been applied with three different PWs (PW=600 min, PW=1200 min, and PW=6000 min). These different PWs assessed different levels of PW on the maintenance operations. Bearing in mind that three replications for each scenario have been decided, this makes the total number of simulation runs for this case to be 150 runs. After this, an analysis of the results obtained will be presented and followed by a validation process.

### 6.4.2 Industrial case 02 results and discussion

This section presents and analyses the results of the different experimentations of case 02. Figures 6-9, 6-10, 6-11, and 6-12 show the comparisons of availability percentages, breakdown percentages, number of failures, and labour utilisation percentages on different experiments. The analysis of each experiment will be presented as follows:

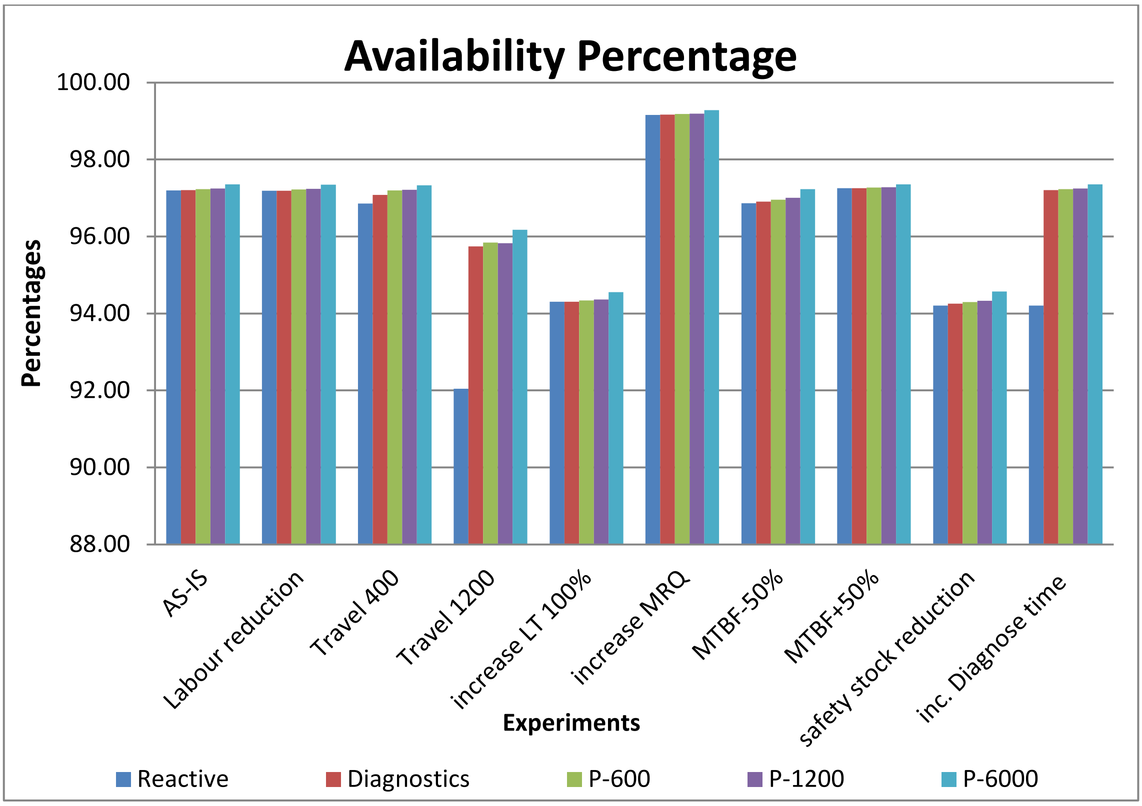


**Figure 6-9 Case 02 availability percentages across different experiments**

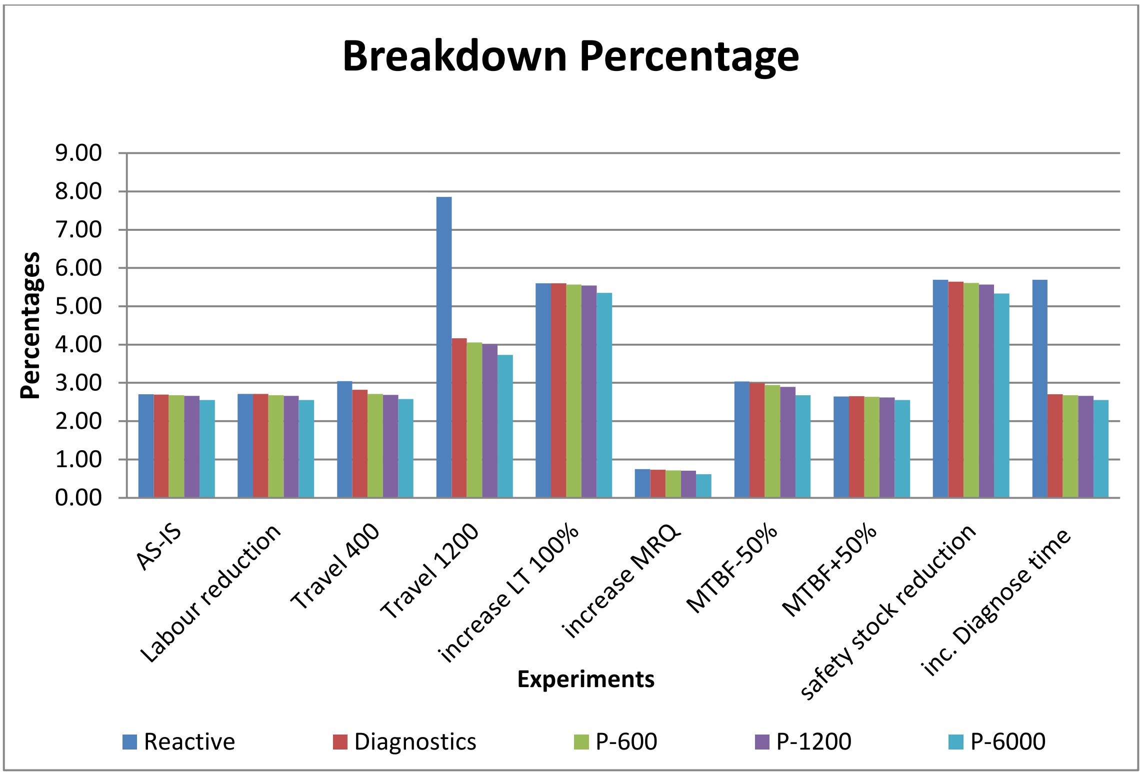


**Figure 6-10 Case 02 breakdown percentages across different experiments**

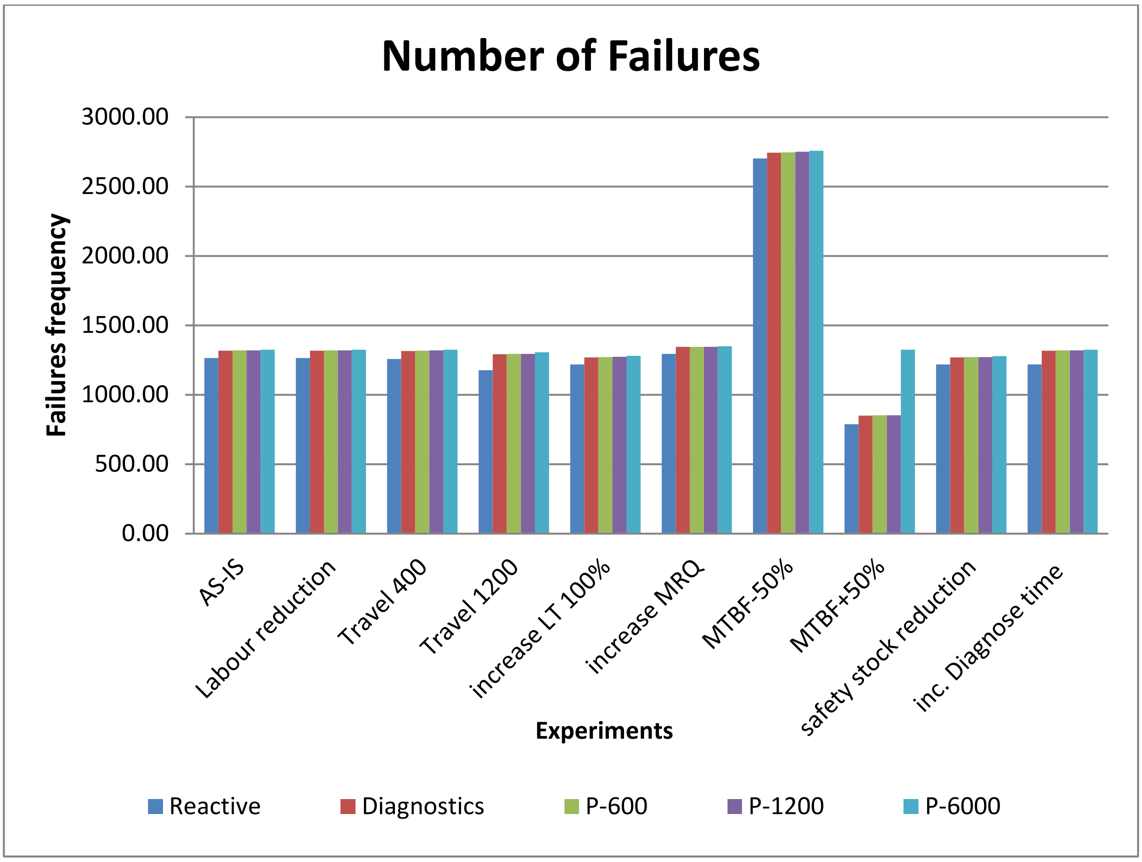


**Figure 6-11 Case 02 No. of failures across different experiments**

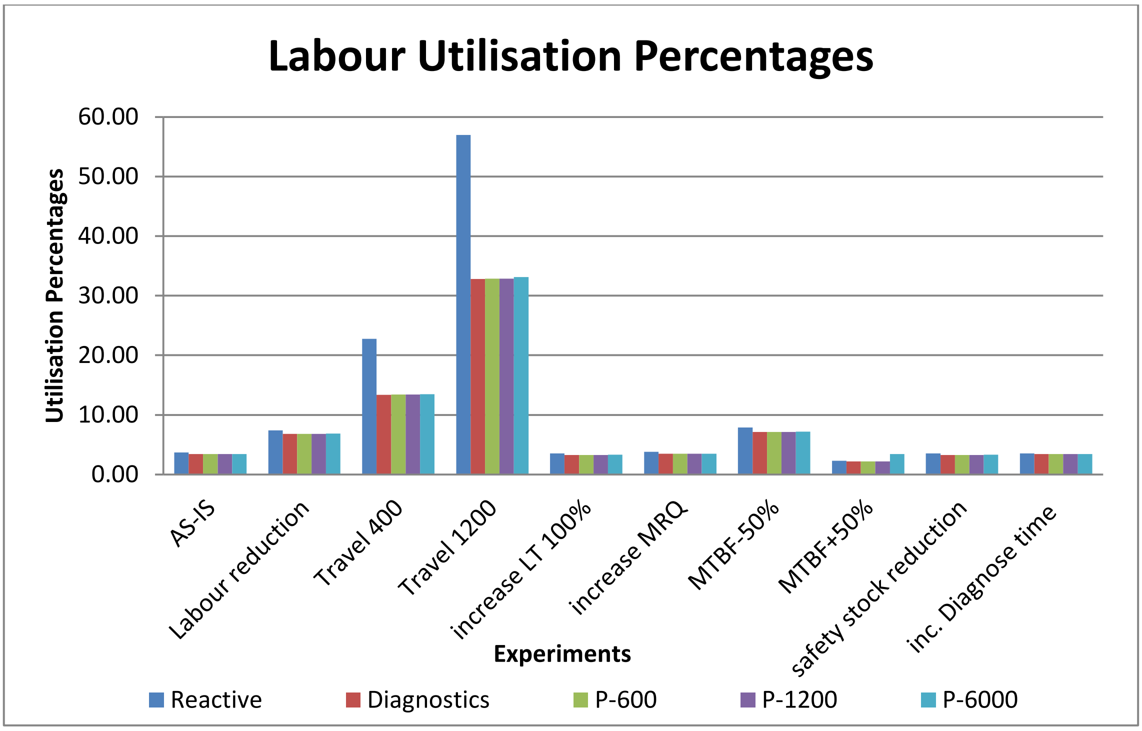


**Figure 6-12 Case 02 labour utilisation percentages across different experiments**

Full result tables of case 02 are presented in Appendix C. while, Appendix E provides PMLS tool snap shot for case02.

- **As-Is and Labour reduction**

This starts with Figure 6-9 which shows the availability percentages across different experiments for case 02. It is evident that the availability slightly increases in the As-Is situation between different monitoring levels. There was slight increase in terms of availability when moving from Reactive to Diagnostic, but slight increases were obtained in the Prognostics levels (P-600,P-1200) which are 0.03%, 0.05% respectively.

An improvement of 0.15% was achieved when moving from the Reactive to the Prognostics level when the PW was set to 6000 minutes (P-6000). This long PW was introduced to assess the complex maintenance operations when the PW is set to be more than the spares lead time which is four days in this case. This increase is due to waiting for labour to attend to the pump. In the Diagnostics level, the labour will be notified when the failure occurs. In contrast, with regard to Prognostics levels, the labour can attend during the PW before the failure actually occurs. Thus, increasing the PW gives a better chance that the labour can attend to the pump before it fails.

The case company has assigned two permanent labour on the customer's site. As the labour utilisation is actually low, changing the labour from two to one did not achieve any differences across different monitoring levels from the As-Is situation, as can be seen in Figure 6-9. Breakdown percentages (Figure 6-10) reflect the opposite direction of availability percentages which is correct as the sum of both availability and breakdown percentages comes to 100%.

Looking at the number of failures (Figure 6-11) in the As-Is and labour reduction situations, Reactive has fewer failures and that is due to a longer breakdown time for each failure. Also, a slight increase is seen in the number of failures among other monitoring levels which is due to the slight availability increase. Diagnostics and Prognostics (P-600 and P-1200) levels give almost the same number of failures while P-6000 gives three more failures than the rest.

Labour utilisation percentages are low as can be seen in Figure 6-12. In the As-Is situation the Reactive level gives more labour utilisation than the others by 0.28% due to manual diagnosis activity in addition to the repair time. Other levels give the equal utilisation percentage as they are matched in the number of failures, with the exception of P-6000 which gives a slight utilisation increase of 0.01% due to a slight increase in the number of failures.

- **Travel time 400 minutes and 1200 minutes**

In terms of availability, the travel time is set to 400 minutes to the pump from the maintenance centre. Generally, a gradual increase of availability has been achieved moving from Reactive to higher levels. Compared to the As-Is situation a drop of 0.38% of availability in the Reactive is due to travel time. The diagnostic level availability in this case drops by 0.12% compared to what it was in the As-Is situation. It can be noted that when the PW is set to 600 minutes, 1200 minutes, and 6000 minutes (P-600, P-1200, and P-6000) the availability almost remains the same as in the As-Is situation. This is due to the fact that the PW is set to more than the travel time of 400 minutes.

An increase of travel time was made to 1200 minutes to understand the effect of having travel time which is more or equal to the PW on the complex maintenance operations. In this case, one of the PWs applied is less than the travel time (P-600), the other PW is matching the travel time (P-1200), and the last PW (P-6000) is set to be more than the travel time as well as being more than the spares lead time. Thus, it is evident that in the Reactive level a 5.05% drop in availability is seen compared to the As-Is situation. Generally, by comparing this experiment with the As-Is situation it can be seen that availability percentages drop due to the inclusion of a high travel time, which is logical, and it ensures that the developed tool is absorbing such change. Applying P-600 and P-1200 gives matching availability in this experiment as both PWs are less or equal to the travel time, whereas when the PW was set to 6000 minutes a better availability was achieved compared to P-600 and P-1200 in the same experiment.

In the case of 400 minutes travel time, the number of failures drops in the Reactive and Diagnostics levels from what it was in the As-Is situation while on the Prognostics level it remains the same as the PW overcomes the travel time compared to As-Is. However, when 1200 minutes was introduced as a travel time, a further drop in the number of failures in all monitoring levels, including Prognostics, was seen compared to the 400 minute travel time experiment as less availability percentages were achieved. P-600 and P-1200 are almost matching in the number of failures while the number of failures increases in the P-6000 as they are repaired more often due to the lengthy PW as the availability increases.

Labour utilisation for both experiments, as seen in Figure 6-12, has increased due to the introduction of travel times in both experiments. Reactive is showing a higher utilisation as longer manual activities are performed. The tool depicts that when travel time was increased from 400 minutes to 1200 minutes then the utilisation increased accordingly. Diagnostics and Prognostics are almost matching in terms of utilisation percentages in the 400 minutes experiment. In the 1200 minutes experiment a higher utilisation than the 400 minutes was achieved due to the increase of travel time. Again, Reactive shows a higher utilisation while Diagnostics and Prognostics show equal utilisation. However, in P-6000 a small increase in utilisation, due to higher availability, is obtained compared to P-600 and P-1200.

- **Increase spares lead time and increase spares Minimum Reorder Quantity (MRQ)**

In this experiment, the researcher first increased the spares lead time by 100%. A drop in availability in all monitoring levels can be seen compared to As-Is. During the same experiment a gradual increase is seen in availability when a higher monitoring level is applied.

Another experiment was conducted in which the researcher retained the same spares lead time as the As-Is situation but this time increased the minimum reorder quantity of spares from 1 to 10 for all spares. In this case, availability has increased compared to the case of the As-Is. As this case has an identical number of pumps (100), the spares reordering quantity will have an impact on availability.

Generally, the number of failures has dropped across monitoring levels when the spares lead time was increased as fewer spares are available which is logical in this case. In contrast, the number of failures increased when the minimum reorder quantity of spares was increased. Utilisation percentages for labour have decreased slightly in the case of increasing lead time and increased slightly when the minimum reorder quantity of spares have been increased.

- **MTBF+50% and MTBF-50%**

As in the previous case, different levels of MTBF have been introduced in order to assess their effect. First, a decrease in MTBF by 50% has been assessed and it shows a slight drop in availability compared to the As-Is situation. In addition, availability increases in a more obvious way with higher monitoring levels. This slight drop in availability in all monitoring levels from the As-Is is due to the diagnose times (in the case of Reactive) and repair times being low, therefore, its impact on availability is low. When increasing the MTBF by 50%, this has improved availability in all levels in a very minor way.

In terms of the number of failures, more failures occurred when the MTBF was decreased and similarly less failures occurred when the MTBF increased. Labour utilisation percentages, in general, increased with the decrease of MTBF while utilisations decreased when MTBF had been increased.

- **Decrease of the Safety stock and increase the diagnose time**

Another experiment was conducted to assess the safety stock effect. Safety stock was decreased from 1 to 0 on all spares. This has decreased the availability by about 2% from the As-Is situation. Slightly better availability is achieved in this experiment when moving from Reactive to Diagnostics to Prognostics levels.

As a result from what was achieved in the MTBF experiments, the researcher has decided to examine the effect of longer diagnose times because in this case, and the previous one, diagnose times were low. An experiment of increasing the diagnose time by 100 is conducted and this decision was made to assess the impact of a high diagnosing time on the maintenance operation. This experiment shows a drop of about 3% in availability in Reactive compared to the As-Is situation. Of course, as this experiment deals with diagnose times, the Reactive level will be effected. Other monitoring levels give the same availability as the As-Is. Within the same experiment, when Diagnostics was applied, an improvement of availability of about 3% was gained compared to Reactive. Prognostic (P-600 and P-1200) gives the same availability. When P-6000 was applied, an increase of availability was gained.

The number of failures in the safety stock experiment shows that in general it gives less failures than the As-Is. However, within the safety stock experiment, the higher the monitoring level then the higher the number of failures. Nevertheless, the difference in the number of failures is relatively low. This is logical as the higher monitoring level gives a higher availability. For the diagnose time experiment, the Reactive level gives the least number of failures. In the Diagnostics and Prognostics levels, the number of failures are similar with the exception that when P-6000 was applied, the number of failures increased.

Labour utilisation percentages for the safety stock experiment shows that the Reactive level has the highest utilisation among other levels. Compared to the As-Is, the utilisation percentages are reduced as the availability was reduced due to the reduction of safety stock. On the other hand, the diagnose time experiment shows that the labour utilisation in the Reactive level is slightly higher than other levels within this experiment. However, by comparing the labour utilisation of this experiment to the labour utilisation in the As-Is situation in the Reactive level, a drop of 0.14% occurred. This experiment has increased the diagnose time by 100 times; this should increase the labour utilisation rather than decrease it. The reason behind this is that due to the high diagnose time, the availability decreases in this case which decreases the labour utilisation. Following on from this, a validation process of these results is presented.

### 6.4.3 Case 02 validation

A web meeting was conducted with the maintenance director and the maintenance scheduler of the case company. The meeting started by explaining the different experiments conducted. Then questions were asked by the researcher about what is the current availability percentage for this customer and what is the current labour utilisation; the answers were 94% and 60% respectively.

The differences of the manager's estimates and what was obtained from the tool were discussed. Both the researcher and the case company's maintenance director agreed that the difference of about 3% on the availability is acceptable, although the significant difference of labour utilisation was due to the fact that they are serving more pumps at this site, as the modelled case is limited to 100 pumps as per the request of the case company. The reasons behind these differences are that the director's and the scheduler's estimates were based on experience and were not based on actual calculations. Also, the input data used in the simulation was based on their experience and it was not obtained from a computerised system due to the fact that they do not currently have a computerised system to log all their maintenance activities. Thus, some deviations were expected.

The researcher explained and discussed all the experiments with the case company. The responses were that the overall results are logical and sensible as this approach has provided a better understanding for the monitoring levels for their maintenance operations. They added that this approach can serve to reduce their operations cost by testing other alternatives.

## 6.5 Industrial case 03

This case presents one of utility companies in the United Arab Emirates (UAE). It owns multiple utility stations all over the UAE. These stations have assets (product) that always need to be in an operational condition to provide the citizens with its services. Breakdowns of these assets are critical and need to be resolved immediately.

As agreed with the case company, the data of the operations will be provided to the researcher from one of its maintenance centres. This maintenance centre serves four stations scattered in the city, and each station has multiple identical assets. These assets has three failure modes and each one of those failures has an associated spare part (e.g. failure mode 1 needs spares 1 and so on). The first station has 23 assets, the second station has 26 assets, the third station has 18 assets, and the fourth station has 31 assets. Data for this case was obtained by the company's computerised system. The data needed was explained and identified in an initial meeting with the case company who then sent the researcher the required data as obtained by the company's computerised system. Bearing in mind that this case is adopting the Diagnostics level to monitor the company's assets, the diagnosing time, which is usually done in the Reactive level, was estimated by maintenance engineers as diagnosing activity is done by sensing technologies. In this maintenance centre there are eight maintenance engineers (labour) to maintain those stations. The following Figure 6-13 shows the schematic diagram of case 03 and Table 6-12 provides the input data used in modelling this case.

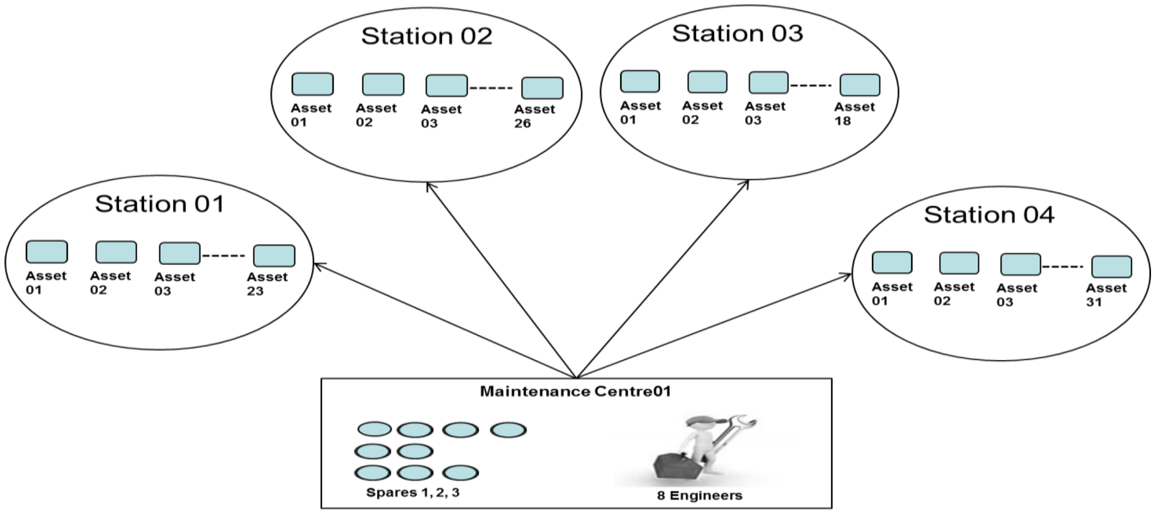


**Figure 6-13 Schematic diagram of case 03**

Triangular distribution has been chosen to represent MTBF, Diagnose, and repair times for ease of estimation.

**Table 6-12 Case 03 input data**

| **Location** | Location01 | Location02 | Location03 | Location04 |
|---|---|---|---|---|
| **No. of assets** | 23 | 26 | 18 | 31 |
| **Travel times (Hrs)** | 6.3 | 5.8 | 7.3 | 8.6 |
| **No. of engineers** | 8 | | | |
| **No. of failure modes** | 3 | | | |
| **Spare parts** | Spare01, Spare02, Spae03 | | | |
| **Failure mode01** | MTBF (mins):Triangular Distribution (211896,332424,697248) | | | |
| | Diagnose time (mins):Triangular Distribution (2880,10080,15840) | | | |
| | Repair time (mins):Triangular Distribution (429.6,536.4,861.6) | | | |
| **Failure mode02** | MTBF (mins):Triangular Distribution (478224,675864,815184) | | | |
| | Diagnose time (mins):Triangular Distribution (4320,8640,23040) | | | |
| | Repair time (mins):Triangular Distribution (523.2,792,1152.6) | | | |
| **Failure mode03** | MTBF (mins):Triangular Distribution (297432,894888,1145016) | | | |
| | Diagnose time (mins):Triangular Distribution (7200,12960,18720) | | | |
| | Repair time (mins):Triangular Distribution (578.4,1222.8,2080.8) | | | |
| **Lead time** | 30 days | | | |
| **Reorder quantity** | 5 each | | | |
| **Safety stock** | 1 each | | | |

The travel times in Table 6-12 were calculated based on the average time from receiving a failure note until the failure is attended by an engineer.

### 6.5.1 Case 03 experiment setup

The setup of the experiments for case 03 were done in the same method as for case 01 and case 02. The run length was decided to be for ten years as multiple failures of each failure mode will occur during this run length. Moreover, the case company would like to assess its maintenance operation over such a long run. The warm-up period has been decided to be for three years (three year warm up, ten years run length). Warm-up period were decided by a Time-series method suggested by Robinson (2004) and the output measure is the labour utilisation as explained in the case01. The Time-series graph is shown in appendix D.

The number of replications has been decided based on a combination of rule of thumb and the confidence interval method. Table 6-13 confirms that three replications are sufficient as the deviation is less than 2%. The calculations were based on the (As-Is) model, and the output measure used for this calculation was the average availability percentage of assets. Combining the rule of thumb and the confidence interval method, the researcher has decided to select three replications to be used in this case.

**Table 6-13 No. of replications calculation based on the confidence interval method for case 03**

| | | | | **Significance level** | **5.0%** | |
|---|---|---|---|---|---|---|
| | | | | **Confidence interval** | | |
| **Replication** | Result | Cum. mean average | Standard deviation | Lower interval | Upper interval | % deviation |
| **1** | 79.37 | 79.37 | n/a | n/a | n/a | n/a |
| **2** | 78.59 | 78.98 | 0.552 | 74.02 | 83.94 | 6.27% |
| **3** | 79.41 | 79.12 | 0.462 | 77.97 | 80.27 | 1.45% |

A set of experiments have been conducted for this case. These experiments were based on the questions raised in section 6.2 and are shown in Table 6-14.

**Table 6-14 Experiments conducted for case 03**

| No. | Experiment description |
|---|---|
| **1** | As-Is |
| **2** | Labour reduction |
| **3** | No travel time |
| **4** | Spares lead time reduction by 50% |
| **5** | Increase minimum reorder quantity by 50% |
| **6** | Spares lead time reduction by 50% & Increase Minimum Reorder Quantity (MRQ) by 50% |
| **7** | Increase MTBF by 50% |
| **8** | Decrease MTBF by 50% |

Three scenarios (Reactive, Diagnostics, and Prognostics) were compared for each of the experiments. Furthermore, different Prognostics Windows (PW) were applied.

Eight different experiments were applied with three monitoring levels. A Prognostics level has been applied with three different PWs which are (PW=500 min, PW=1000 min, and PW=43500 min). These different PWs were decided to assess different levels of PW on maintenance operations. Bearing in mind that three replications for each scenario have been decided, this makes the total number of simulation runs for this case come to 120 runs. After this, an analysis of the results obtained will be presented and followed by a validation process.

### 6.5.2 Industrial case 03 results and discussion

This section presents and analyses the results of the different experimentations of case 03. Figures 6-14, 6-15, 6-16, and 6-17 show the comparisons of availability percentages, breakdown percentages, number of failures, and labour utilisation percentages on the different experiments. The analysis of each experiment will be presented as follows:

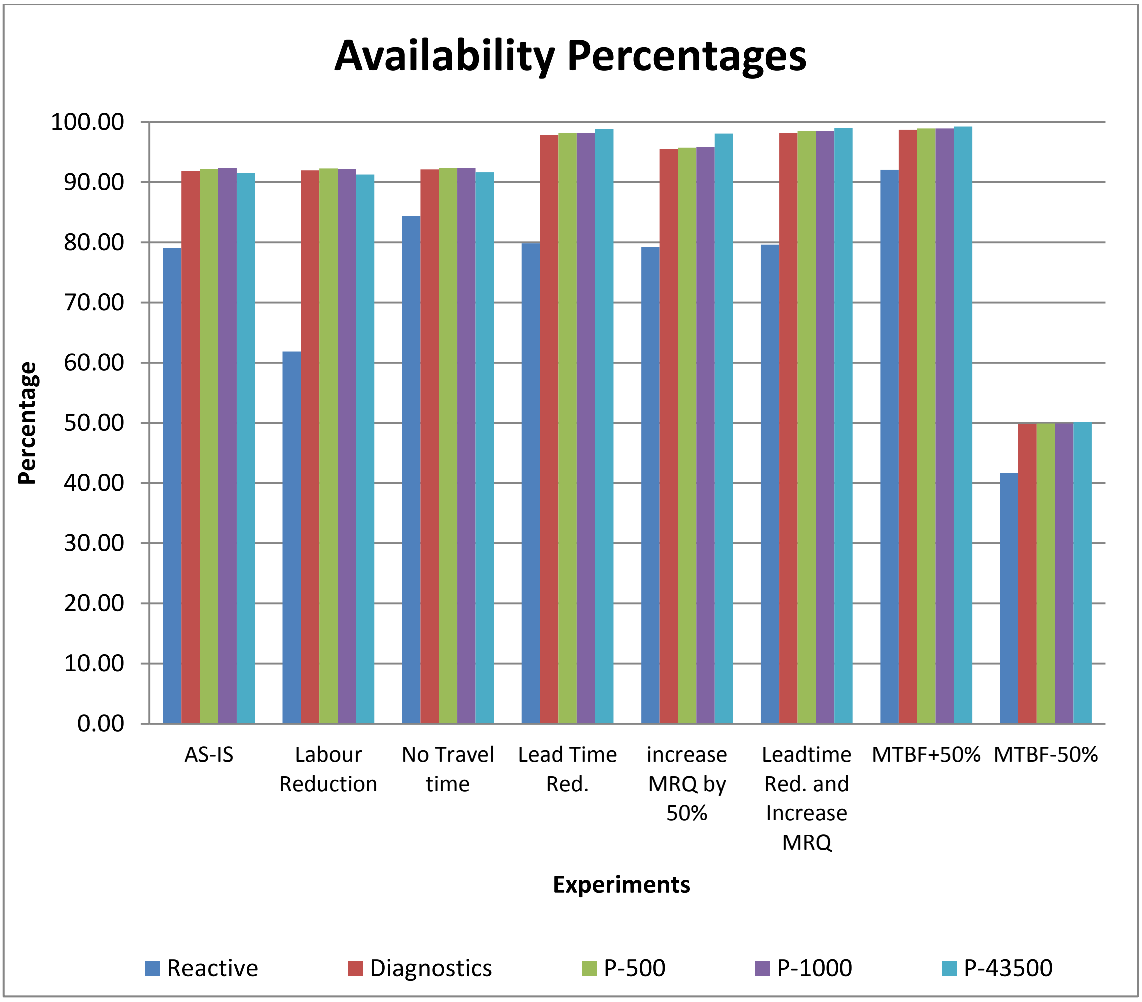


**Figure 6-14 Case 03 availability percentages across different experiments**

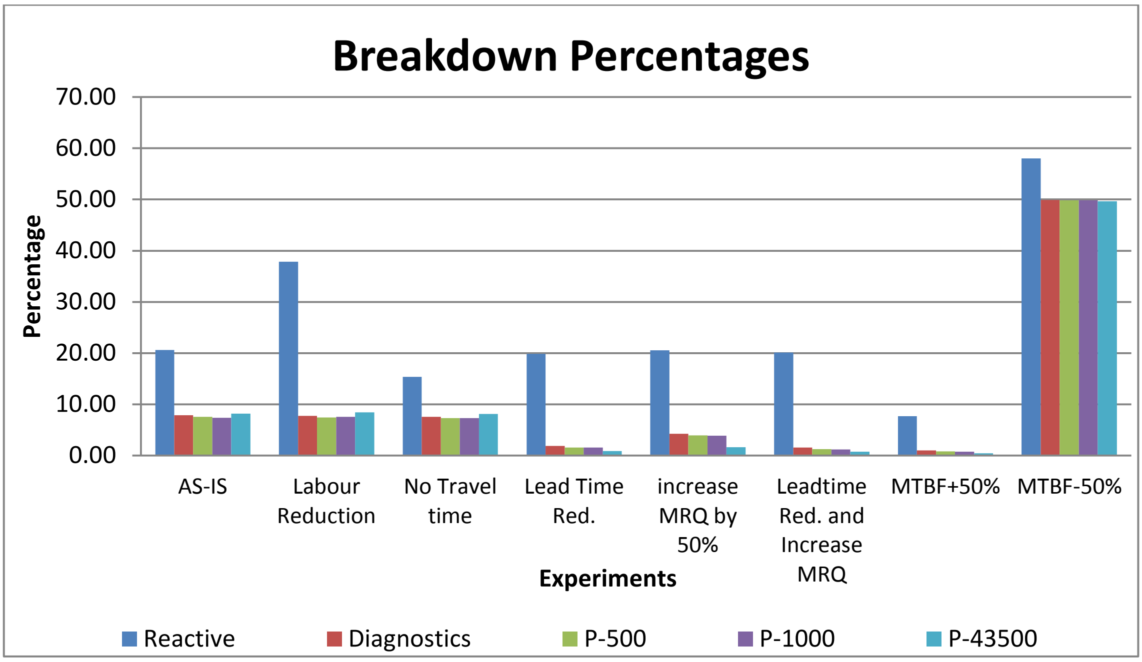


**Figure 6-15 Case 03 breakdown percentages across different experiments**

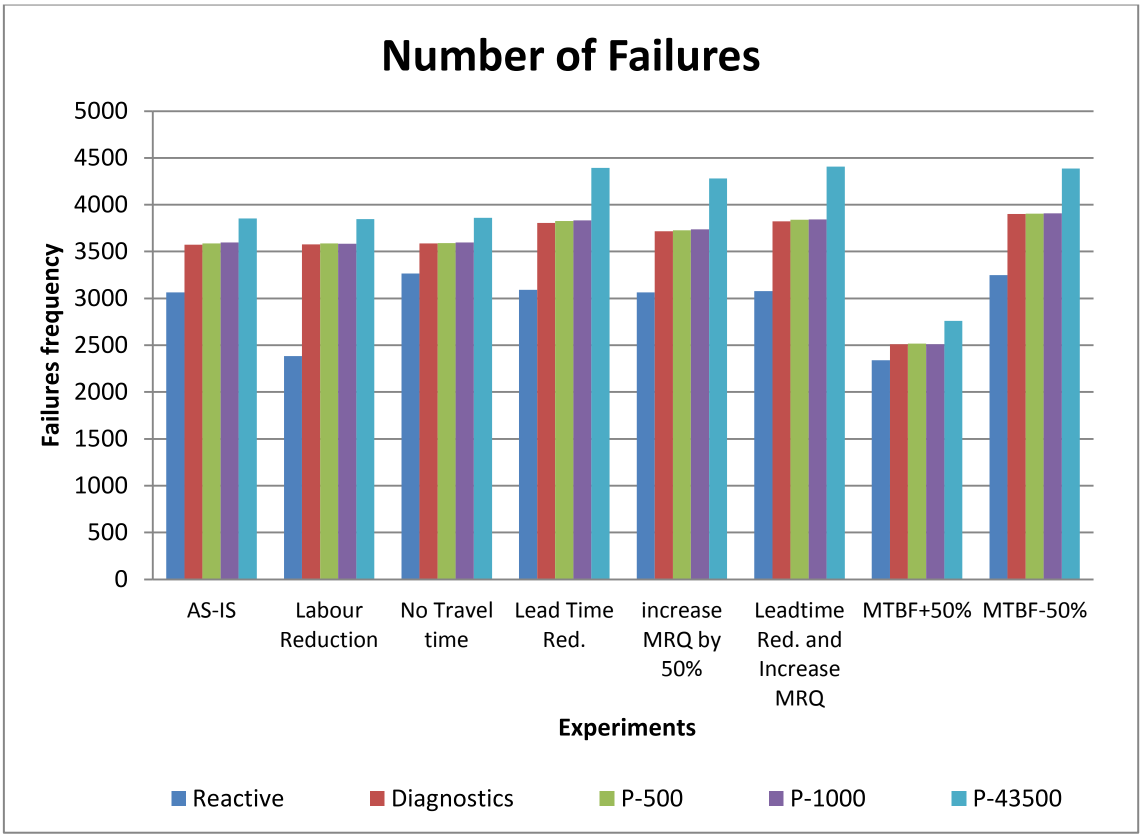


**Figure 6-16 Case 03 No. of failures across different experiments**

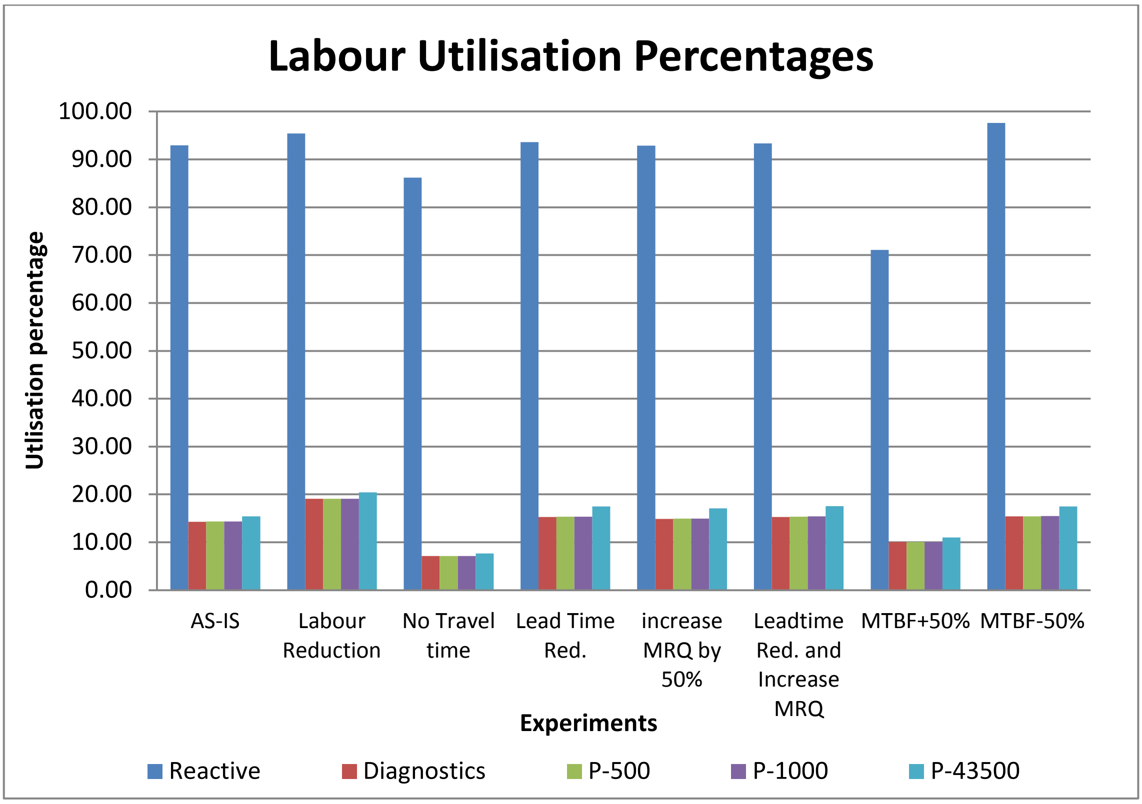


**Figure 6-17 Case 03 labour utilisation percentages across different experiments**

Full result tables of case 03 are presented in Appendix C. while, Appendix E provides PMLS tool snap shot for case03.

- **As-Is and labour reduction**

The As-Is situation shows (Figure 6-14) that the Reactive level gives about 79% of availability. A sharp increase of availability to 91.9% is reached when the Diagnostics level is applied. This is due to travel time (Reactive level needs 2 travel times for repair as explained earlier) in addition, the manual diagnosing time in this industrial case is very high. Moving to the Prognostics level with a PW of 500 minutes (P-500) only an increase of 0.35% has been gained compared to Diagnostics. Applying a PW of 1000 minutes (P-1000) gave an increase of 0.55% compared to Diagnostics. The availability is almost the same between Diagnostics and Prognostics levels due to the travel time is the same in both cases as well as the manual diagnosing process is eliminated.

A longer PW was applied (P-43500) to more than the spares lead time of 30 days to assess its impact. A drop in the availability occurred as it gives the same availability as in Diagnostics. This is due to more frequent repairs (more than is actually needed) which have been made due to the lengthy PW selected.

Another experiment was conducted to assess the impact of labour reduction where labour was reduced from eight to six. This shows a further drop of 17.25% in availability in the Reactive level compared to the As-Is situation. However, other monitoring levels gave almost the same availability as in the As-Is. Breakdown percentages reflect the opposite direction of availability percentages which is correct as the sum of both availability and breakdown percentages comes to 100%.

The number of failures (Figure 6-16) in the As-Is situation increases as a higher monitoring level is applied. Moving from the Reactive to the Diagnostics level, an increase of 507 failures was made and that is simply due to repairs being carried out faster when Diagnostics technologies are implemented. From Diagnostics (P-500) a slight increase of 14 failures occurred while a further 9 failures took place moving to (P-1000) compared to (P-500). Longer PW (P-43500) gave the highest number of failures as it increases the failures by 259 compared to (P-1000). In the same manner, when the labour reduction experiment was applied a further decrease in the number of failures was made as a lower availability was obtained. Other monitoring levels almost have same level of number of failures as in the As-Is situation.

Labour utilisation (Figure 6-17) shows clearly in both the As-Is and labour reduction experiments that the Reactive level gives more than 90% utilisation. This drops dramatically to about 15% when other monitoring levels were applied. This drop is based on the fact that these assets require a significant amount of time to conduct manual diagnosis for their failures.

- **No travel time**

Comparing the Reactive level in this experiment with the As-Is, it can be noted that availability has risen by 5.23% as a result of removing the travel time.

Comparing other monitoring levels with the As-Is, it shows that generally little improvement was gained.

Likewise, the number of failures were expected to increase moving from the As-Is situation as in this experiment travel times were removed. Reactive shows the highest number of failures where other levels show a slight increase moving from Diagnostic to Prognostics in the same experiment.

Utilisation of the labour dropped in general compared to the As-Is, as travel time was excluded. Reactive shows higher utilisation percentages among other levels as usual.

- **Lead time reduction and increasing the Minimum Reorder Quantity (MRQ)**

The researcher has conducted three spare parts related experiments. Firstly, the spares lead time reduction has been examined. After that, an increase in the spares Minimum Reorder Quantity (MRQ) was assessed. This was followed by combining both experiments into one experiment.

Reducing the spare parts lead time by 50% shows that in the Reactive level a 0.74% increase in the availability was gained compared to the As-Is. An increase of about 6% in availability was achieved in all other levels compared to the As-Is with the exception of the lengthy PW (P-43500) which gave a 7% increase.

The MRQ has increased while keeping the spares lead time as in the base model (As-Is). Generally, this led to a slight increase of availability compared to the As-Is situation. In Reactive the increase was 0.1% while in Diagnostics and both Prognostics (P-500 and P-100) it increased by about 3.5%. When the PW was set to 43500 an increase of 6.6% was gained in availability compared to the As-Is.

The third experiment was to combine both experiments and this shows an improvement in terms of availability compared to the As-Is. In Reactive the increase was 0.53% while in Diagnostics and both Prognostics (P-500 and P-100) it increased by about 6.3%. Prognostics (P-43500) achieved an increase of 7.4% compared to the As-Is.

In all of the three experiments, the number of failures was seen to be higher as a higher monitoring level was applied.

Labour utilisations are similar in all three experiments. The Reactive shows a very high utilisation due to the high diagnose time for such assets. Other monitoring levels show similar utilisation.

- **MTBF+50% and MTBF-50%**

Two experiments were carried out to assess the implications of increasing and decreasing the MTBF as made in previous cases. Firstly, increasing the MTBF by 50% was assessed. Logically, an increase of availability percentages was expected compared to the As-Is. Thus, a raise in availability from the As-Is model was gained. Decreasing the MTBF by 50% gives a drop of 37% in availability in Reactive while other monitoring levels dropped by about 42%.

The number of failures dropped generally in the MTBF+50 experiment while there was an increase in MTBF-50% compared to the As-Is. Reactive gives the least number of failures; the higher the monitoring level the higher the number of failures occurred. When the PW was set to 43500 minutes, an obvious increase of failures occurs. This is also true of the labour utilisation in both experiments. After this, a validation process of these results is presented.

### 6.5.3 Case 03 validation

A web meeting was established with the case company’s maintenance planner to discuss the results obtained. The meeting started by the researcher asking the maintenance planner about the current assets availability and labour utilisation. The answer was based on their computerised system which presented 88.6% as an average assets availability while labour utilisation was 84.3%. Comparing these to the simulation tool results, the average assets availability is 91.87% bearing in mind that the current maintenance operation is applying the Diagnostics level.

Experiments were discussed one by one, and the case company expressed satisfaction as the difference in availability between the actual and the simulation was only 3.3% while the difference in the labour utilisation was significant at about 70%. After discussing this difference in utilisation, the planner elaborated that this tool is assuming ideal Diagnostic operations as no fault was found and the wrong diagnosis was not modelled. In other words, sometimes the sensing technology will sense a failure and it will be reported, but when labour attends the fault they will discover that the asset is working smoothly. This is called 'as no fault found'. In other cases, the sensing technology will give the wrong diagnosis. In addition, more assets were to be maintained by labour which are not included in this study.

## 6.6 Validation workshop

After the case companies' validations were conducted, the researcher decided to invite academic and industrial experts to a validation workshop. The purpose of this workshop is to demonstrate the developed tool and get the experts' feedback on the results obtained from the case studies.

A professor, a reader, a lecturer, and a consultant were all invited to attend. They were chosen as their expertise lies in maintenance, simulation, and operations management. The consultant was not able to attend due to personal reasons. The researcher decided to conduct the workshop as planned and to plan a separate meeting with the consultant at a later date. Both meetings were conducted and the outcomes are as follows:

A case by case description was provided to the experts and the experiments' results were explained and discussed. Two main issues were raised by the experts. The first issue was why did the researcher not consider applying Factorial Experimental (FE) rather than experimenting with One Factor At a Time (OFAT). This was explained in section 6.2 of this thesis as the purpose of the study is to gain further insight and a better understanding about the effect of each factor on the complex maintenance operation rather than providing a solution for a specific case where the factors interaction would be vital.

The second issue raised was about the similarity of the industrial cases used in this research. The researcher agrees partly with this comment, as the cases do share similarities in terms of field maintenance operations but they are different in terms of configuration. These cases have differences as in the single and multiple maintenance centres and product locations. In addition, they are different in terms of the monitoring level applications as case 01 and case 02 are applying the Reactive level while case 03 applies Diagnostics level. The researcher was not able to find a case study that applies Prognostics level.

Generally, after discussing the results of the conducted experiments, the experts agreed that all the results obtained from the simulation tool in different experiments were sensible and logical.

## 6.7 Summary

This chapter serves to explain the experimental approach applied in the cases' experimentation. A description of each case study is presented along with the set-up of the experiments. After this, a thorough explanation of the results along with the case company validation process is described. This is followed by the experts' validation workshop.

These cases were used to validate the developed simulation tool. This chapter has answered the third research question of this thesis. The next chapter will be dedicated to the thesis discussion along with a cross case discussion and lessons learned from the PhD process.

# 7 RESEARCH DISCUSSION

## 7.1 Introduction

The chapter will begin by discussing the research idea and why the chosen approach is appropriate. After this, a cross case discussion is presented into what insight the PMLS tool provided in assessing such complex maintenance operations.

## 7.2 Research remarks

Product monitoring levels have been classified into three monitoring levels which are Reactive, Diagnostics, and Prognostics. These classifications were based on the literature discussion made earlier in section 2.3 and are explained as follows:

- Reactive maintenance level (No monitoring): in this strategy maintenance activities will only take place when the product has failed. Manual diagnosis will be carried out, followed by a spare part request and then a repair activity.

- Diagnostics maintenance level (Medium monitoring level): where the product is able to diagnose itself and identify the failed part. Therefore, the labour will only travel to the asset when the spare part is in stock to perform the repair activity.

- Prognostics maintenance level (High monitoring level): where the product is able to predict the future failure of a part. It is hoped that the labour will have the required spare part to hand so as to be able to travel and replace the degraded part before the failure occurs.

Literature shows that the decision of which monitoring level should be implemented is based on the cost and severity of the breakdown. In addition, it has been regarded that the higher the monitoring level, the higher product availability is guaranteed. This was based on reasoning, not on experimental/empirical methods as discussed in section 2.2.1. Therefore, further experimental research is required to observe the influence of such monitoring levels on complex product maintenance operation systems as a whole. This will allow a dynamic quantitative approach to be developed to support decision makers in selecting the appropriate monitoring level that suits their complex maintenance operations.

The comparison of different modelling approaches was discussed in the literature chapter (sections 2.4.1 and 2.4.2). Simulation techniques have the capability to analyse the performance of any operating system without affecting the real system. Discrete Event Simulation (DES) is based on the assumption that time only exists at determined points, and that events will only take place at these points, hence the proposed approach is more appropriate for detailed operations systems where each item needs to be traced within the organisation’s dynamics (Robinson, 2004). This is particularly relevant to the process modelling of maintenance systems. Simulation has been described as the second most widely used technique in operations management (Pannirselvam et al., 1999) and has the potential to represent the complexity of different maintenance processes. However, when seen in the context of a wider manufacturing analysis, maintenance modelling is poorly covered within available literature.

A categorisation of simulation applications in maintenance research has been developed based on the literature review. It shows that maintenance modelling work entails production as well as business processes as it covers material movement and information. It is more difficult and complex to model a maintenance operation, since maintenance operation is not as developed as the manufacturing system operation model; this is mainly due to the fact that in the former, more sub-systems are working together in a complex manner. Usually, the sub-systems, such as production, maintenance staff, and spare parts inventory, are modelled separately (in isolation). Literature have focused on the maintenance operations of manufacturing systems rather than the product. Moreover, assessing different product monitoring levels using a simulation approach has not been developed although simulation shows its suitability (section 2.4.2) to model such a complex system.

This work, through its Product Monitoring Levels Simulation (PMLS) tool, has integrated complex maintenance operations sub-systems, such as modelling different products at various customers' locations with different spare part inventories and ordering policies. Additionally, it was able to mimic the different processes of the product monitoring level to provide a better understanding.

In order to develop and assess the proposed approach generic requirements needed to be gathered. First of all, literature on maintenance models have been analysed to gather the modelling requirements. After this, to counteract any limitations in literature, interviews with experts have been conducted. Difficulties have been experienced when planning expert interviews as a number of experts did not respond to the interview requests. It was noted that academic experts are more willing to take part in the interviews than industrial experts.

The generic requirements of modelling complex maintenance operations have been gathered. This led to developing a generic conceptual model of a wider product maintenance system which reflected the requirements gathered. This novel conceptual model combines the different processes of the different monitoring levels applied.

Converting this conceptual model into a computer code is a difficult and time consuming task as different processes of dealing with breakdowns needed to be modelled depending on the monitoring level. Furthermore, integrating multiple customers and products with labour and spares inventories and comparing the different monitoring levels is a very complex task. The PMLS tool has been developed to rapidly create complex maintenance operations scenarios to allow a better understanding when applying different product monitoring levels.

Comparing different performance metrics such as (availability, spare part used, etc.) by the PMLS tool would lead to better understanding of the overall maintenance system under different monitoring levels. However, the only real measure of comparison is money. Translating availability, travel time, spares cost, etc., into this universal quantity would have led to unambiguous comparisons. This can be done if the costs are known by easily calculating the cost of breakdown, travel time, spare parts used, inventory costs, etc. The researcher was not able to calculate this due to the sensitivity of obtaining the cost data from the case company. This was also discussed in section 5.2.3 of this thesis.

Industrial case studies were needed to validate the developed approach. Gaining access to industrial cases to acquire sensitive data was a difficult step for the researcher. The researcher contacted several companies with no success even when the companies were offered a confidentiality agreement. Finally, three industrial cases agreed to share their data. Two of the companies apply the Reactive level while the third applies Diagnostics. Under these circumstances finding a case study for a company which applied the higher monitoring level (Prognostics) was not achievable due to the limited number of companies who apply this high monitoring level and the sensitivity of data sought. The absence of an industrial case which applies Prognostics level was not considered a major disadvantage as the modelling work presented back to each of the three companies included a projection of likely Prognostics performance for their evaluation.

Industrial case studies have been utilised to validate the developed approach ,so as to gain a better understanding of different product monitoring levels. The results of each case have been analysed and discussed in Chapter 6 of this thesis. The next section will present a cross case discussion.

## 7.3 Cross case discussion

The previous chapter has discussed and analysed the results of each experiment with the different industrial cases. In this section, the researcher will draw some common findings throughout the experiments conducted across different case studies. These findings were based on the three cases and cannot be generalised unless further cases can be assessed using this approach. These findings are as follows:

- Travel time and spare parts lead time plays an important role in deciding what Prognostics Window (PW) is needed.

- The number of failures increases towards higher monitoring levels. This is due to increasing equipment availability which leads to greater use, then the failures will be reached more often. Although the number of failures have increased the actual percentage downtime remains the same.

- When all resources are available (labours and spare parts) and no travel time is involved then Diagnostics and Prognostics provide almost identical availability levels.

- Diagnostics and Prognostics gives better availability than Reactive, although there is no significant increase between Diagnostics and Prognostics.

- There is a positive relationship between increasing the availability and increasing the number of failures. This increase is due to some extent to the longer run time of the product.

- A longer PW may reduce the availability as parts will be replaced more often.

- The spare part lead time has a direct impact on availability. As can be seen throughout all the conducted cases, when lead time was set as a constraint it affected the product availability.

- Travel time and diagnose time plays an important role when deciding to move to a higher monitoring level. As when travel time is involved, the PW is suggested to be higher than the travel time in order to reach the product before it fails. Also, if the diagnose time is not relatively high then Reactive may provide a reasonable availability.

- Prognostics level gives better availability than Diagnostics, when the Prognostics Window (PW) is more than the travel time, or more than the spare lead time.

- Labour utilisation drops from Reactive when going to Diagnostics and Prognostics although it is almost the same when moving between Diagnostics and Prognostics.

- Higher monitoring levels of a product do not necessarily result in higher product performance. As can be seen from the experiments conducted with the industrial cases, Prognostics gives (in some cases) almost identical availability to that achieved by Diagnostics.

- Each maintenance operation should evaluate the maintenance strategies combined with their spare parts and labour before deciding which maintenance strategy should be implemented.

It has been proved that the proposed approach can provide a better understanding of different product monitoring levels. In addition, it proves that the simulation can discern the differences in product performance in a complex maintenance operation with different monitoring levels.

## 7.4 Research question summary

This section will review the research questions that were raised in Chapter 2 by discussing how the researcher has addressed each of them throughout the thesis. The questions that were raised are as follows:

**RQ1- How can the behaviour of a complex maintenance system for product monitoring levels be simulated?**

Two sub-questions were formed as follows:

**SRQ1.1- What are the generic requirements for modelling complex maintenance operations for products in use taking into account the wider system (equipment, labour, spare parts, etc.)?**

**SRQ1.2- What is the conceptual model of complex maintenance operations of products in use?**

In order to assess how to represent complex product maintenance systems it would be intuitive to identify which generic requirements need to be modelled. The requirements have been gathered by a literature review and by conducting interviews, as discussed and explained in Chapter 4. These requirements have then been used to form and create the conceptual model.

These requirements have been gathered in two ways (literature and interviews) to ensure that requirements needing to be modelled were incorporated as much as possible. Conducting interviews with experts is time consuming as their availability is limited. In addition, some of the experts have not responded to the interview requests. Academics are more likely to respond than industrial experts. Interviews were basically started by asking the interviewees about their objectives when conducting such a simulation model followed by the input/output requirements. The researcher has chosen to apply interviews to augment the limited literature.

Answering these two sub-questions has made clear the different processes involved in simulating complex product maintenance systems. Additionally, it assisted in guiding the researcher to translate this complex conceptual model into a computer tool.

**RQ2- How can discrete event simulation models be created to capture the behaviour of complex maintenance operations?**

The developed conceptual model identified three main different product monitoring levels. These levels approach the product repair in a different and complex manner. Therefore, different complex simulation modules were built according to the monitoring levels identified. Chapter 5 has answered and discussed in detail how these different modules were built.

**RQ3- Can discrete event simulation identify differences in the product's dynamic performance in complex maintenance operations with different monitoring levels?**

The answer to this third research question is that simulation can identify differences in the product's dynamic performance in complex maintenance operations when different monitoring levels are applied. This is evident in Chapter 6 where the PMLS tool was applied to different industrial cases.

This has shown how different product monitoring levels can be discerned by simulations. In addition, different experiments were carried out for each case which led to a better understanding of the monitoring levels in such complex maintenance operations.

## 7.5 Summary

This chapter has presented the research discussion and additionally a cross case discussion was described where a common theme of applying different product monitoring levels was identified. The next chapter will conclude this research thesis by stating the conclusion and future research. Furthermore, it will present the contributions gained by conducting this research and the lessons learned throughout the PhD process.

# 8 RESEARCH CONCLUSION AND FUTURE WORK

## 8.1 Introduction

This chapter presents the conclusion drawn from conducting such research. Moreover, it will suggest some areas for future work in order to build on this research. Additionally, the novelty of this research regarding both knowledge and practice will be presented. In this chapter, the researcher will share some of the lessons learned throughout the PhD process.

## 8.2 Conclusion

The move towards more efficient maintenance strategies has been driven by the need to eliminate waste and increase the product availability to customers. Recently, the pressure has increased for high availability of products. Manufacturers, suppliers, and maintenance contractors are more concerned about product availability, particularly in the case of Product Service Systems (PSS) where the sale of the product’s use is demanded rather than the sale of the product itself . Authors such as Lightfoot et al. (2011) have suggested that sensing technologies to monitor the health of the product would increase product performance. Logical reasoning has been used to date to justify that higher product monitoring will deliver better overall system performance but this is not supported by empirical, experimental data. The contribution of this research is to verify this by applying a simulation approach.

Simulation, in particular Discrete Event Simulation (DES) has the characteristics to be able to discern complex operations. A review of literature has identified an absence of dynamic tools to assess complex maintenance operations. This research started by gathering the required input and output of such complex and dynamic operations. This research then gathered the generic requirements for modelling complex product maintenance operations (by literature and interviews). These requirements have formed the conceptual model of the maintenance operations which include different processes of dealing with a failure according to the product monitoring level applied. These requirements were built into a simulation software package representing the different monitoring levels (Reactive, Diagnostics, and Prognostics). An Excel interface has been developed for rapid model configuration which also has the potential to assist inexperienced users to insert their input and obtain their output without interfering with the simulation software.

The developed PMLS tool enabled the assessment of complex maintenance operations by examining the implications of different product monitoring levels for different fleets of product, product locations, labour requirements, spare parts inventory, etc.

This research, through conducting different experiments, concluded that the proposed approach can discern different product monitoring levels and provides a better understanding for product monitoring levels in complex maintenance operations. It also showed that higher monitoring levels do not guarantee higher product availability as different system constrains (such as: spares inventory, labour levels, travel time, etc.) affect the maintenance operations.

## 8.3 Future work

The work contains a number of limitations, some of which are the basis for future work.

In the first place, the model logic assumes perfect monitoring, information records and staff competence. The modelling work did not consider sensor failure, loss of information, incorrect information on the availability of spares, failure to repair the product due to mistakes or repairs triggering further faults. This could have been modelled through increasing the breakdowns or adding control logic but was considered to be an addition of unnecessary complexity.

Secondly, the experiments were conducted by changing one factor at a time rather than a design of experiments. This was considered acceptable as the purpose was to demonstrate the potential of the modelling approach rather than to provide solutions to optimise the scenario’s performance.

Lastly, larger models across a wide range of applications could be considered as this would disclose whether the value of the modelling was greater or more limited in certain cases.

## 8.4 Contributions

This research offers contributions to both knowledge and practice and these are presented in the next sub-sections.

### 8.4.1 Contributions to knowledge

The novelty of this research to knowledge lies in the following key points:

- It was shown that Discrete Event Simulation (DES) is an appropriate approach to assess such operational complexity and to compare different product monitoring levels. This was done through assessing its characteristics and matching them with the problem situation.

- Categorisations of simulation applications in maintenance research has been developed. This categorisation serves to identify how simulation was conducted in different maintenance categories. In addition, a number of key gaps were identified to warrant further investigations. These categorisations have been published in Alabdulkarim et al, (2013).

- The generic requirements for modelling complex product maintenance systems were gathered by both analysing the literature review and conducting interviews with experts.

- A generic conceptual model was developed for product maintenance operations. The novelty of this conceptual model lies in integrating different sub-systems of product maintenance operations in a complex manner. Additionally, this conceptual model has incorporated different processes in dealing with a breakdown according to the different levels of product monitoring.

- A novel simulation approach was developed to assess the performance of different product monitoring levels on complex maintenance operations.

- The approach allows a better understanding of the monitoring levels and their effect on product performance. Additionally, it identifies the drivers of performance that exist in maintenance models. The proposed approach has integrated all sub-systems in maintenance operations in a novel way as usually maintenance sub-systems are modelled in isolation. This approach has proved to provide numerical evidence on the implications of the monitoring levels on product performance.

### 8.4.2 Contributions to practice

This research contributes to practice in the following key points:

- A guide on how to develop different product monitoring level modules and the complete PMLS tool.

- A quantitative decision tool (PMLS tool) that enables decision makers to select the appropriate monitoring level for their specific maintenance operation.

- A decision making tool enabling decision makers to assess the appropriate Prognostics Window (PW) for their specific maintenance operations.

## 8.5 Lessons learned

The researcher would like to share some lessons learned during the PhD process. During this research experience, the researcher has leaned a number of skills which will be beneficial for future career development. Among these skills is an important one on how to conduct a research project. This skill will allow the researcher to identify gaps and link them with proper methodology to present future research. The researcher attended different short courses regarding this subject, one of which was the Research Methodology Workshop held in Cambridge University. In addition, the author took part in the core skill programme that provides short courses for PhD researchers at Cranfield University. Additionally, advanced skills were gained in the use of simulation which give a better insight on how to develop complex models.

One of the most important skills that any researcher should learn is how to present the research. I have learned this skill gradually from the onset of my PhD and I am now able to present my research at international conferences and in peer reviewed journals. I have learned a lot from the reviewers' comments from these conferences and journals, not just by reflecting their comments into my work but by understanding how to review research papers.

Even though the PhD is a slow process, I have enjoyed it as it makes you question things and inspires you to be excited and willing to investigate. Also, I have learnt from fellow PhD researchers whom I have met at Cranfield, or at conferences, or workshops as their comments and questions about your research usually lead you to look at your research in a different light.

## 8.6 Summary

This chapter concluded this research thesis by presenting the conclusion remarks. It showed that future research that can be built on this work and furthermore, declared where the novelty of this research lies. Finally, the researcher has provided some comments about the lessons learned throughout the PhD process.

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# Appendix A Application of simulation in maintenance research categorisation

Table B-1 and table B-2 below provide legendary to be used in table B-3. Table B-3 provides the full list of 148 papers that were examined. Each paper was classified into which maintenance category it belongs to and what application type of simulation was applied.

**Table A-1 Legend of maintenance categories**

| | | | |
|---|---|---|---|
| **A** | General | **B** | Maintenance policy |
| **C** | Maintenance scheduling | **D** | Condition-based |
| **E** | Maintenance cost | **F** | Maintenance reliability |
| **G** | Maintenance Staffing ( resource allocation) | **H** | Maintenance operations performance |
| **I** | Maintenance inventory | | |

**Table A-2 Legend of the applications type of simulation in maintenance research**

| | | | |
|---|---|---|---|
| **1** | evaluation, comparison, or validation | **2** | combination of simulation with optimisation techniques |

**Table A-3 List of papers and their application areas**

| Authors | A | | B | | C | | D | | E | | F | | G | | H | | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Percy and Kobbacy (2000) | | | | | X | | | | | | | | | | | | | |
| Pruett and Lau (1982) | | | | | | | | | | | | | | | X | | | |
| Seal (1995) | | | | | | | | | | | | | | | X | | | |
| Adamides et al, (2004) | | | | | | | | | | | | | | | X | | | |
| Agbulos et al, (2006) | | | | | | | | | | | | | X | | | | | |
| Agnihothri and Karmarkar (1992) | | | | | | | | | | | | | X | | X | | | |
| Aissani et al, (2009) | | | | | X | | | | | | | | | | | | | |
| Albino et al, (1992) | | | X | | | | | | | | | | | | | | | |
| Al-Zubaidi and Christer (1997) | | | | | | | | | | | | | X | | | | | |
| Andijani & Duffuaa (2002) | X | | | | | | | | | | | | | | | | | |
| Antoniol et al, (2004) | | | | | | | | | | | | | X | | | | | |
| Baek (2007) | | | | | X | | X | | X | | | | | | | | | |
| Balakrishnan et al, (2006) | | | X | | | | | | | | | | | | | | | |
| Banerjee and Burton (1990) | | | X | | | | | | | | | | X | | | | | |
| Barata et al, (2002) | | | | | | | X | | | | | | | | | | | |
| Barnett and Blundell (1981) | | | | | | | | | | | | | X | | | | | |

| Authors | A | | B | | C | | D | | E | | F | | G | | H | | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Basile et al, (2007) | | | | | | | | | | | X | | | | | | | |
| Bengu and Ortiz (1994) | | | | | | | | | | | | | | | X | | | |
| Boschian et al, (2009) | | | X | | | | | | | | | | | | | | | |
| Boulet et al, (2009) | | | | | | | | | | X | | X | | | | | | |
| Boussabaine and Kirkham (2004) | | | | | | | | | X | | | | | | | | | |
| Bris et al, (2008) | | | | | | | | | | X | | X | | | | | | |
| Burton et al, (1989) | | | | | X | | | | | | | | | | | | | |
| Caesarendra et al, (2010) | | | | | | | X | | | | | | | | | | | |
| CASSADY et al, (2000) | | | | X | | | | | | | | | | | | | | |
| Cavory et al, (2001) | | | | | | X | | | | | | | | | | | | |
| Celik et al, (2010) | | | | | X | | | | | | | | | | | | | |
| Chang et al, (2007) | | | | | | | | | X | | | | X | | | | | |
| Chasey et al, (2002) | | | X | | | | | | X | | | | | | | | | |
| Chen and Tseng (2003) | | | | | | | | | | X | | | | | | X | | |
| Cheu et al, (2004) | | | | | | X | | | | | | | | | | | | |
| Cheung et al, (2005) | | | | | X | | | | | | | | | | | | | |
| Chew et al, (2008) | | | | | | | | | | | X | | | | | | | |
| Chootinan et al, (2006) | | | | | | X | | | | | | | | | | | | |
| Chua et al, (1993) | | | | | X | | | | | | | | | | | | X | |
| Ciarallo et al, (2005) | | | | | | | | | | | X | | | | | | | |
| Coolen-Schrijne et al, (2006) | | | | | | | X | | | | | | | | | | | |
| Crocker and Sheng (2008) | | | X | | | | | | | | | | | | | | | |
| da Silva et al, (2008) | | | X | | | | | | X | | | | | | | | | |
| de Smidt-Destombes et al, (2006) | | | | | | | X | | | | X | | | | | | X | |
| de Smidt-Destombes et al, (2007) | | | | | | | | | | | X | | | | | | X | |
| Dekker and Smeitink (1991) | | | X | | | | | | | | | | | | | | | |
| Deris et al, (1999) | | | | | X | | | | | | | | | | | | | |
| Dessouky and Bayer (2002) | | | | | | | | | X | | | | | | | | | |
| Dhakar et al, (1994) | | | | | | | | | | | | | | | | | X | |
| Duffuaa and Raouf (1992) | | | | | | | | | | | | | X | | | | | |
| Duffuaa et al, (2001) | X | | | | | | | | | | | | | | | | | |
| El Hayek et al, (2005) | | | | | | | | | | | X | | | | | | | |
| Finger and Mehrez (1985) | | | X | | | | | | | | | | | | | | | |
| Gertman (1992) | | | | | | | | | | | | | X | | | | | |
| Gharbi and Kenne (2005) | | | | X | | | | | | X | | | | | | | | |
| Gong and Tang (1997) | | | X | | | | X | | X | | | | | | | | | |
| Greasley (2000) | | | | | | | | | | | X | | | | X | | | |
| Guarnieri et al, (2006) | | | | | X | | | | | | | | X | | | | | |
| Gupta and Lawsirirat (2006) | | | | | | X | | | | | | | | | | | | |

| **Authors** | A | | B | | C | | D | | E | | F | | G | | H | | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Taha et al, (1989) | | | | | | | | | | | X | | | | | | | |
| Hani et al, (2008) | | | | | | X | | | | | | | | | | X | | |
| Heidergott (1999) | | | | | | | | | X | | | | | | | | | |
| Hennequin et al, (2009) | | | | X | | | | | | | | | | | | | | |
| Humphrey et al, (1998) | | | | | | | | | | | | | | | | | X | |
| Iwamoto and Dohi (2008) | | | | | | | | | X | | | | | | | | | |
| javadpour and knapp (2003) | | | | | | | X | | | | | | | | | | | |
| Joo et al, (1997) | | | X | | | | | | | | | | | | | | | |
| Kaegi et al, (2009) | | | X | | | | | | | | X | | | | | | | |
| Ke and Lin (2005) | | | | | | | | | | | X | | | | | | | |
| Kenne and Gharbi (1999) | | | | X | | | | | | | | | | | | | | |
| Kilpi et al, (2009) | | | X | | | | | | | | | | | | | | X | |
| Kim et al, (1994) | | | | | | X | | | | | | | | | | | | |
| Kuei and Madu (1994) | | | | | | | | | | | | X | | | | | | |
| Kumara et al, (1994) | | | | | | | | | | | | | | | | | | X |
| Kurien et al, (1993) | | | | | | | | | | | X | | | | | | | |
| Langer et al, (2010) | | | X | | | | | | | | | | | | | | | |
| Lanza and Ruhl (2009) | | | | | | | | | X | | | | | | | | | |
| Lau et al, (2006) | | | | | | | | | | | | | | | | | X | |
| Lavy and Shohet (2007) | | | | | | | | | X | | | | X | | | | | |
| Lei et al, (2010) | | | X | | | | | | | | | | | | | | | |
| Li & Ni (2009) | | | X | | | | | | | | | | | | | | | |
| Liao et al, (2009) | | | X | | | | X | | | | | | | | | | | |
| Lin and Chien (1995) | | | | X | | | | | | | | | | | | | | X |
| Logendran and Talkington (1997) | | | X | | | | | | | | | | | | | | | |
| Louit and Knights (2001) | | | | | | | | | | | | | | | X | | X | |
| Madu and Georgantaz (1988) | | | X | | | | | | | | | | | | | | | |
| Madu and Kuei (1992) | | | X | | | | | | | | | | | | | | | |
| Madu and Kuei (1993) | | | | | | | | | | | | X | | | | | | |
| Madu (1999) | | | X | | | | | | | | | | X | | | | | |
| Madu et al, (1990) | | | | | | | | | | | | | | | X | | | |
| Marquez and Lung (2007) | | | | | | | | | | | X | | | | | | | |
| Marquez et al, (2005) | | | X | | | | | | | | | | | | | | | |
| Marquez et al, (2006) | | | | | X | | | | | | | | | | | | | |
| Marseguerra and Zio (2000) | | | | X | | | | | | | | | | | | | | |
| Marseguerra et al, (2002) | | | | | | | | X | | | | | | | | | | |
| Mathew and Rajendran (1993) | | | | | X | | | | | | | | | | | | | |
| Mattila et al, (2008) | | | X | | | | | | | | X | | X | | X | | | |
| Michaelides et al, (2003) | | | | | | | | | | | | | | | | | X | |
| Mjema (2002) | | | | | | | | | | | | | X | | | | | |

| **Authors** | A | | B | | C | | D | | E | | F | | G | | H | | I | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Mohanty (1989) | | | | | X | | | | | | | | | | | | | |
| Mosley et al, (1998) | | | | | X | | | | | | | | | | | | | |
| Newman (1985) | | | | | | | | | | | | | | | | | X | |
| Ng et al, (2008) | | | | | | | X | | | | | | | | | | | |
| Ntuen and Park (1999) | | | | | | | | | | | | | X | | | | | |
| Oke and Charles-Owaba (2006) | | | | | X | | | | | | | | | | | | | |
| Oke (2005) | | | | | | | | | X | | | | | | | | | |
| Okogbee and Huang (1992) | | | X | | | | | | | | | | | | | | | |
| Oyarbide-Zubillaga et al, (2008) | | | | X | | | | | | | | | | | | | | |
| Padalkar et al, (1995) | | | | | | | X | | | | | | | | | | | |
| Petrovic et al, (1982) | | | | | | | | | | | | X | | | | | | X |
| Pulcini (2001) | | | | | | | | | | | X | | | | | | | |
| Quintana et al, (2009) | | | | | X | | | | X | | X | | | | X | | | |
| Radhoui et al, (2009) | | | | X | | | | | | | | | | | | | | |
| Rao et al, (2007) | | | | | | | | | | | X | | | | | | | |
| Rees et al, (1984) | | | | | | | | | X | | | | | | | | | |
| Rezg et al, (2005) | | | | X | | | | | | | | | | | | | | X |
| Rishel et al, (2006) | | | X | | | | | | X | | | | | | | | | |
| Roux et al, (2008) | | | | X | | | | | | | | | | | X | | | |
| Sarker and Haque (2000) | | | X | | | | | | | | | | | | | | X | |
| Savsar (1997) | | | X | | | | | | | | | | X | | | | | |
| Savsar (2005) | | | | X | | | | | | | | | | | | | | |
| Savsar (2006) | | | | X | | | | | | | | | | | | | | |
| Scudder (1984) | | | | | X | | | | | | | | | | | | X | |
| Semra (1993) | | | X | | | | | | | | | | | | X | | | |
| Dinesh and Bhadury (1993) | | | | | | | | | | | | | X | | | | X | |
| Sheu and Lin (2006) | | | | | X | | | | | | | | | | | | | |
| Simeu-Abazi and Bouredji (2006) | | | | | | | | | | | | | | | X | | | |
| Sleptchenko et al, (2002) | | | | | | | | | | | | | | | | | X | |
| Sloan and Shanthikumar (2002) | | | X | | | | | | | | | | | | | | | |
| Smith (1973) | | | | | X | | | | | | | | | | | | | |
| Sohn and Oh (2004) | | | | | | | | | | | | | | | X | | | |
| Spanjers et al, (2005) | | | | | | | | | | | | | | | | | X | |
| Sun et al, (2007) | | | | | | | | | | | X | | | | | | | |
| Szczerbicki and White (1998) | | | | | | | X | | | | | | | | | | | |
| Tersine (1983) | | | X | | | | | | | | | | | | | | | |
| Vardar et al, (2007) | | | | | | | | X | | X | | | | | | | | |
| Verrijdt et al, (1998) | | | | | | | | | | | | | | | | | X | |
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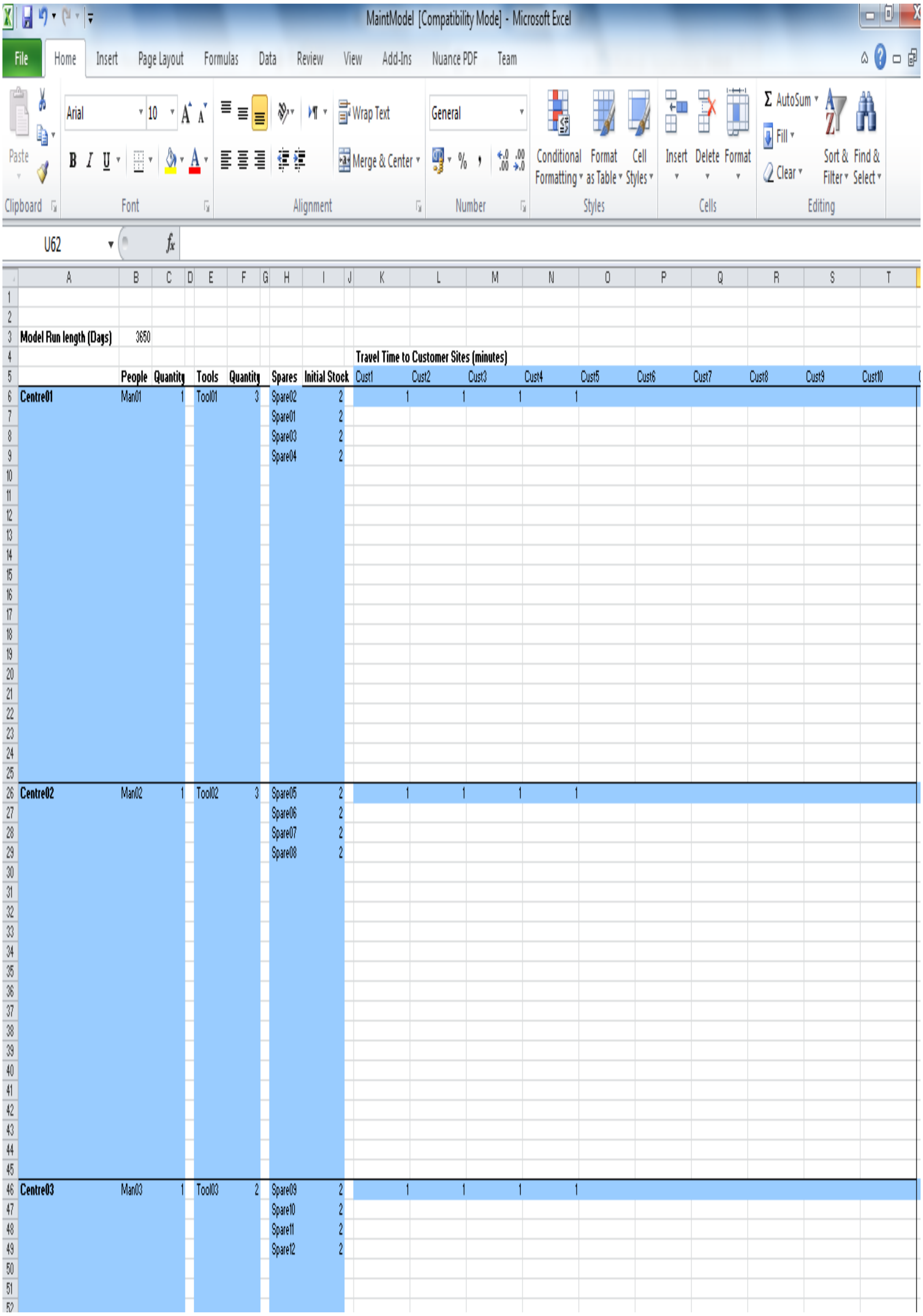
# Appendix B Interface input sheets

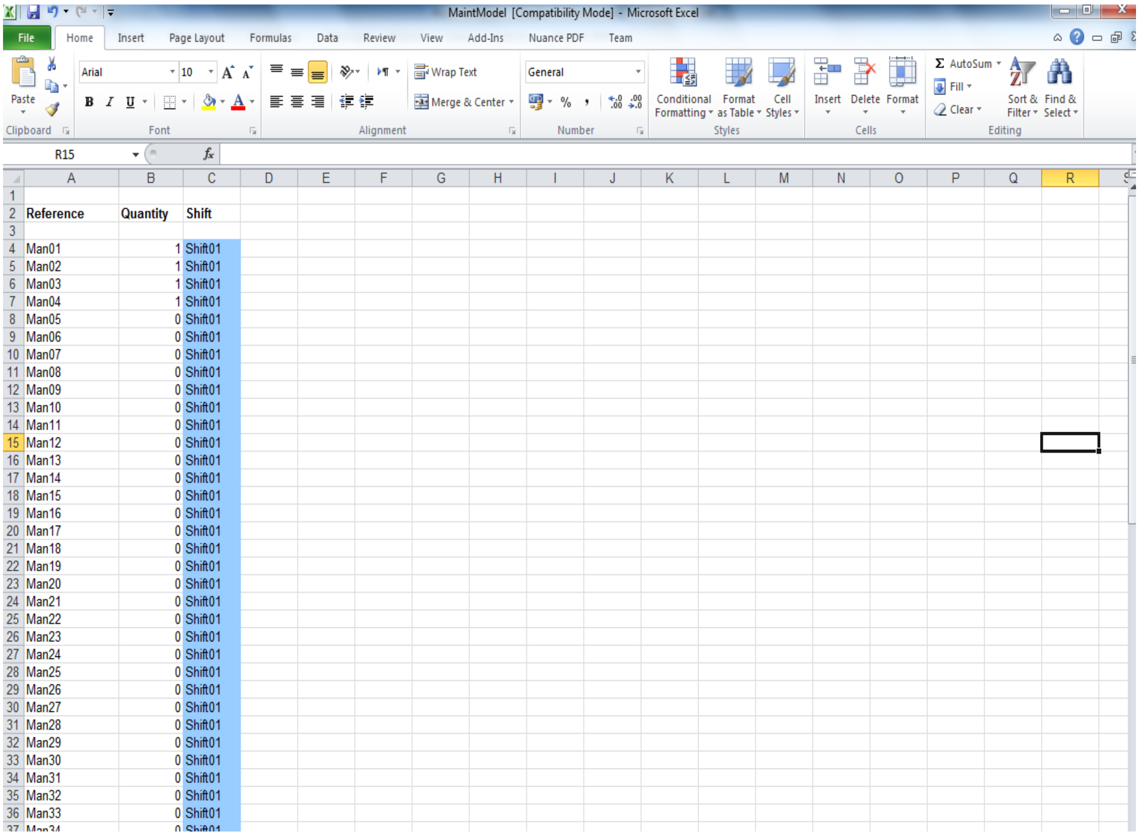
## B.1 Maintenance centre input sheet



MaintModel [Compatibility Mode] - Microsoft Excel

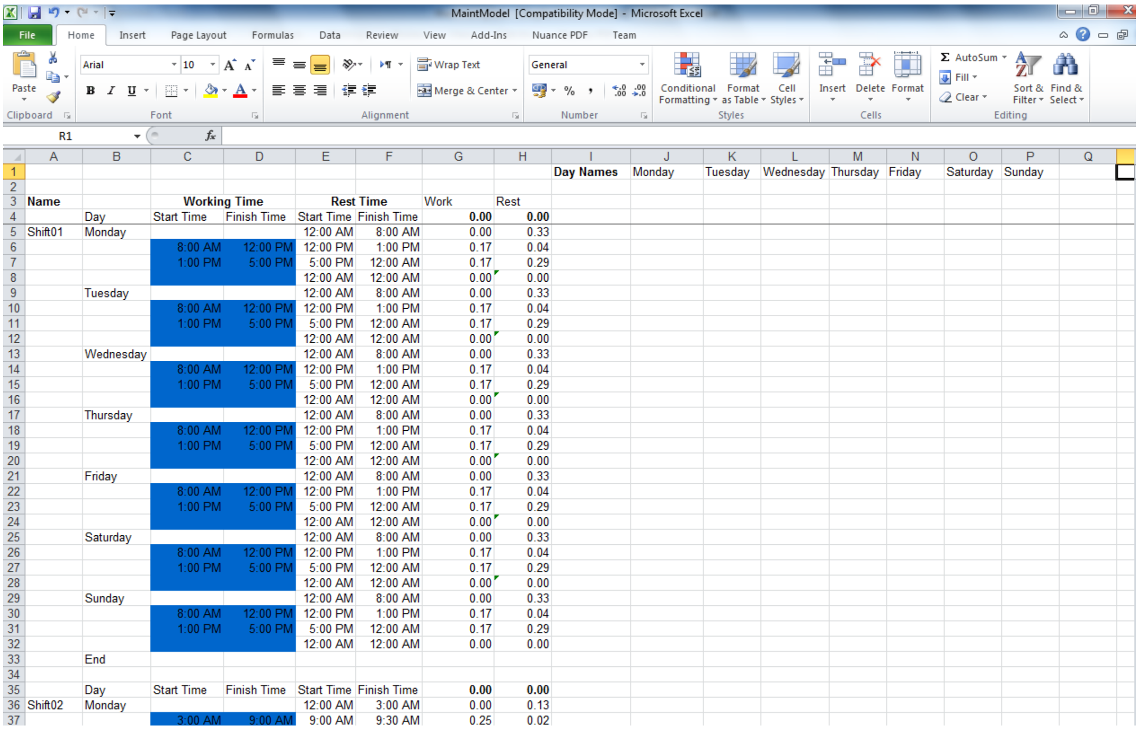
| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Model Run length (Days) | 3650 | | | | | | | | | | | | | | | |
| | | | | | | | Travel Time to Customer Sites (minutes) | | | | | | | | | |
| | People | Quantity | Tools | Quantity | Spares | Initial Stock | Cust1 | Cust2 | Cust3 | Cust4 | Cust5 | Cust6 | Cust7 | Cust8 | Cust9 | Cust10 |
| Centre01 | Man01 | 1 | Tool01 | 3 | Spare02 | 2 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | | Spare01 | 2 | | | | | | | | | | |
| | | | | | Spare03 | 2 | | | | | | | | | | |
| | | | | | Spare04 | 2 | | | | | | | | | | |
| Centre02 | Man02 | 1 | Tool02 | 3 | Spare05 | 2 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | | Spare06 | 2 | | | | | | | | | | |
| | | | | | Spare07 | 2 | | | | | | | | | | |
| | | | | | Spare08 | 2 | | | | | | | | | | |
| Centre03 | Man03 | 1 | Tool03 | 2 | Spare09 | 2 | 1 | 1 | 1 | 1 | | | | | | |
| | | | | | Spare10 | 2 | | | | | | | | | | |
| | | | | | Spare11 | 2 | | | | | | | | | | |
| | | | | | Spare12 | 2 | | | | | | | | | | |

## B.2 People input sheet



| Reference | Quantity | Shift |
|---|---|---|
| Man01 | 1 | Shift01 |
| Man02 | 1 | Shift01 |
| Man03 | 1 | Shift01 |
| Man04 | 1 | Shift01 |
| Man05 | 0 | Shift01 |
| Man06 | 0 | Shift01 |
| Man07 | 0 | Shift01 |
| Man08 | 0 | Shift01 |
| Man09 | 0 | Shift01 |
| Man10 | 0 | Shift01 |
| Man11 | 0 | Shift01 |
| Man12 | 0 | Shift01 |
| Man13 | 0 | Shift01 |
| Man14 | 0 | Shift01 |
| Man15 | 0 | Shift01 |
| Man16 | 0 | Shift01 |
| Man17 | 0 | Shift01 |
| Man18 | 0 | Shift01 |
| Man19 | 0 | Shift01 |
| Man20 | 0 | Shift01 |
| Man21 | 0 | Shift01 |
| Man22 | 0 | Shift01 |
| Man23 | 0 | Shift01 |
| Man24 | 0 | Shift01 |
| Man25 | 0 | Shift01 |
| Man26 | 0 | Shift01 |
| Man27 | 0 | Shift01 |
| Man28 | 0 | Shift01 |
| Man29 | 0 | Shift01 |
| Man30 | 0 | Shift01 |
| Man31 | 0 | Shift01 |
| Man32 | 0 | Shift01 |
| Man33 | 0 | Shift01 |

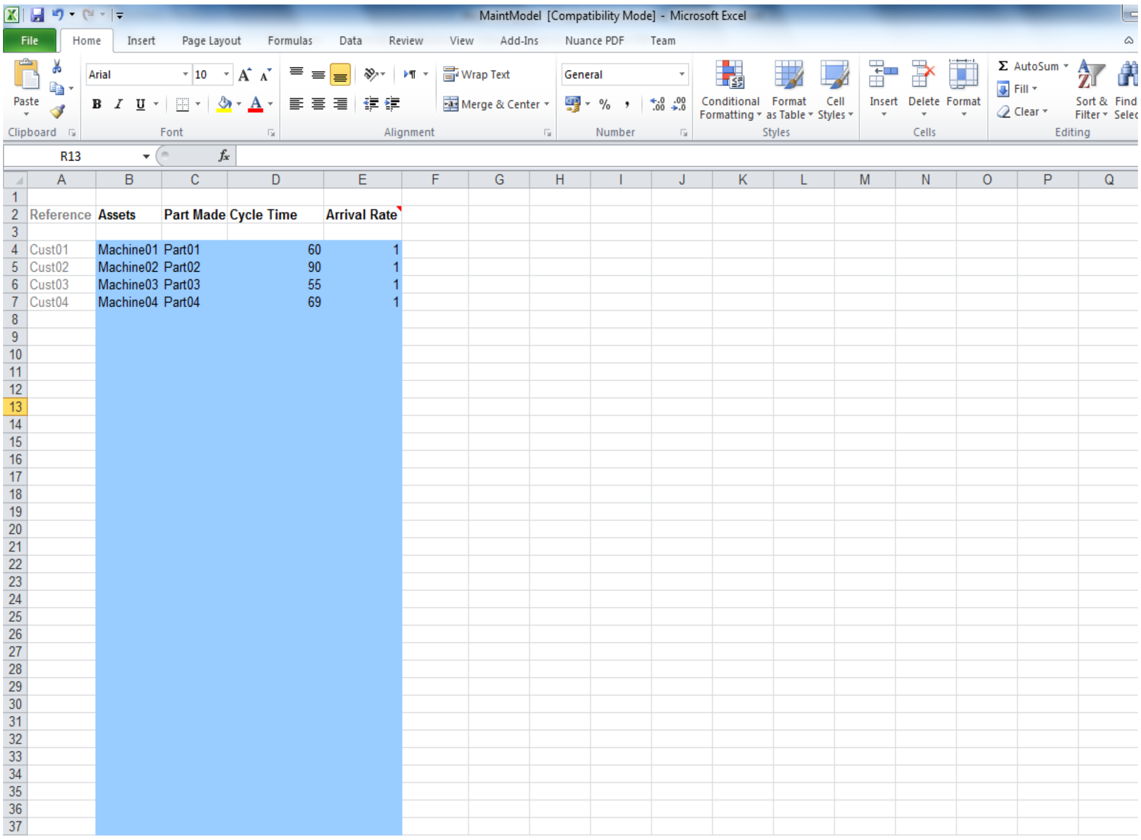
## B.3 Shift input sheet



| Day Names | Monday | Tuesday | Wednesday | Thursday | Friday | Saturday | Sunday |
|---|---|---|---|---|---|---|---|

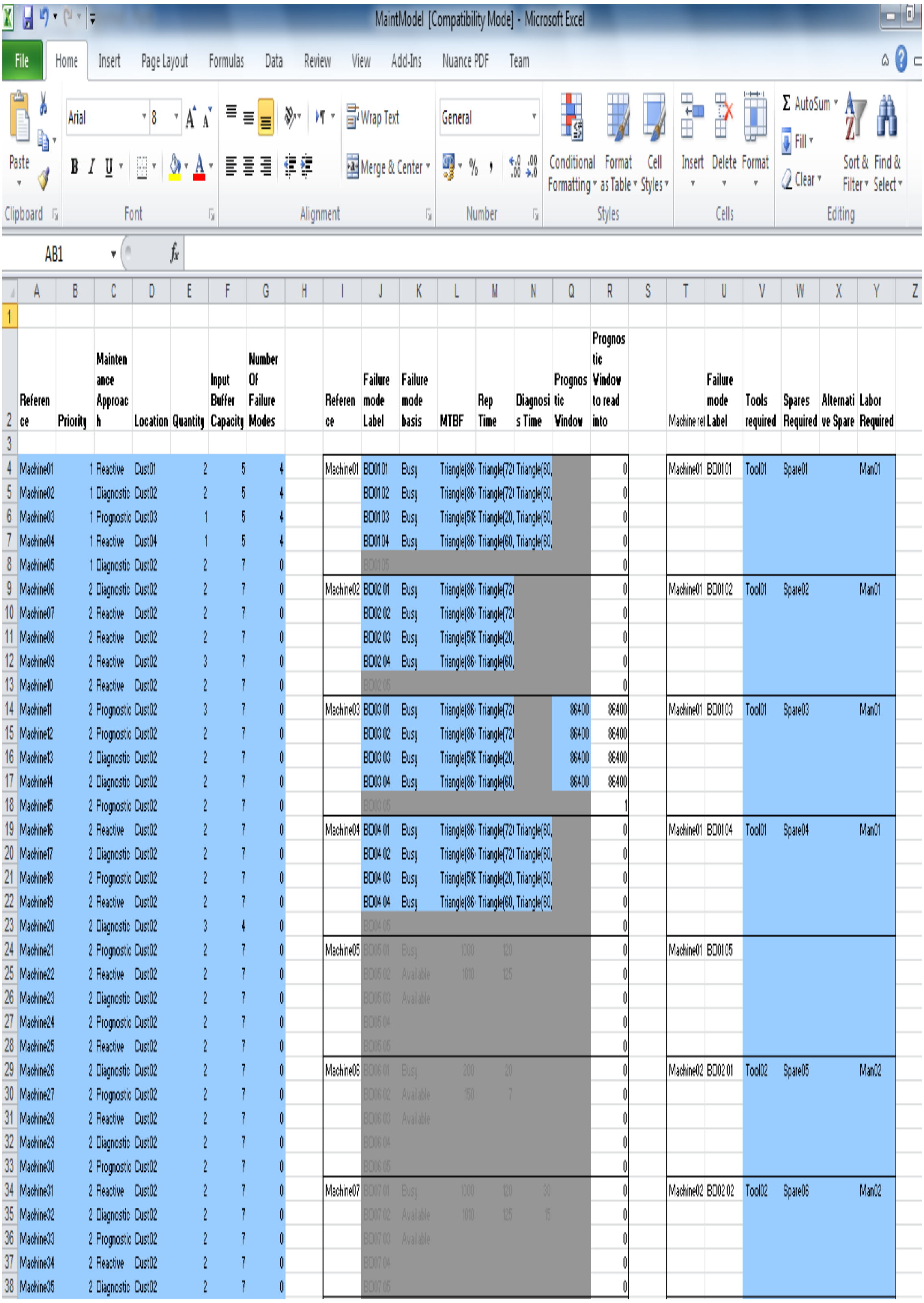
| Name | | Working Time | | Rest Time | | Work | Rest |
|---|---|---|---|---|---|---|---|
| | Day | Start Time | Finish Time | Start Time | Finish Time | **0.00** | **0.00** |
| Shift01 | Monday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Tuesday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Wednesday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Thursday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Friday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Saturday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | Sunday | | | 12:00 AM | 8:00 AM | 0.00 | 0.33 |
| | | 8:00 AM | 12:00 PM | 12:00 PM | 1:00 PM | 0.17 | 0.04 |
| | | 1:00 PM | 5:00 PM | 5:00 PM | 12:00 AM | 0.17 | 0.29 |
| | | | | 12:00 AM | 12:00 AM | 0.00 | 0.00 |
| | End | | | | | | |
| | | | | | | | |
| | Day | Start Time | Finish Time | Start Time | Finish Time | **0.00** | **0.00** |
| Shift02 | Monday | | | 12:00 AM | 3:00 AM | 0.00 | 0.13 |
| | | 3:00 AM | 9:00 AM | 9:00 AM | 9:30 AM | 0.25 | 0.02 |

# B.4 Order input sheet



| Reference | Assets | Part Made | Cycle Time | Arrival Rate |
|---|---|---|---|---|
| Cust01 | Machine01 | Part01 | 60 | 1 |
| Cust02 | Machine02 | Part02 | 90 | 1 |
| Cust03 | Machine03 | Part03 | 55 | 1 |
| Cust04 | Machine04 | Part04 | 69 | 1 |

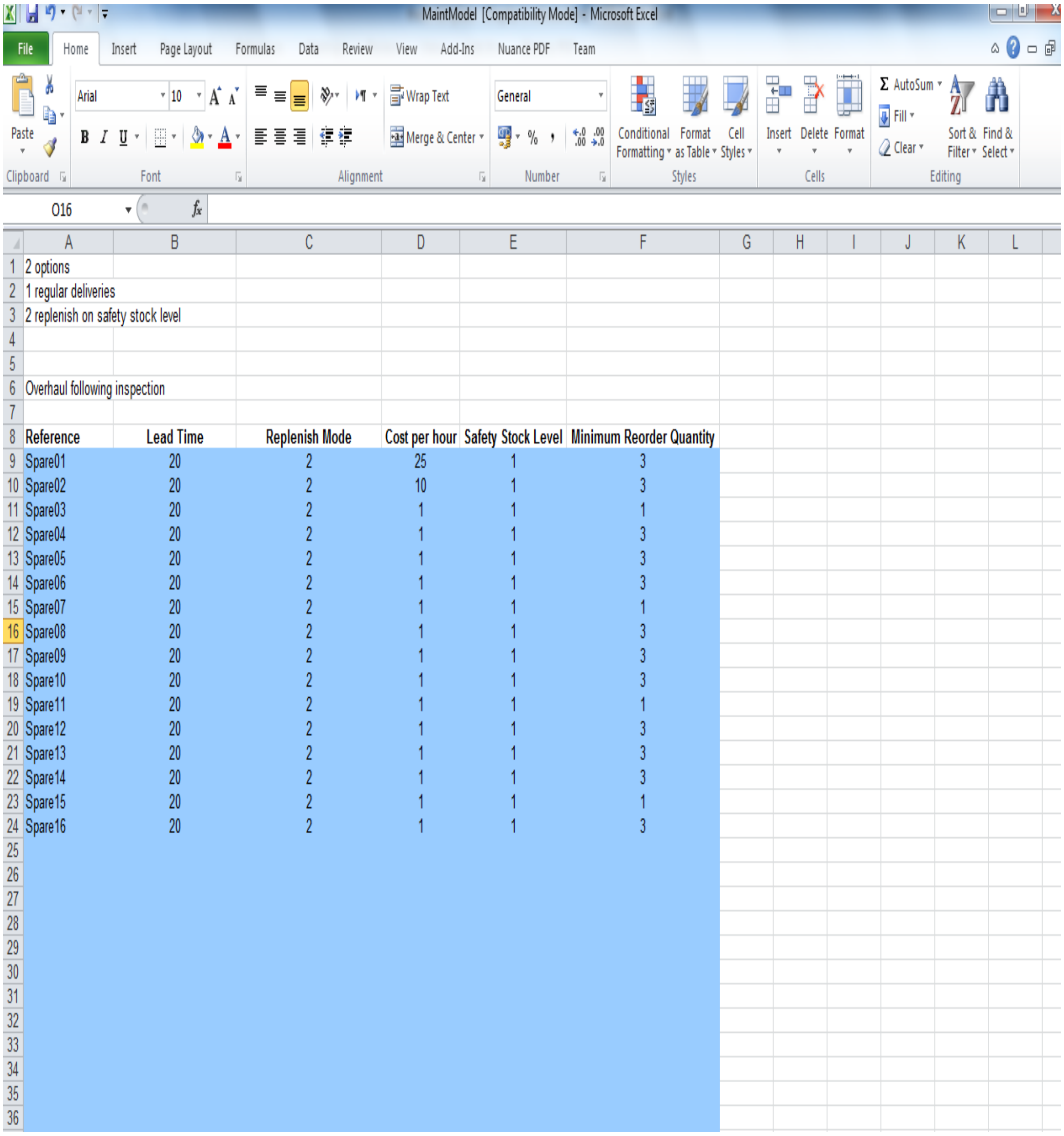
## B.5 Product input sheet



MaintModel [Compatibility Mode] - Microsoft Excel

| | A | B | C | D | E | F | G | I | J | K | L | M | N | Q | R | T | U | V | W | X | Y |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | Reference | Priority | Maintenance Approach | Location | Quantity | Input Buffer Capacity | Number Of Failure Modes | Reference | Failure mode Label | Failure mode basis | MTBF | Rep Time | Diagnosis Time | Prognostic Window | Prognostic Window to read into | Machine rel | Failure mode Label | Tools required | Spares Required | Alternative Spare | Labor Required |
| 4 | Machine01 | 1 | Reactive | Cust01 | 2 | 5 | 4 | Machine01 | BD01 01 | Busy | Triangle(86 | Triangle(72 | Triangle(60, | | 0 | Machine01 | BD01 01 | Tool01 | Spare01 | | Man01 |
| 5 | Machine02 | 1 | Diagnostic | Cust02 | 2 | 5 | 4 | | BD01 02 | Busy | Triangle(86 | Triangle(72 | Triangle(60, | | 0 | | | | | | |
| 6 | Machine03 | 1 | Prognostic | Cust03 | 1 | 5 | 4 | | BD01 03 | Busy | Triangle(51 | Triangle(20, | Triangle(60, | | 0 | | | | | | |
| 7 | Machine04 | 1 | Reactive | Cust04 | 1 | 5 | 4 | | BD01 04 | Busy | Triangle(86 | Triangle(60, | Triangle(60, | | 0 | | | | | | |
| 8 | Machine05 | 1 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD01 05 | | | | | | 0 | | | | | | |
| 9 | Machine06 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | Machine02 | BD02 01 | Busy | Triangle(86 | Triangle(72 | | | 0 | Machine01 | BD01 02 | Tool01 | Spare02 | | Man01 |
| 10 | Machine07 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD02 02 | Busy | Triangle(86 | Triangle(72 | | | 0 | | | | | | |
| 11 | Machine08 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD02 03 | Busy | Triangle(51 | Triangle(20, | | | 0 | | | | | | |
| 12 | Machine09 | 2 | Reactive | Cust02 | 3 | 7 | 0 | | BD02 04 | Busy | Triangle(86 | Triangle(60, | | | 0 | | | | | | |
| 13 | Machine10 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD02 05 | | | | | | 0 | | | | | | |
| 14 | Machine11 | 2 | Prognostic | Cust02 | 3 | 7 | 0 | Machine03 | BD03 01 | Busy | Triangle(86 | Triangle(72 | | 86400 | 86400 | Machine01 | BD01 03 | Tool01 | Spare03 | | Man01 |
| 15 | Machine12 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD03 02 | Busy | Triangle(86 | Triangle(72 | | 86400 | 86400 | | | | | | |
| 16 | Machine13 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD03 03 | Busy | Triangle(51 | Triangle(20, | | 86400 | 86400 | | | | | | |
| 17 | Machine14 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD03 04 | Busy | Triangle(86 | Triangle(60, | | 86400 | 86400 | | | | | | |
| 18 | Machine15 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD03 05 | | | | | | 1 | | | | | | |
| 19 | Machine16 | 2 | Reactive | Cust02 | 2 | 7 | 0 | Machine04 | BD04 01 | Busy | Triangle(86 | Triangle(72 | Triangle(60, | | 0 | Machine01 | BD01 04 | Tool01 | Spare04 | | Man01 |
| 20 | Machine17 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD04 02 | Busy | Triangle(86 | Triangle(72 | Triangle(60, | | 0 | | | | | | |
| 21 | Machine18 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD04 03 | Busy | Triangle(51 | Triangle(20, | Triangle(60, | | 0 | | | | | | |
| 22 | Machine19 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD04 04 | Busy | Triangle(86 | Triangle(60, | Triangle(60, | | 0 | | | | | | |
| 23 | Machine20 | 2 | Diagnostic | Cust02 | 3 | 4 | 0 | | BD04 05 | | | | | | 0 | | | | | | |
| 24 | Machine21 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | Machine05 | BD05 01 | Busy | 1000 | 120 | | | 0 | Machine01 | BD01 05 | | | | |
| 25 | Machine22 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD05 02 | Available | 1010 | 125 | | | 0 | | | | | | |
| 26 | Machine23 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD05 03 | Available | | | | | 0 | | | | | | |
| 27 | Machine24 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD05 04 | | | | | | 0 | | | | | | |
| 28 | Machine25 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD05 05 | | | | | | 0 | | | | | | |
| 29 | Machine26 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | Machine06 | BD06 01 | Busy | 200 | 20 | | | 0 | Machine02 | BD02 01 | Tool02 | Spare05 | | Man02 |
| 30 | Machine27 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD06 02 | Available | 150 | 7 | | | 0 | | | | | | |
| 31 | Machine28 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD06 03 | Available | | | | | 0 | | | | | | |
| 32 | Machine29 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD06 04 | | | | | | 0 | | | | | | |
| 33 | Machine30 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD06 05 | | | | | | 0 | | | | | | |
| 34 | Machine31 | 2 | Reactive | Cust02 | 2 | 7 | 0 | Machine07 | BD07 01 | Busy | 1000 | 120 | 30 | | 0 | Machine02 | BD02 02 | Tool02 | Spare06 | | Man02 |
| 35 | Machine32 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD07 02 | Available | 1010 | 125 | 15 | | 0 | | | | | | |
| 36 | Machine33 | 2 | Prognostic | Cust02 | 2 | 7 | 0 | | BD07 03 | Available | | | | | 0 | | | | | | |
| 37 | Machine34 | 2 | Reactive | Cust02 | 2 | 7 | 0 | | BD07 04 | | | | | | 0 | | | | | | |
| 38 | Machine35 | 2 | Diagnostic | Cust02 | 2 | 7 | 0 | | BD07 05 | | | | | | 0 | | | | | | |

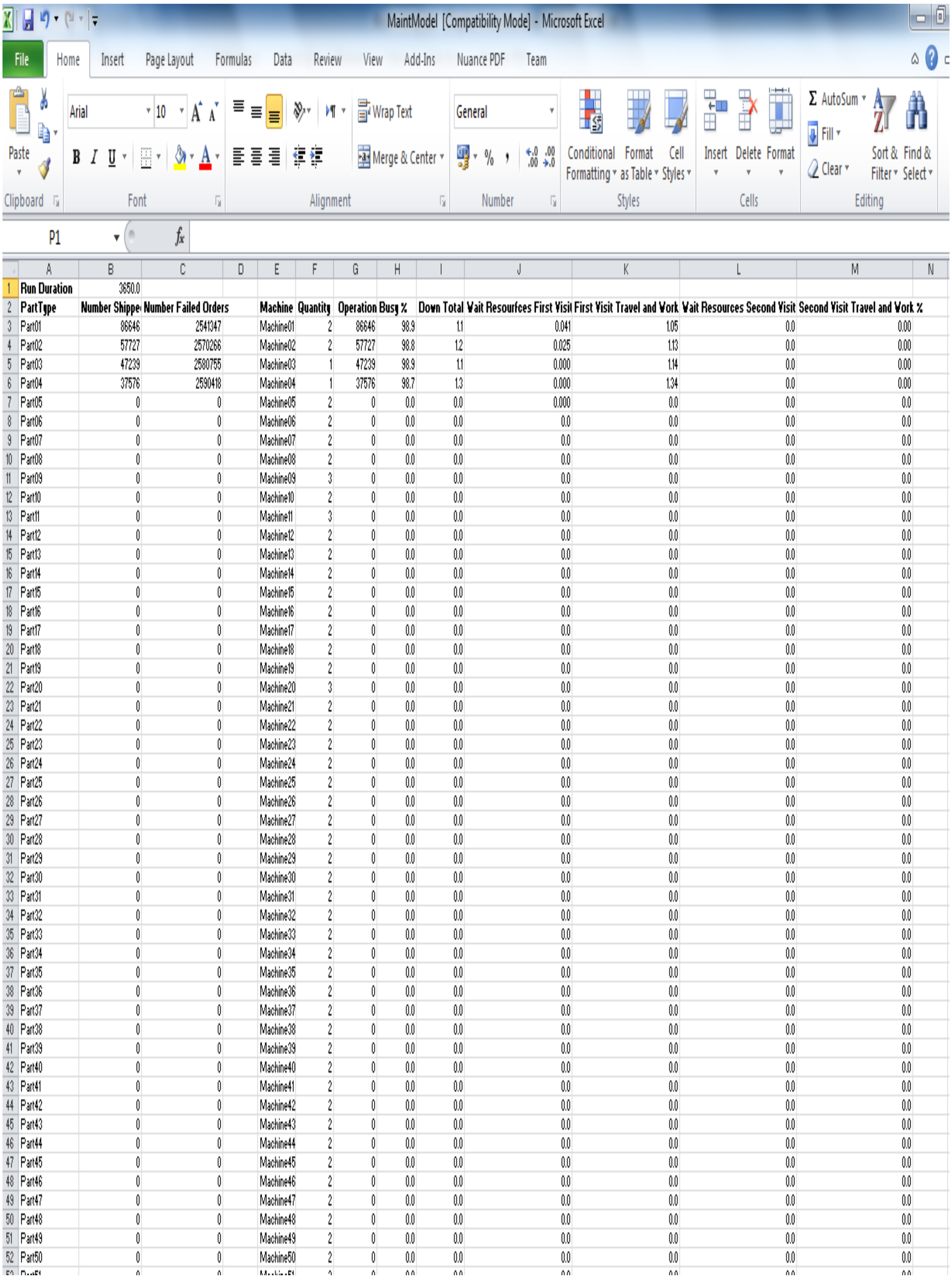
## B.6 Spares input sheet




| | | | | | |
|---|---|---|---|---|---|
| 2 options | | | | | |
| 1 regular deliveries | | | | | |
| 2 replenish on safety stock level | | | | | |
| | | | | | |
| | | | | | |
| Overhaul following inspection | | | | | |
| | | | | | |
| Reference | Lead Time | Replenish Mode | Cost per hour | Safety Stock Level | Minimum Reorder Quantity |
| Spare01 | 20 | 2 | 25 | 1 | 3 |
| Spare02 | 20 | 2 | 10 | 1 | 3 |
| Spare03 | 20 | 2 | 1 | 1 | 1 |
| Spare04 | 20 | 2 | 1 | 1 | 3 |
| Spare05 | 20 | 2 | 1 | 1 | 3 |
| Spare06 | 20 | 2 | 1 | 1 | 3 |
| Spare07 | 20 | 2 | 1 | 1 | 1 |
| Spare08 | 20 | 2 | 1 | 1 | 3 |
| Spare09 | 20 | 2 | 1 | 1 | 3 |
| Spare10 | 20 | 2 | 1 | 1 | 3 |
| Spare11 | 20 | 2 | 1 | 1 | 1 |
| Spare12 | 20 | 2 | 1 | 1 | 3 |
| Spare13 | 20 | 2 | 1 | 1 | 3 |
| Spare14 | 20 | 2 | 1 | 1 | 3 |
| Spare15 | 20 | 2 | 1 | 1 | 1 |
| Spare16 | 20 | 2 | 1 | 1 | 3 |

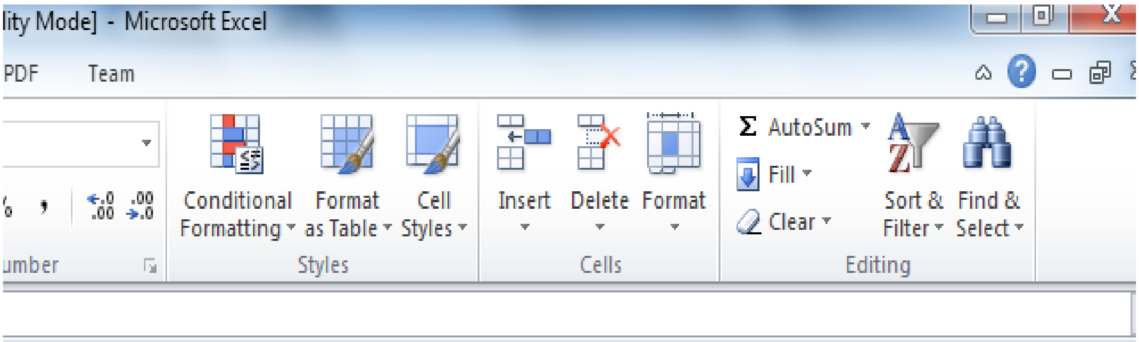
## B.7 Results input sheet

### B.7.1 First part of the result input sheet



| Run Duration | 3650.0 | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PartType | Number Shippe | Number Failed Orders | | Machine | Quantity | Operation | Busy % | Down | Total Wait Resourfces First Visit | First Visit Travel and Work | Wait Resources Second Visit | Second Visit Travel and Work % |
| Part01 | 86646 | 2541347 | | Machine01 | 2 | 86646 | 98.9 | 1.1 | 0.041 | 1.05 | 0.0 | 0.00 |
| Part02 | 57727 | 2570266 | | Machine02 | 2 | 57727 | 98.8 | 1.2 | 0.025 | 1.13 | 0.0 | 0.00 |
| Part03 | 47239 | 2580755 | | Machine03 | 1 | 47239 | 98.9 | 1.1 | 0.000 | 1.14 | 0.0 | 0.00 |
| Part04 | 37576 | 2590418 | | Machine04 | 1 | 37576 | 98.7 | 1.3 | 0.000 | 1.34 | 0.0 | 0.00 |
| Part05 | 0 | 0 | | Machine05 | 2 | 0 | 0.0 | 0.0 | 0.000 | 0.0 | 0.0 | 0.0 |
| Part06 | 0 | 0 | | Machine06 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part07 | 0 | 0 | | Machine07 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part08 | 0 | 0 | | Machine08 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part09 | 0 | 0 | | Machine09 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part10 | 0 | 0 | | Machine10 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part11 | 0 | 0 | | Machine11 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part12 | 0 | 0 | | Machine12 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part13 | 0 | 0 | | Machine13 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part14 | 0 | 0 | | Machine14 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part15 | 0 | 0 | | Machine15 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part16 | 0 | 0 | | Machine16 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part17 | 0 | 0 | | Machine17 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part18 | 0 | 0 | | Machine18 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part19 | 0 | 0 | | Machine19 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part20 | 0 | 0 | | Machine20 | 3 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part21 | 0 | 0 | | Machine21 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part22 | 0 | 0 | | Machine22 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part23 | 0 | 0 | | Machine23 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part24 | 0 | 0 | | Machine24 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part25 | 0 | 0 | | Machine25 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part26 | 0 | 0 | | Machine26 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part27 | 0 | 0 | | Machine27 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part28 | 0 | 0 | | Machine28 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part29 | 0 | 0 | | Machine29 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part30 | 0 | 0 | | Machine30 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part31 | 0 | 0 | | Machine31 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part32 | 0 | 0 | | Machine32 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part33 | 0 | 0 | | Machine33 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part34 | 0 | 0 | | Machine34 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part35 | 0 | 0 | | Machine35 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part36 | 0 | 0 | | Machine36 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part37 | 0 | 0 | | Machine37 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part38 | 0 | 0 | | Machine38 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part39 | 0 | 0 | | Machine39 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part40 | 0 | 0 | | Machine40 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part41 | 0 | 0 | | Machine41 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part42 | 0 | 0 | | Machine42 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part43 | 0 | 0 | | Machine43 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part44 | 0 | 0 | | Machine44 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part45 | 0 | 0 | | Machine45 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part46 | 0 | 0 | | Machine46 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part47 | 0 | 0 | | Machine47 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part48 | 0 | 0 | | Machine48 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part49 | 0 | 0 | | Machine49 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Part50 | 0 | 0 | | Machine50 | 2 | 0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |

### B.7.2 Second part of the result input sheet




| Spare | Number Used | Average Stock | Max. Stock | Min. Stock | Tools | Quantity | Time Used |
|---|---|---|---|---|---|---|---|
| Spare01 | 14 | 2.75 | 4 | 0 | Tool01 | 0 | 0.00 |
| Spare02 | 31 | 2.69 | 4 | 0 | Tool02 | 0 | 0.00 |
| Spare03 | 6 | 1.94 | 2 | 0 | Tool03 | 0 | 0.00 |
| Spare04 | 29 | 2.74 | 4 | 0 | Tool04 | 0 | 0.00 |
| Spare05 | 17 | 2.74 | 4 | 0 | Tool05 | 0 | 0.00 |
| Spare06 | 31 | 2.51 | 4 | 0 | Tool06 | 0 | 0.00 |
| Spare07 | 6 | 1.93 | 2 | 0 | Tool07 | 0 | 0.00 |
| Spare08 | 28 | 2.53 | 4 | 0 | Tool08 | 0 | 0.00 |
| Spare09 | 9 | 2.89 | 4 | 1 | Tool09 | 0 | 0.00 |
| Spare10 | 15 | 2.81 | 4 | 1 | Tool10 | 0 | 0.00 |
| Spare11 | 3 | 1.97 | 2 | 1 | Tool11 | 0 | 0.00 |
| Spare12 | 15 | 2.88 | 4 | 1 | Tool12 | 0 | 0.00 |
| Spare13 | 9 | 2.82 | 4 | 1 | Tool13 | 0 | 0.00 |
| Spare14 | 17 | 2.75 | 4 | 1 | Tool14 | 0 | 0.00 |
| Spare15 | 3 | 1.97 | 2 | 1 | Tool15 | 0 | 0.00 |
| Spare16 | 16 | 2.73 | 4 | 1 | Tool16 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool17 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool18 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool19 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool20 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool21 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool22 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool23 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool24 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool25 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool26 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool27 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool28 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool29 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool30 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool31 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool32 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool33 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool34 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool35 | 0 | 0.00 |
| 0 | 0 | 0.00 | 0 | 0 | Tool36 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool37 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool38 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool39 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool40 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool41 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool42 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool43 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool44 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool45 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool46 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool47 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool48 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool49 | 0 | 0.00 |
| 0 | 0 | 0 | 0 | 0 | Tool50 | 0 | 0.00 |

# Appendix C    Case studies full result tables

## C.1 Case 01 result tables

### C.1.1 Average availability percentage for case 01

| | Average Availability % | | | | | | |
|---|---|---|---|---|---|---|---|
| | As-is | Labour Reduced | Travel 240 | Travel 720 | MTBF+50% | MTBF-50% | Inc. Lead time & Dec. Reorder Qty. |
| Reactive | 98.28 | 98.25 | 97.17 | 95.00 | 98.85 | 96.59 | 86.32 |
| Diagnostics | 98.83 | 98.81 | 98.46 | 97.72 | 99.24 | 97.64 | 86.36 |
| Prognostics-400 | 98.83 | 98.82 | 98.83 | 98.33 | 99.23 | 97.63 | 86.35 |
| Prognostics-1000 | 98.82 | 98.82 | 98.83 | 98.83 | 99.23 | 97.61 | 86.39 |
| Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | 89.13 |

### C.1.2 Average breakdown percentage for case 01

| | Average Breakdown % | | | | | | |
|---|---|---|---|---|---|---|---|
| | As-is | Labour Reduced | Travel 240 | Travel 720 | MTBF+50% | MTBF-50% | Inc. Lead time & Dec. Reorder Qty. |
| Reactive | 1.72 | 1.75 | 2.83 | 5.00 | 1.15 | 3.41 | 13.68 |
| Diagnostics | 1.17 | 1.19 | 1.54 | 2.28 | 0.76 | 2.36 | 13.65 |
| Prognostics-400 | 1.17 | 1.18 | 1.17 | 1.67 | 0.77 | 2.37 | 13.65 |
| Prognostics-1000 | 1.18 | 1.18 | 1.17 | 1.17 | 0.77 | 2.39 | 13.61 |
| Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | 10.87 |

### C.1.3 Average number of failures for case 01

| | Average No. of Failures | | | | | | |
|---|---|---|---|---|---|---|---|
| | As-is | Labour Reduced | Travel 240 | Travel 720 | MTBF+50% | MTBF-50% | Inc. Lead time & Dec. Reorder Qty. |
| Reactive | 250.33 | 250.33 | 247.67 | 243.00 | 161.00 | 498.67 | 219.67 |
| Diagnostics | 249.67 | 249.67 | 249.00 | 246.00 | 162.67 | 504.33 | 218.00 |
| Prognostics-400 | 250.33 | 250.33 | 249.67 | 248.33 | 163.00 | 507.00 | 217.67 |
| Prognostics-1000 | 251.33 | 251.33 | 251.00 | 250.33 | 163.67 | 511.00 | 217.67 |
| Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | 308.33 |

## C.1.4 Total number of spares used for case 01

| | | Total No. Spare used | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SP1 | SP2 | SP3 | SP4 | SP5 | SP6 | SP7 | SP8 | SP9 | SP10 | SP11 | SP12 | SP13 | SP14 | SP15 | SP16 |
| As-is | Reactive | 18 | 31 | 6 | 28 | 16 | 32 | 5 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Diagnostics | 16 | 32 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-400 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-1000 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Labour Reduced | Reactive | 18 | 31 | 6 | 28 | 16 | 32 | 5 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Diagnostics | 16 | 32 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-400 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-1000 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Travel 240 | Reactive | 18 | 31 | 6 | 28 | 16 | 32 | 5 | 28 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Diagnostics | 16 | 32 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 2 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-400 | 16 | 32 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-1000 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Travel 720 | Reactive | 18 | 30 | 5 | 28 | 16 | 31 | 5 | 28 | 9 | 15 | 3 | 14 | 9 | 15 | 3 | 14 |
| | Diagnostics | 16 | 32 | 5 | 29 | 17 | 31 | 6 | 28 | 9 | 16 | 2 | 14 | 9 | 16 | 3 | 14 |
| | Prognostics-400 | 16 | 32 | 5 | 29 | 17 | 31 | 6 | 29 | 9 | 16 | 2 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-1000 | 16 | 33 | 5 | 30 | 17 | 31 | 6 | 29 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| MTBF +50% | Reactive | 13 | 20 | 4 | 20 | 11 | 21 | 3 | 19 | 6 | 10 | 2 | 10 | 6 | 11 | 2 | 10 |
| | Diagnostics | 10 | 22 | 3 | 19 | 10 | 21 | 4 | 20 | 6 | 11 | 2 | 9 | 6 | 10 | 2 | 9 |
| | Prognostics-400 | 10 | 22 | 3 | 19 | 10 | 21 | 4 | 20 | 6 | 11 | 2 | 9 | 6 | 10 | 2 | 9 |
| | Prognostics-1000 | 10 | 22 | 3 | 19 | 10 | 21 | 4 | 20 | 6 | 11 | 2 | 9 | 6 | 10 | 2 | 9 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| MTBF -50% | Reactive | 35 | 62 | 12 | 56 | 34 | 64 | 12 | 57 | 18 | 32 | 6 | 28 | 17 | 32 | 6 | 29 |
| | Diagnostics | 32 | 66 | 11 | 59 | 34 | 64 | 12 | 58 | 17 | 31 | 6 | 29 | 17 | 33 | 6 | 29 |
| | Prognostics-400 | 32 | 66 | 11 | 59 | 34 | 64 | 12 | 59 | 17 | 32 | 6 | 29 | 17 | 33 | 6 | 30 |
| | Prognostics-1000 | 32 | 66 | 11 | 60 | 35 | 65 | 12 | 59 | 18 | 32 | 6 | 30 | 17 | 33 | 6 | 30 |
| | Prognostics-86400 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| Leadtime 60 | Reactive | 15 | 25 | 4 | 24 | 13 | 26 | 4 | 23 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Diagnostics | 12 | 27 | 4 | 24 | 13 | 25 | 5 | 24 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-400 | 12 | 27 | 4 | 24 | 13 | 25 | 4 | 24 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-1000 | 12 | 27 | 4 | 24 | 13 | 25 | 4 | 24 | 9 | 16 | 3 | 14 | 9 | 16 | 3 | 15 |
| | Prognostics-86400 | 18 | 31 | 5 | 30 | 19 | 31 | 5 | 30 | 12 | 27 | 3 | 26 | 12 | 27 | 3 | 25 |

## C.2 Case 02 result tables

### C.2.1 Average availability percentage for case 02

| | Average Availability % | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-600 | P-1200 | P-6000 |
| AS-IS | 97.20 | 97.20 | 97.23 | 97.25 | 97.35 |
| Labour reduction | 97.19 | 97.19 | 97.22 | 97.24 | 97.35 |
| Travel 400 | 96.86 | 97.08 | 97.20 | 97.22 | 97.33 |
| Travel 1200 | 92.05 | 95.74 | 95.84 | 95.83 | 96.18 |
| increase LT 100% | 94.31 | 94.31 | 94.34 | 94.36 | 94.56 |
| increase MRQ | 99.16 | 99.17 | 99.18 | 99.20 | 99.29 |
| MTBF-50% | 96.87 | 96.91 | 96.95 | 97.01 | 97.23 |
| MTBF+50% | 97.26 | 97.25 | 97.27 | 97.28 | 97.35 |
| safety stock reduction | 94.21 | 94.26 | 94.30 | 94.33 | 94.57 |
| inc. Diagnose time | 94.21 | 97.20 | 97.23 | 97.25 | 97.35 |

### C.2.2 Average breakdown percentage for case 02

| | Average Breakdown % | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-600 | P-1200 | P-6000 |
| AS-IS | 2.71 | 2.70 | 2.68 | 2.66 | 2.55 |
| Labour reduction | 2.72 | 2.71 | 2.68 | 2.66 | 2.55 |
| Travel 400 | 3.05 | 2.82 | 2.71 | 2.69 | 2.58 |
| Travel 1200 | 7.85 | 4.16 | 4.06 | 4.01 | 3.73 |
| increase LT 100% | 5.60 | 5.60 | 5.57 | 5.54 | 5.35 |
| increase MRQ | 0.75 | 0.73 | 0.72 | 0.71 | 0.62 |
| MTBF-50% | 3.04 | 3.00 | 2.95 | 2.90 | 2.68 |
| MTBF+50% | 2.65 | 2.65 | 2.63 | 2.62 | 2.55 |
| safety stock reduction | 5.70 | 5.64 | 5.61 | 5.57 | 5.33 |
| inc. Diagnose time | 5.70 | 2.70 | 2.68 | 2.66 | 2.55 |

### C.2.3 Average number of failures for case 02

| | Average No. of Failure | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-600 | P-1200 | P-6000 |
| AS-IS | 1263.67 | 1318.00 | 1318.33 | 1319.33 | 1323.67 |
| Labour reduction | 1264.00 | 1317.33 | 1318.67 | 1319.00 | 1323.33 |
| Travel 400 | 1258.00 | 1315.00 | 1318.00 | 1319.00 | 1323.00 |
| Travel 1200 | 1177.33 | 1292.67 | 1294.33 | 1293.67 | 1306.00 |
| increase LT 100% | 1218.67 | 1269.33 | 1271.67 | 1272.67 | 1279.67 |
| increase MRQ | 1294.00 | 1344.00 | 1345.00 | 1345.67 | 1350.00 |
| MTBF-50% | 2701.67 | 2744.00 | 2746.33 | 2750.00 | 2757.33 |
| MTBF+50% | 787.00 | 850.00 | 850.67 | 850.67 | 1323.67 |
| safety stock reduction | 1218.00 | 1268.67 | 1270.67 | 1272.00 | 1279.00 |
| inc. Diagnose time | 1218.00 | 1318.00 | 1318.33 | 1319.33 | 1323.67 |

### C.2.4 Total number of spare used for case 02

| | Total Spare Part Used | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-600 | P-1200 | P-6000 |
| AS-IS | 1263.67 | 1317.67 | 1318.00 | 1319.33 | 1323.67 |
| Labour reduction | 835.67 | 1317.33 | 1318.33 | 1319.00 | 1323.33 |
| Travel 400 | 1257.67 | 1315.00 | 1317.67 | 1318.67 | 1322.67 |
| Travel 1200 | 1175.00 | 1292.67 | 1294.33 | 1293.67 | 1306.00 |
| increase LT 100% | 1218.33 | 1269.00 | 1270.33 | 1271.67 | 1279.00 |
| increase MRQ | 1294.00 | 1344.00 | 1345.00 | 1345.67 | 1350.00 |
| MTBF-50% | 2700.67 | 2743.33 | 2746.00 | 2749.33 | 2757.33 |
| MTBF+50% | 787.00 | 850.00 | 850.67 | 850.67 | 1323.67 |
| safety stock reduction | 1216.67 | 1268.00 | 1269.33 | 1270.00 | 1278.33 |
| inc. Diagnose time | 1216.67 | 1317.67 | 1318.00 | 1319.33 | 1323.67 |

### C.2.5 Average labour utilisation for case 02

| | Labour Utilisation% | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-600 | P-1200 | P-6000 |
| AS-IS | 3.69 | 3.41 | 3.41 | 3.41 | 3.42 |
| Labour reduction | 7.38 | 6.82 | 6.82 | 6.83 | 6.84 |
| Travel 400 | 22.77 | 13.38 | 13.41 | 13.42 | 13.46 |
| Travel 1200 | 57.00 | 32.82 | 32.88 | 32.85 | 33.14 |
| increase LT 100% | 3.55 | 3.28 | 3.28 | 3.28 | 3.31 |
| increase MRQ | 3.78 | 3.47 | 3.48 | 3.48 | 3.49 |
| MTBF-50% | 7.89 | 7.14 | 7.14 | 7.15 | 7.20 |
| MTBF+50% | 2.28 | 2.18 | 2.18 | 2.18 | 3.42 |
| safety stock reduction | 3.55 | 3.28 | 3.27 | 3.28 | 3.30 |
| inc. Diagnose time | 3.55 | 3.41 | 3.41 | 3.41 | 3.42 |

## C.3 Case 03 result tables

### C.3.1 Average availability percentage for case 03

| | Average Availability% | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-500 | P-1000 | P-43500 |
| AS-IS | 79.13 | 91.87 | 92.22 | 92.41 | 91.57 |
| Labour Reduction | 61.87 | 92.00 | 92.29 | 92.21 | 91.30 |
| No Travel time | 84.36 | 92.18 | 92.42 | 92.44 | 91.67 |
| Lead Time Red. | 79.87 | 97.88 | 98.18 | 98.22 | 98.88 |
| increase MRQ by 50% | 79.23 | 95.49 | 95.79 | 95.89 | 98.13 |
| Leadtime Red. and Increase MRQ | 79.66 | 98.23 | 98.53 | 98.56 | 99.00 |
| MTBF+50% | 92.10 | 98.75 | 98.96 | 98.98 | 99.30 |
| MTBF-50% | 41.70 | 49.87 | 49.89 | 49.88 | 50.10 |

### C.3.2 Average breakdown percentage for case 03

| | Average Breakdown % | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-500 | P-1000 | P-43500 |
| AS-IS | 20.62 | 7.88 | 7.53 | 7.33 | 8.18 |
| Labour Reduction | 37.87 | 7.75 | 7.46 | 7.54 | 8.44 |
| No Travel time | 15.39 | 7.57 | 7.33 | 7.31 | 8.08 |
| Lead Time Red. | 19.88 | 1.87 | 1.57 | 1.53 | 0.86 |
| increase MRQ by 50% | 20.52 | 4.26 | 3.96 | 3.86 | 1.62 |
| Leadtime Red. and Increase MRQ | 20.09 | 1.52 | 1.21 | 1.19 | 0.75 |
| MTBF+50% | 7.65 | 0.99 | 0.79 | 0.77 | 0.45 |
| MTBF-50% | 58.05 | 49.88 | 49.86 | 49.87 | 49.64 |

### C.3.3 Average number of failure percentage for case 03

| | Average No. of Failure | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-500 | P-1000 | P-43500 |
| AS-IS | 3065 | 3573 | 3587 | 3596 | 3855 |
| Labour Reduction | 2385 | 3576 | 3586 | 3585 | 3846 |
| No Travel time | 3266 | 3588 | 3591 | 3598 | 3859 |
| Lead Time Red. | 3092 | 3806 | 3826 | 3832 | 4395 |
| increase MRQ by 50% | 3064 | 3718 | 3726 | 3738 | 4282 |
| Leadtime Red. and Increase MRQ | 3077 | 3823 | 3838 | 3842 | 4406 |
| MTBF+50% | 2339 | 2511 | 2517 | 2511 | 2761 |
| MTBF-50% | 3249 | 3901 | 3905 | 3909 | 4386 |

### C.3.4 Total number of spare used for case 03

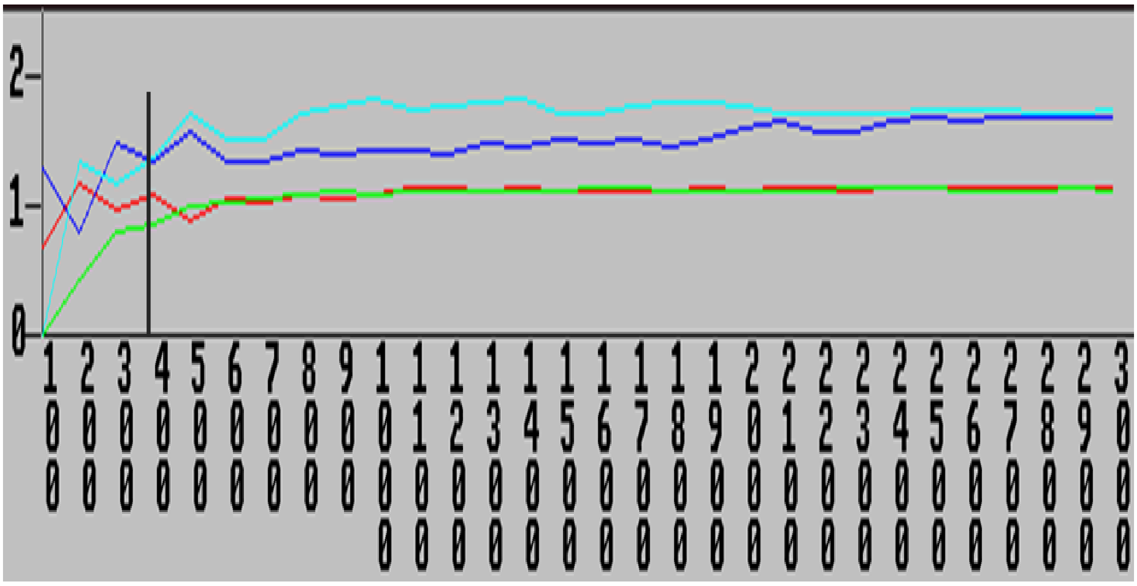
| | Total Spare Part Used | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-500 | P-1000 | P-43500 |
| AS-IS | 3045 | 3569 | 3581 | 3588 | 3838 |
| Labour Reduction | 2348 | 3575 | 3580 | 3579 | 3827 |
| No Travel time | 3255 | 3580 | 3587 | 3593 | 3839 |
| Lead Time Red. | 3072 | 3811 | 3826 | 3832 | 4395 |
| increase MRQ by 50% | 3072 | 3811 | 3826 | 3832 | 4395 |
| Leadtime Red. and Increase MRQ | 3061 | 3823 | 3838 | 3842 | 4406 |
| MTBF+50% | 2334 | 2511 | 2517 | 2519 | 2761 |
| MTBF-50% | 3195 | 3849 | 3854 | 3857 | 4318 |

### C.3.5 Average labour utilisation percentage for case 03

| | Average labour utilisation % | | | | |
|---|---|---|---|---|---|
| | Reactive | Diagnostics | P-500 | P-1000 | P-43500 |
| AS-IS | 92.94 | 14.28 | 14.32 | 14.35 | 15.38 |
| Labour Reduction | 95.43 | 19.06 | 19.09 | 19.09 | 20.45 |
| No Travel time | 86.22 | 7.12 | 7.14 | 7.15 | 7.68 |
| Lead Time Red. | 93.62 | 15.25 | 15.32 | 15.34 | 17.51 |
| increase MRQ by 50% | 92.90 | 14.88 | 14.91 | 14.96 | 17.08 |
| Leadtime Red. and Increase MRQ | 93.37 | 15.31 | 15.37 | 15.38 | 17.55 |
| MTBF+50% | 71.09 | 10.04 | 10.06 | 10.07 | 10.99 |
| MTBF-50% | 97.60 | 15.42 | 15.44 | 15.46 | 17.49 |

# Appendix D Time-series for warm-up period calculations for the industrial cases.

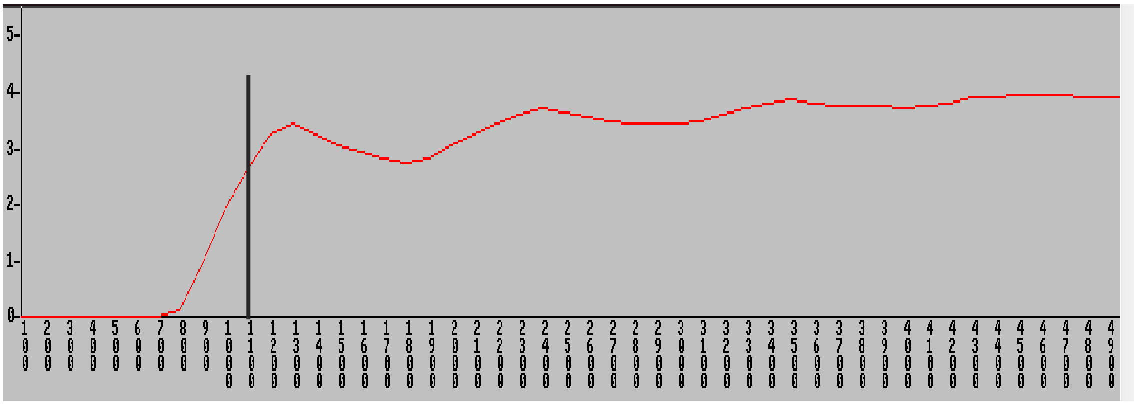
## D.1 Time-series method for warm-up period calculation for Case01 based on labour utilisation percentage




Days

As can be seen from the above Time-series for the labour utilisation for case01, the utilisation arrives to the steady-state after one year.

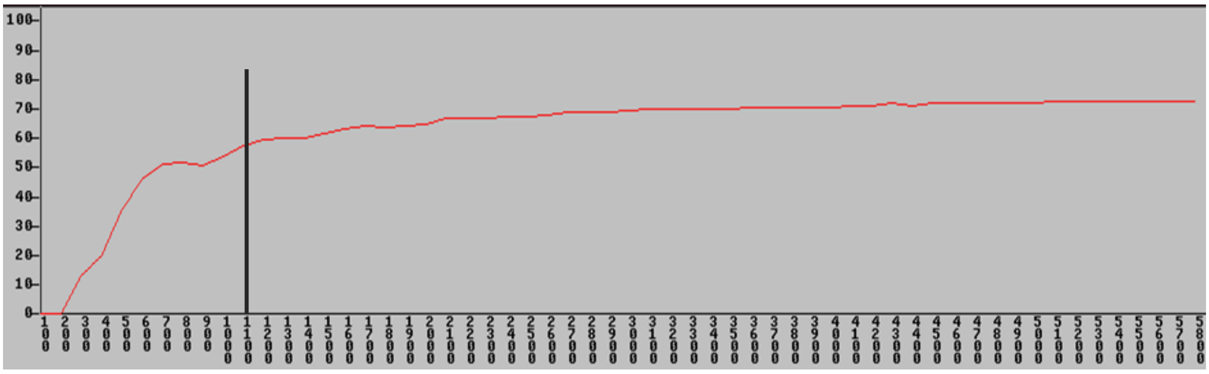
## D.2 Time-series method for warm-up period calculation for Case02 based on labour utilisation percentage




Days

As can be seen from the above Time-series for the labour utilisation for case02, the utilisation arrives to the steady-state after three years.

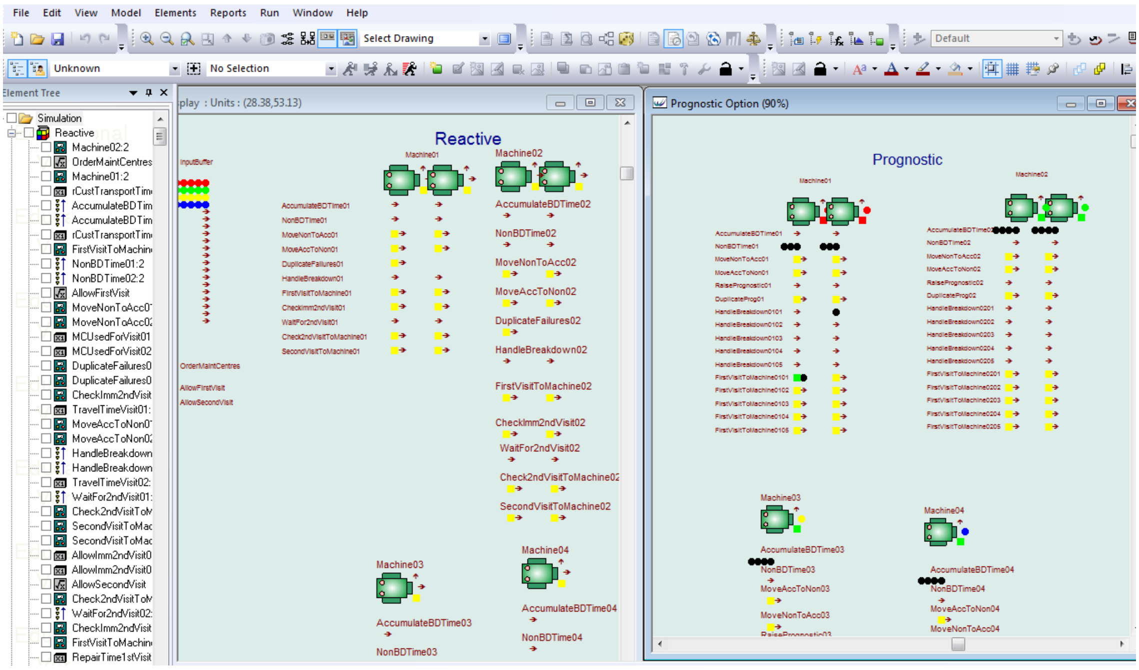
## D.3 Time-series method for warm-up period calculation for Case03 based on labour utilisation percentage



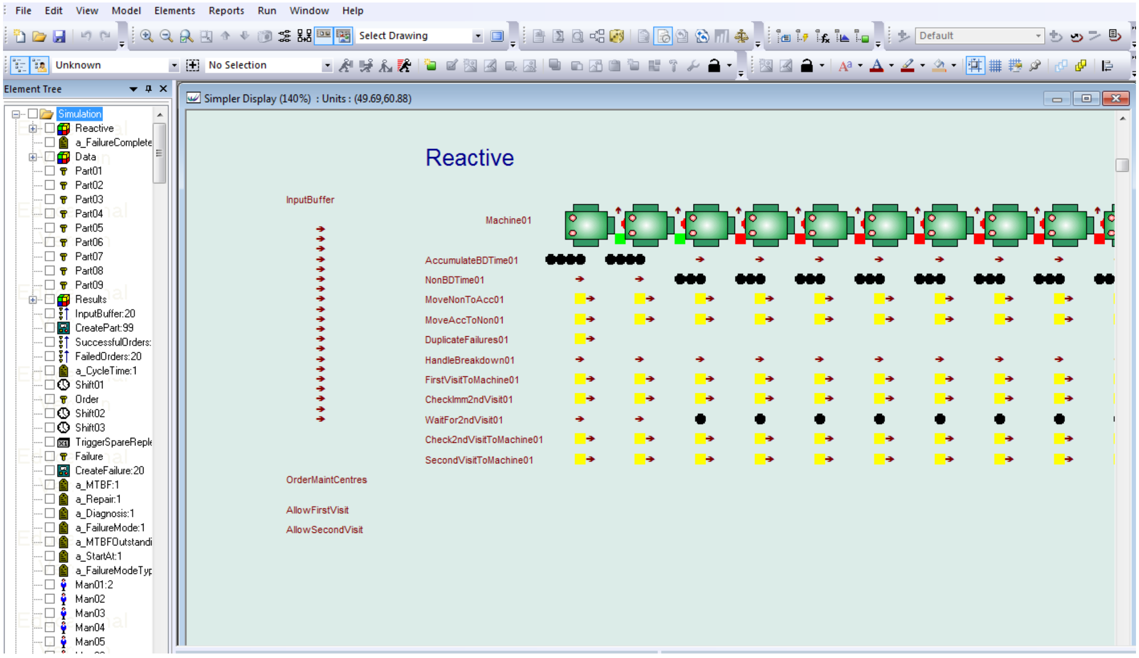

As can be seen from the above Time-series for the labour utilisation for case03, the utilisation arrives to the steady-state after three years.

# Appendix E Snap shot of the PMLS tool while running

## E.1 Case01 model snap shot while running on Prognostics level.




## E.2 Case02 model snap shot while running on Reactive level.



## E.3 Case03 model snap shot while running on Diagnostics level.