An Investigation into the Applicability of Lean Thinking in an Operational Maintenance Environment

by

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Thesis presented in fulfilment of the requirements for the degree of Master of Science in Engineering in the Faculty of Engineering at Stellenbosch University

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December 2013

DECLARATION

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02 August 2013

OPSOMMING

Daar word bespiegel dat die beginsels van besparende denke ("lean thinking") suksesvol toegepas kan word op enige industrie. As gevolg van hierdie hipotese is daar groot vooruitgang op die gebied van besparende denke buite die "tradisionele" gebied van vervaardiging. Een sodanige vooruitgang is op die gebied van die verrigting van instandhouding waar besparende denke bekend is as die konsep van "lean maintenance". Die problem is dat die vooruitgang tot dusver beperk is tot die vervaardigingsomgewing waar besparende instandhouding beskou word as 'n vereisde vir besparende vervaardiging. Daar word min gebruik gemaak van raamwerke of modelle om besparende denke te toets of om dit toe te pas in instandhoudingsomgewings buite die vervaardigingskonteks.

Die hoofdoelwit van hierdie navorsing is om te vore te kom wet 'n raamwerk wat gegrond is op besparende denke en relevante prestasie maatstawwe, en wat die toepaslikheid van besparende denke , al dan nie, op die verrigting van instandhouding buite die tradisionele gebied van vervaardiging sal bewys. 'n Gevalle studie van die Soutrivier Depot van PRASA Metrorail, wat tipies is van 'n nie-tradisionele gebied vir besparende denke, is gebruik vir die bou en stawing van die raamwerk. Die analitiese hiëragiese proses (AHP) tesame met die kwaliteits funksionele ontplooiing (QFD) proses word gebruik in die kies van elemente vir die raamwerk. Die waarde stroom bestuursproses word gebruik om die moontlik uitkomste van die gebruik van die voorgestelde raamwerk, te voorspel. Die studie is gegrond op die hipotese dat besparende denke ook toegepas kan word op nie-vervaarding-georienteerde instandhoudingsorganisasies.

Die raamwerk word gebruik om te bewys dat die besparende denke benadering gebruik kan word in nie-vervaardiging–georienteerde instandhoudingsomgewings en dus kennis hieroor uit te brei. Die raamwerk kan ook gebruik word as 'n padkaart deur Metrorail en ander soortgelyke instandhoudingsorganisasies in die spoorweg industrie, om hulle

huidige werksverrigting deur waarde toevoeging te verbeter en om verkwisting te voorkom.

ABSTRACT

It has been postulated that lean thinking principles can be successfully applied to any industry. Following on that postulation, there have been great advances in the area of lean thinking outside the "traditional" domain of manufacturing. One such advancement has been in the area of maintenance operations where lean thinking has been used through the concept of lean maintenance. However, a problem lies in the fact that the work that has been done so far has been largely limited to the manufacturing environment where lean maintenance is practised as a prerequisite for lean manufacturing. Little evidence exists of the use of frameworks or models that can test, let alone apply, lean thinking in operational maintenance environments outside of the manufacturing context.

The main objective of this research was to come up with a framework, based on lean thinking tools and relevant performance measures, which will prove the applicability or otherwise, of lean thinking in an operational maintenance environment outside the traditional domain of manufacturing. A case study of the rolling stock section of the Salt River depot of PRASA, Metrorail, which is a typical non-traditional domain for lean thinking, was used to build and verify the framework. The Analytic Hierarchy Process (AHP) together with the Quality Function Deployment (QFD) process, is used in building and quantifying the judgements made in developing elements of the framework. The Value Stream Management process is used to predict the possible outcomes of using the proposed framework in the case study. The study was based on the hypothesis that lean thinking can also be applicable to non-manufacturing oriented maintenance organisations.

The ensuing framework is used to make the argument for the use of the lean thinking approach in non-manufacturing oriented maintenance environments and hence expand the body of knowledge in this subject area. It also provides a roadmap for PRASA, Metrorail and other similar maintenance organisations in the rail industry to streamline and improve current operations through value addition and waste elimination efforts.

ACKNOWLEDGEMENTS

I would like to acknowledge the following people:

- Prof C.J Fourie for his wise guidance and support throughout the period of this research.
- To the staff and workforce of the Salt River depot of PRASA, Metrorail for providing me with very useful information and virtually unlimited access to their workplace.
- To my PRASA office colleagues for the pleasurable company and support as I toiled day after day with my work.
- To Mr and Mrs Masiyiwa and the Capernaum Trust team who provided me with a significant portion of the funding needed to cover my studies and general upkeep.
- To my mother, Mrs. Tendayi, for the support and love which only a mother can give.
- To my girlfriend, Girlie, for her patience and words of encouragement as the going sometimes got really tough.
- To Pastor Jurie, Maggie and members of the Stellenbosch International Fellowship for providing priceless spiritual support, fellowship and a "home away from home".
- Last but certainly not least, to my Heavenly Father and my Lord Jesus Christ, who provided the foundation for all this to take place.

"For other foundation can no man lay than that is laid, which is Jesus Christ."
(1Corinthians 3:11 KJV)

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GLOSSARY

AHP	Analytic Hierarchy Process
JIPM	Japan Institute of Plant Maintenance
MCDM	Multi-Criteria Decision-Making
ME	Maintenance Excellence
MRO	Maintenance Repair and Overhaul
MSC	Maintenance Supply Chain
PRASA	Passenger Rail Agency of South Africa
QFD	Quality Function Deployment
RCM	Reliability Centered Maintenance
SCM	Supply Chain Management
TPM	Total Productive Maintenance
TPS	Toyota Production System
VSM	Value Stream Management

CHAPTER ONE: INTRODUCTION

1.1 Background and Rationale

After having empirically verified the benefits of lean production in manufacturing through case studies of several automobile plants and other industries, it was postulated that lean principles can be applied to any industry (Womack, Jones 2003). In the last two decades, there has been an increasing application of lean thinking outside the "traditional" domain of manufacturing. Some of these areas include the service sector, software development and Maintenance, Repair and Overhaul (M.R.O).

There has also been an increasing interest in improving maintenance operations through the concept of Total Productive Maintenance (TPM). The core objective of TPM is to reduce major equipment effectiveness losses or waste in the maintenance operation. Because of this core objective, TPM has found common ground with lean thinking and has resulted in the birth of lean maintenance, in which TPM acts as the foundation (Smith, Hawkins 2004). As the concept of lean maintenance evolved, its relationship to lean manufacturing began to be closely looked at. Those in authority later concluded that lean maintenance is a prerequisite for lean manufacturing (Kister & Hawkins 2006).

The Maintenance, Repair and Overhaul (MRO) industry is beginning to warm up to the lean philosophy. And within the MRO industry, there are the maintenance and repair activities of rolling stock in the rail industry. The Salt River rolling stock section of the Passenger Rail Agency of South Africa (PRASA), Metrorail, offers one such example. This scenario offers a potential testing ground for the use of lean thinking in maintenance operations outside the traditional domain of manufacturing.

1.2 Research Problem and Objectives

The problem is that in the work that has been done so far, lean thinking in maintenance operations, through the concept of lean maintenance, has been largely limited to the manufacturing environment without much evidence to prove its validity outside this scope. Few frameworks or models have been developed to test its applicability in an existing and operational maintenance environment and rarely has the issue of identifying relevant performance measures been brought up in these models. As a result of this problem, the following research questions arise:

- What is likely to happen when lean thinking principles that have worked so well in manufacturing oriented maintenance environments are applied in an environment in which there is no lean manufacturing as the successor?
- What lean thinking tools are relevant to such an environment and what corresponding performance measures can be used to determine the success or otherwise of such an initiative?
- What does a supply chain in a non-manufacturing maintenance environment consist of and what are the necessary constituents in order to create a lean maintenance supply chain?

The main objective of this research is to develop a framework, based on lean thinking tools and relevant performance measures, which will prove the applicability or otherwise, of lean thinking in an operational maintenance environment outside the traditional domain of manufacturing. An important sub-objective of the research is to identify a novel scientific way of selecting and prioritising organisational objectives in any environment but more specifically in a maintenance operations context through the use of maintenance excellence criteria combined with Quality Function Deployment (QFD) and the Analytic Hierarchy Process (AHP).

1.3 Research Design and Methodology

The research carried out involves a combination of non-empirical and empirical research methods. It is non-empirical in the sense that the core elements of the framework are developed through a conceptual literature study and empirical in the sense that a case study is used to verify and validate the proposed framework. As the reader will discover, the two research methods are inter-twined throughout the study.

In order to carry out the research, the following methodology is followed:

1) The author carries out a critical literature review of existing and previous studies in lean manufacturing, lean maintenance and on the advances of lean thinking in non-manufacturing environments and in particular within the maintenance context.

2) A survey, interviews with key personnel and physical observations from the shop floor are obtained from a case study at the rolling stock division of the Salt River depot of PRASA, Metrorail. Verification of the information obtained, especially from the survey, is done using the AHP methodology.

3) Using information collected from the case study together with findings from the literature review, a conceptual framework consisting of lean thinking tools and corresponding performance measures, for use in non-manufacturing maintenance environments is developed. The combined AHP-QFD approach is used to verify, quantify and rank the various elements within this framework.

4) Implications of the proposed framework are then established by using the value stream management process on a section of the case study to find out if indeed lean thinking can be successfully used in such a context.

1.4 Research Hypothesis

As has been discussed earlier, the main objective of this research is to prove the applicability or otherwise, of lean thinking in an operational maintenance environment outside the traditional domain of manufacturing. From this objective, the following research hypothesis can be made:

> *"Lean thinking, that has worked relatively well in manufacturing-oriented maintenance organisations, can also be applicable to non-manufacturing-oriented maintenance organisations."*

1.5 Thesis Outline

Figure 1.1 shows the outline that the thesis follows. A brief description of each of the sections is given below:

Chapter 1: - background and reasons for carrying out this research are laid out.

Chapter 2: - contains a literature survey that introduces the reader to the core themes of the research starting with a broad view and then narrowing down to the specific scope of this study.

Chapter 3: - a literature survey coupled with a description of the tools and methodologies that have been deemed relevant to carry out this particular study.

Chapter 4: - is a brief description of the case study starting with Metrorail as a whole and then narrowing it down to the key processes at the Salt River rolling stock division of PRASA, Metrorail.

Chapter 5: - focuses on developing the framework using findings from literature and also information obtained from the case study.

Chapter 6: – investigates the potential implications of using the proposed framework at the case study in question.

Chapter 7: – summarises the whole research and highlights the main findings. It also discusses the limitations of the research and makes recommendations on how they can be overcome through future work.

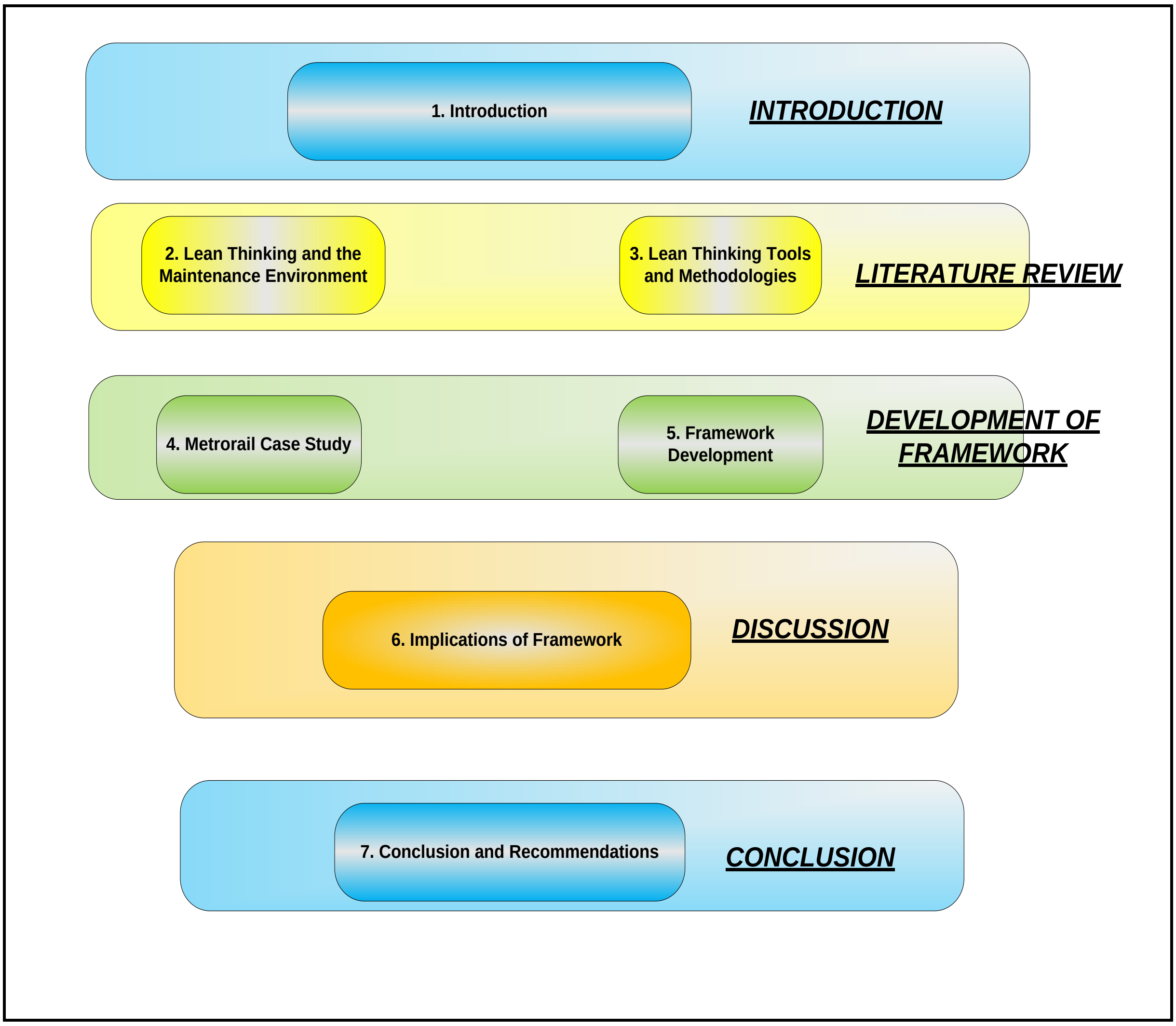

Figure 1.1 Thesis Outline

CHAPTER TWO: LEAN THINKING AND THE MAINTENANCE ENVIRONMENT

2.0 Introduction

The main focus of this chapter is on the body of knowledge that is used to develop the research problem. A broader picture on lean thinking as a subject area is first given before exploring advances that have been made in using it outside its traditional scope. The literature review is then narrowed down to focus on how lean thinking has been used in both manufacturing and non-manufacturing areas of maintenance management. A literature study is conducted on the research carried out regarding the way the supply chain supports these maintenance processes. Finally, the literature review presents an overview of the research carried out in the use of lean thinking in the maintenance of rolling stock.

2.1 "Traditional" Lean Thinking in Practice

2.1.1 Definition

Many practitioners have sought to formulate a definition that can capture the many different facets of lean thinking. One has defined it as "the dynamic, knowledge-driven, and customer focused process through which all people in a defined enterprise continuously eliminate waste with the goal of creating value" (Murman 2002). This definition presents three intrinsic properties of any process that is said to be "lean", i.e. waste elimination, value creation and continuous improvement. This is what the originators of the phrase have to state when describing the term lean thinking;

> *"It provides a way to specify value, line up value-creating actions in the best sequence, conduct these activities without interruption whenever somebody requests them, and perform them more and more effectively"*
>
> *(Womack & Jones 2003)*

In this definition, the three intrinsic properties mentioned before can also be inferred as being the essential ingredients of a lean process. (Smith & Hawkins 2004) put forward three pre-eminent principles that define a lean enterprise and these are; it is has to be customer focused, there should be waste elimination, and there should be quality at the source.

In lean thinking, any operation that does not add value is considered waste, or *muda*. These operations can be anything from parts, practices, processes, design elements, work environments, organisation elements or policies (Kister & Hawkins 2006). This value is defined by the customers, both internal and external, depending on their needs. Lean thinking recognises seven types of waste as originally defined by (Ohno 1988). These wastes are in the context of production and they are namely over-production, waiting, unnecessary motions, transporting, over-processing, unnecessary inventory and defects. As waste or non-value-adding work is eliminated from the system, there is also a need to identify which work adds value. The first three steps in the implementation of lean thinking involve specifying the value, identifying the value stream and making the value flow. Value must be specified from the viewpoint of the customer's requirement rather than from the constraints of the manufacturing facility, that is, in the case of production. A failure to do this correctly will result in going through with processes that do not add value to the customer and waste resources on the part of the provider. After specifying the values of the processes, the value stream of the process is then identified. This value stream is used to sort actions in a process into three categories which according to (Womack & Jones 2003) are:

1) Those which actually create value as perceived by the customer;
2) Those which create no value but are currently required and so can't be eliminated just yet.
3) Those actions which don't create value as perceived by the customer and so can be eliminated immediately.

Continuous incremental improvement or *kaizen,* as it is known in Japanese, is the path that every lean enterprise should be following in as far as lean thinking is concerned. According to (Womack & Jones 2003), lean enterprises should continually revisit the value question with their product teams and ask if they have really got the best answers in order to produce steady results towards the "path to perfection". (Adam & New 2003) present a very useful study that highlights the effectiveness of *kaizen* as practised in a selection of Japanese companies. They reach the conclusion that *kaizen* evolves uniquely within each organisation with considerable diversity in the way in which it may be operated. According to them, *Kaizen* appears to be less of a stand-alone suite of techniques and practices and more of an integral part of an overall system of operations planning. Another case study based research is carried out by (Bessant, Caffyn & Gallagher. 2001) who look at six companies at different levels of implementation of continuous improvement with varying levels of success. The main argument from their observations is that continuous improvement is not a short term activity but an evolution and aggregation of a set of key behavioural routines within a firm.

2.1.2 "Traditional" Areas of Application

Lean thinking has its origins in the Toyota Production System (TPS) through the work of a Japanese engineer called Taichi Ohno (Ohno 1988). Through TPS, he identified several types of waste within a workplace and established how organisations could work to eliminate wasteful activity. As has been mentioned earlier, these are all production related wastes and as such, it is in production that lean thinking has found acceptance and widest use and hence it is commonly referred to as lean manufacturing. As lean manufacturing was proving to be a success at Toyota, other automobile manufacturers followed suit and initiated a transition to lean manufacturing. A lot of them now have mature systems in place and have experienced dramatic performance gains (Yingling, Detty & Sottile 2000). A specific example is at General Motors where the company achieved relative success through a tailor-made lean manufacturing model called the Global Manufacturing System (Brondo & Baba 2010).

Other manufacturing industries successfully took up lean manufacturing after having witnessed its successful implementation in the automotive industry. (Womack & Jones 2003) give examples of some of the earliest non-automotive manufacturing applications of lean. Chinese industries also have a long history of lean manufacturing with sectors such as the petroleum industry and electronics demonstrating proven success (Taj 2008). Even smaller manufacturing organisations have followed suit and witnessed improvements. A case in point being a small furniture production company which witnessed decreased inventories, decreased processing times and even managed to make their supply more green and sustainable (Miller, Pawloski & Standridge 2010). However, it should be pointed out that there are fewer success stories in these smaller companies and according to (Aulakh & Gill 2008), the main reason behind the failures is the lack of understanding on the 'bigger picture' of lean manufacturing.

2.2 Advances in Lean Thinking

As has been mentioned before, lean thinking has found common use in the manufacturing environment and this has become its "traditional" area of use. However, from a review of recent literature, it is becoming apparent that lean thinking is expanding into "non-traditional" areas. (Womack, Jones & Roos 1990) hypothesize that lean principles can be applied to any industry. (Yingling et al. 2000) present a study which shows the applicability of lean production principles in the mining industry. Principles such as value definition and value stream analysis, standardised work, quality-at-the-source, set-up reduction techniques and continuous improvement approaches could be implemented directly in mining. (Agbulos et al. 2006) present a paper that explores the application of lean concepts and simulation analysis to improve the efficiency of drainage operations maintenance crews in the City of Edmonton, Canada. The simulation results showed potential improvements in productivity of drainage operations after lean concepts were applied.

Lean thinking has even extended into the services sector. One example is in the legal services where (Åhlström 2004) presents two case studies, one on the Portuguese court system and the second on the Welsh Legal Services Commission. Issues that are addressed include variable lead times and problems of waste, rescheduling and effective human resourcing. It is the conclusion of the study that lean thinking can be applied in the legal sector although with a greater degree of attention being paid to "people issues." (King, Ben-Tovim & Bassham 2006) investigate the application of lean thinking to healthcare by studying the Emergency Department (ED) of Flinders Medical Center in Adelaide, South Australia. The main problems to be addressed included overcrowding of the ED which disrupted work of the ED and surgical services resulting in safety concerns. Through process mapping and identification of value streams, a significant decline was realised in waiting times and total durations of stay in the ED.

2.3 "Traditional" Lean Maintenance

2.3.1 Definition

The term "lean maintenance" is relatively new having only been coined in the last decade of the 20th Century, well after lean manufacturing (Smith & Hawkins 2004). A lengthy definition is given which states that;

> "*Lean Maintenance is a proactive maintenance operation employing planned and scheduled maintenance activities through total productive maintenance (TPM) practices, using maintenance strategies developed through application of reliability centred maintenance (RCM) decision logic and practiced by empowered (self-directed) action teams using the 5S process, weekly Kaizen improvement events, and autonomous maintenance together with multi-skilled, maintenance technician-performed maintenance through the committed use of their work order system and their computer managed maintenance system (CMMS) or enterprise asset management (EAM) system*."
>
> *(Smith & Hawkins 2004)*

A more abbreviated definition of the term is given by (Clarke, Mulyran & Liggan 2010) who state that it is the delivery of maintenance services to customers with as little waste as possible hence promoting achievement of a desirable outcome with fewest inputs possible. Definitions are few and hard to come by as most simply prefer to refer to it as the application of lean to maintenance, repair & overhaul (MRO). Whatever expression is used, that is whether it is "lean maintenance" or "lean in MRO", the underlying focus for the application of lean is in the reduction of waste (Ayeni, Baines, Lightfoot & Ball 2011). This view is also shared by (Ghayebloo 2010) who states that the main purpose of lean maintenance is to eliminate all forms of waste in the maintenance process without taking into account serious reliability issues.

2.3.2 Waste in Maintenance

Just as in manufacturing activities, maintenance activities also contain value-adding and non-value-adding activities (waste). (Davies & Greenough 2003) offer a useful analysis of lean maintenance wastes by giving an analogy between these type of wastes to those wastes found in lean production as given by (Ohno 1988) and (Bicheno 2004). This analogy is illustrated in Figure 2.1. (Clarke et al. 2010) make their own list of activities that are associated with wasteful maintenance practices and this list includes; unproductive work, delays in motion, unnecessary motion, poor management of inventory, rework, under-utilisation of resources, ineffective data management and misapplication of machinery. Even though this list differs from the previous one in what it considers as waste within maintenance processes, it is nevertheless apparent that the first list is simply breaking down the same wastes into more specific terms.

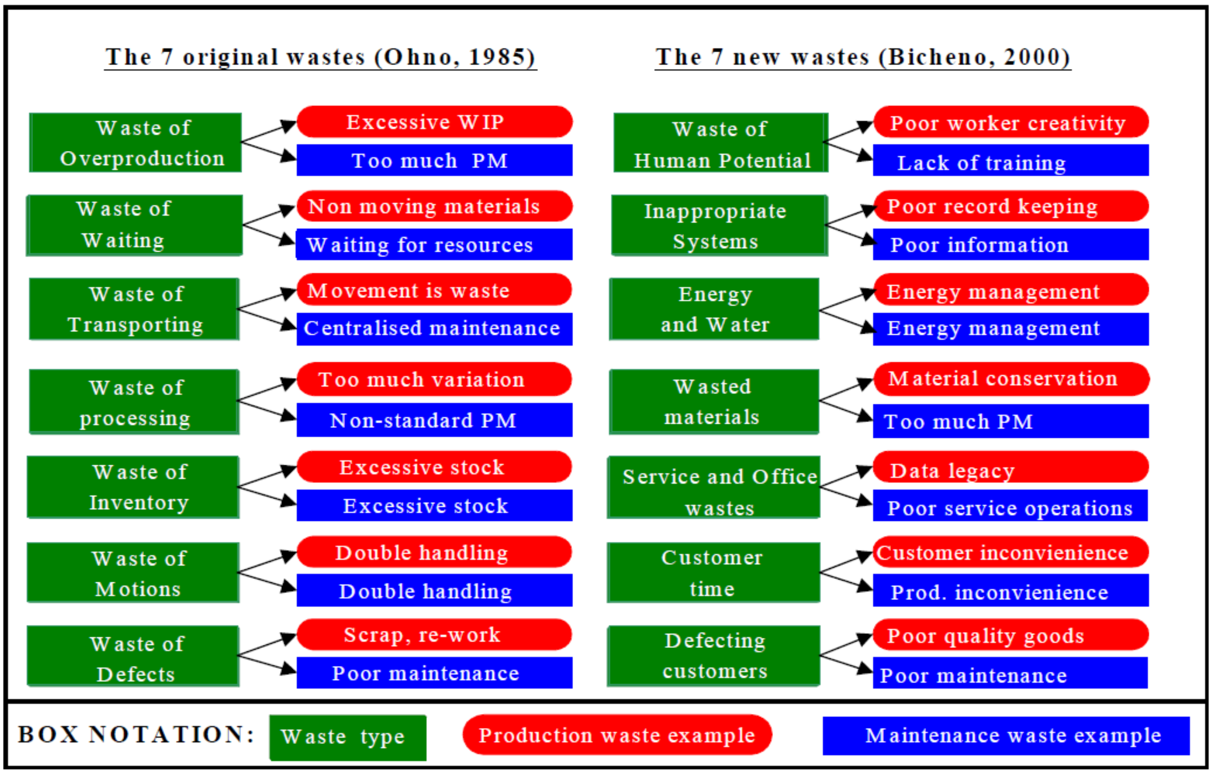

Figure 2.1 Lean Production vs. Lean Maintenance Wastes (Bicheno 2004)

2.3.3 Lean Maintenance, T.P.M and R.C.M

(Smith & Hawkins 2004) state in their book that lean maintenance is Total Productive Maintenance (TPM) "fine-tuned". In other words, the assertion is that TPM is the foundation of lean maintenance and in order to achieve a truly lean environment, TPM first has to be perfected. This view is supported by (Kister & Hawkins 2006) who state that TPM is the fundamental program that is the very foundation of lean maintenance. By definition, TPM is a well-defined and organised maintenance program that places a high value on teamwork, consensus building and continuous improvement (Moayed 2009). A major theme of TPM is that of having a much higher involvement of the machine operator in equipment maintenance. TPM is also a recognised and proven tool of lean production (Yingling et al. 2000). This means that when a production system is changing from non-lean to lean, the maintenance system should be upgraded from unplanned to planned maintenance, then to preventive maintenance and eventually to TPM as explained by (Moayed 2009).

(Nakajima 1988) lists five elements or "pillars" that are considered to be prerequisite for the effective implementation of TPM. These are; elimination of big losses, autonomous maintenance, preventive maintenance, skills enhancement and early management. These were later expanded to eight by the Japan Institute of Plant Maintenance (JIPM) (McCarthy & Rich 2004) and they are; Overall Equipment Effectiveness, Autonomous Maintenance, Planned Maintenance, Education and Training, Early Equipment Management, Quality Maintenance, Office TPM, and Safety, Health and Environment. The JIPM also identified six categories of equipment loss which are; Breakdowns due to Equipment Failures; Set up and Unnecessary Adjustments, Idling and Minor Stops, Running at Reduced Speed, Start-Up Losses, Re-Work and Scrap.

In order to "fine-tune" TPM as discussed above, Reliability Centered Maintenance (RCM) is needed (Smith & Hawkins 2004). RCM is based on the idea of developing life-time maintenance and logistic support programmes through the use of a well-disciplined decision logic analysis process which focuses on the consequences of failure and the actual preventive maintenance tasks. The RCM programme was first used by the airline industry in the early 1970s and has now found wide application and acceptance in many complex high-level systems (Anderson 1990). It is also described by (Balsan 2006) as a data intensive quantitative analysis approach that begins with a Failure Modes, Effects, and Criticality Analysis (FMEA) of every reasonably likely failure mode. Some of the benefits of implementing RCM include increased asset availability, overall reduction in maintenance costs, reduced recurring failures and so on.

2.4 Advances in Lean Maintenance

Although lean thinking and subsequently lean maintenance, has found wide usage in the manufacturing environment as its "traditional" domain, it was originally created in an environment containing large volume and low variety of products. However, from an investigation of recent literature, it is apparent that lean maintenance is now expanding beyond this domain to include areas which are not necessarily manufacturing environments. The following are examples of such applications:

- In the maintenance of drainage operations where after applying some lean concepts to the processes carried out by the drainage maintenance crew, simulation results showed an improvement of as much as 16.6% in productivity (Agbulos, Mohamed, Al-Hussein, Abourizk & Roesch 2006).

- (Verma & Ghadmode 2004) present a study that investigates lean principles in ship repair and maintenance, which is different from maintenance in the manufacturing environment mainly because of its unpredictable nature. After reviewing case studies in both ship repair and maintenance and in aircraft maintenance, where significant improvements were realised, they build their own Integrated Lean Implementation Model for use in fleet repair and maintenance.
- (Ayeni et al. 2011) carry out a "state-of-the-art" review of lean within the aviation Maintenance Repair and Overhaul (MRO) industry. It is concluded in the study that lean is viable within this sector with significant benefits being realised when applied to both independent and airline operated or third party MRO organisations. But according to the author, there is still a lack of sustainable methodology as well as proper application of supporting management tools and technology.

2.5 Lean Thinking in Maintenance Supply Chains

In order for lean thinking to be effectively carried out in maintenance operations, the supply chain that supports these operations has to be streamlined and also made lean. A supply chain is a set of three or more organisations linked directly by one or more of the upstream or downstream flows of products, services, finances, and information from a source to a customer. Supply Chain Management (SCM) involves proactively managing the two-way movement and coordination of goods, services, information, and funds from raw material to end user (Trent 2008). The majority of existing research on supply chains focuses on the manufacturing sector with comparatively little research being done in service-oriented supply chains which include maintenance supply chains (Sengupta, Heiser, & Cook, 2006). The following sections compare supply chains in the manufacturing sector to those in the service sector before focusing on maintenance supply chains and how lean thinking has been used there.

2.5.1 Manufacturing vs. Service Oriented Supply Chains

All manufacturing supply chains have in common a movement of goods from suppliers to manufacturers, possibly through a distributor and then to the customer and may vary on the number of levels of each of the stages with some having multiple levels. (Lee, Jeong & Moon 2002) present the structure of the supply chain in a flexible industrial manufacturing process in which the chain has four levels namely supply, fabrication, assembly, customer as illustrated in Figure 2.2. (Li-Chih Wang 2011) presents another structure with the same levels but goes further to show that within those levels there are other sub-levels which follow their own supply chains from one stage to the next. The main objective of organisations with respect to their manufacturing supply chains is to coordinate orders and delivery of finished products at the time and place the customer desires it and in a manner that minimises total costs for the supply chain members (Al-Mutawah, Lee & Cheung 2009).

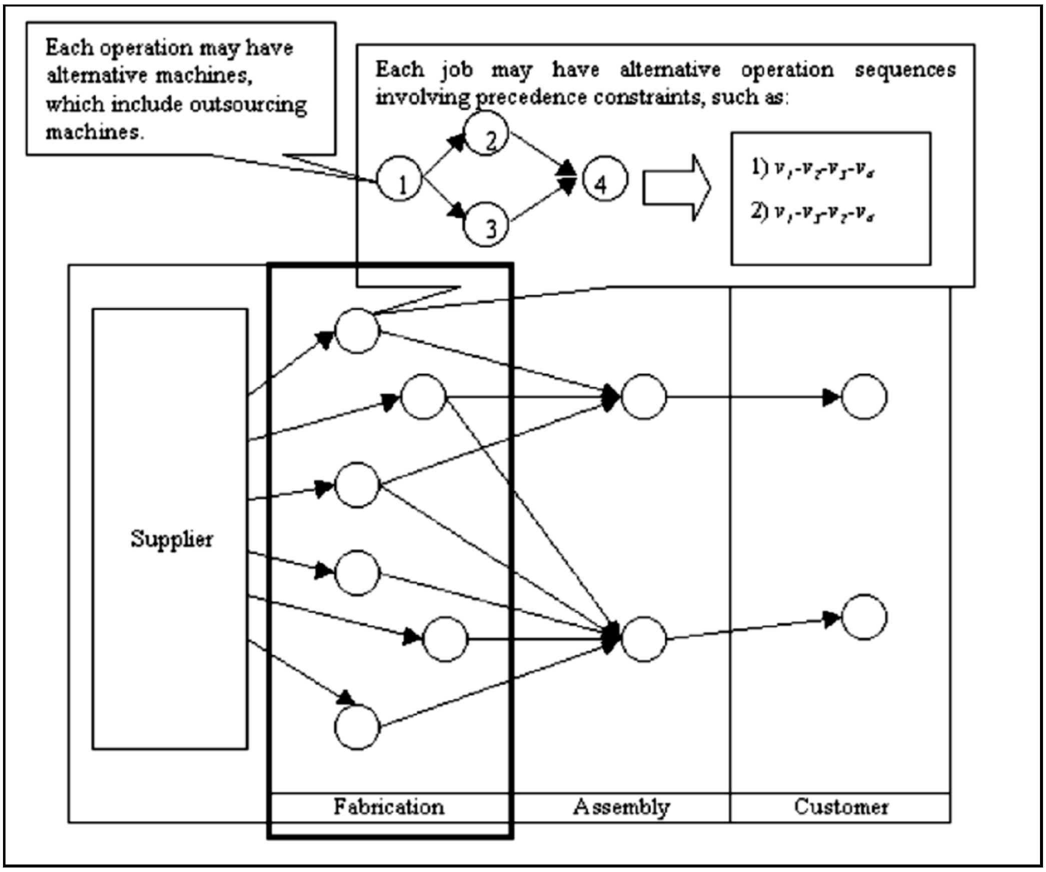

Figure 2.2 Supply Chain in a Flexible Industrial Manufacturing Process (Lee et al. 2002)

On the other hand, the service sector is essentially everything except manufacturing, farming and mining and includes segments like transportation, communication and utilities, wholesale trade, retail trade, finance, insurance and so forth (Ellram, Tate & Billington 2004). The service sector is characterised by the intangibility of their output which refers to the fact that the output of many services may just be a performance, a process or an act, which does not result in transfer of ownership (Giannnakis 2011). (Ellram et al. 2004) also present an ideal services supply chain model which consists of suppliers, purchasing, internal users/stakeholders, finance and the ultimate customer (in that order) as the inherent entities which all interact with the information flow as illustrated in Figure 2.3. The underlying objective in service supply chains is to design and manage a supply chain that best meets the needs of the customers in a cost-effective manner by controlling assets and uncertainties.

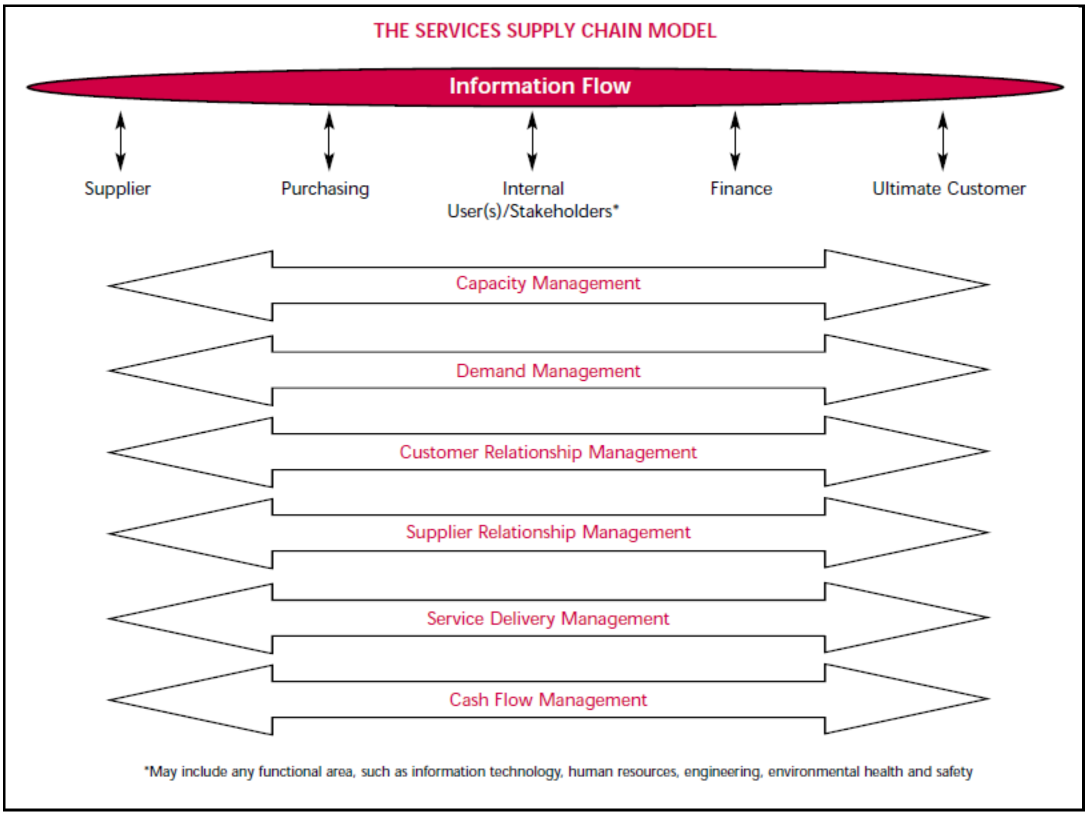

Figure 2.3 An Ideal Services Supply Chain Model (Ellram et al. 2004)

2.5.2 Maintenance Supply Chains

(MacDonnell & Clegg 2007) present an aircraft MRO supply chain reference model which essentially records the activities and material flow of a small airline, a primary maintenance provider, a sub-contract repair facility and a parts trader. It highlights an important feature of MSCs which is the fact that movement of material occurs in both directions hence creating a closed loop supply chain. A model related to the afore-mentioned is given by (Jeong 2003) which consists of three tiers namely; operational level, intermediate level and depot level maintenance facilities. (Cook 2007) likewise presents an improved model for use in military helicopter maintenance and it consists of the aircraft cycle and the stock cycle intersecting at the corrective maintenance activity. A specific MSC model for a nuclear power plant is given by (Androjna, Bizjak & Rosi 2009) and illustrated in Figure 2.4, which describes the relationships between the main contractor and sub-contractors, Original Equipment Manufacturers (OEM) and material suppliers. It also highlights the flow of information, decisions, transactions, material and services between the different players in the chain.

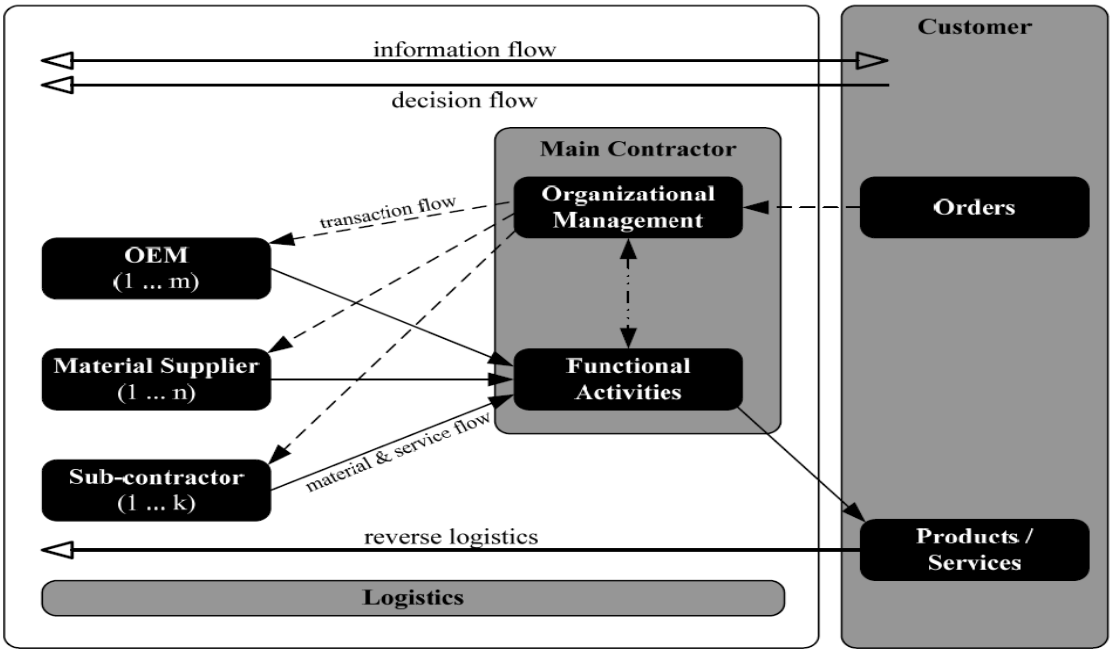

Figure 2.4 MSC Model for a Nuclear Power Plant (Androjna et al. 2009)

2.5.3 General Application of Lean Thinking In Supply Chains

The application of lean principles has extended to the field of supply chain management and today's competitive environment has made it an essential part of the strategy for all contributors of a supply chain (Amirjabbari & Bhuiyan 2011). Examples of industrial application of lean thinking in supply chains can be found in industries such as:

- Automotive industry e.g. Ford Motor Company (Wee & Wu 2009)
- Food industry e.g. meat supply chains in the UK (Cox, Chicksand & Palmer 2007) and in Spain (Perez, de Castro, Simons & Gimenez 2010).
- Aircraft maintenance e.g. optimisation of supply chains used to maintain helicopters belonging to the UK Ministry of Defence (Cook 2007)

(Giannnakis 2011) discusses in detail the aspects of value addition in service supply chains. He argues that unlike manufacturing supply chains, value in service supply chains is added through the management of information and knowledge flows and during the interaction process with the customers.

Performance measures for assessing the leanness of a supply chain vary depending on an organisation's lean objectives. (Trent 2008) emphasises that there is no accepted measure of leanness and states that at best one can provide examples of measures that could be part of the measurement portfolio if these measures align with the organisation's strategic objectives. Performance measures also vary depending on the industry in which the supply chain exists. For instance, in the aerospace supply chain, performance measures such as asset availability and fill-rate are very important (Jeong 2003).

2.5.4 Application of Lean Thinking in Maintenance Supply Chains

In as far as lean thinking in the MSC is concerned, research is scarce with (MacDonnell & Clegg 2007) being one of the few studies to investigate the subject. In their study, they present a model used to tie into the lean enterprise model developed by the Lean Aircraft Initiative programme at the Massachusetts Institute of Technology. It provides proven benefits with the potential to minimise stock holding costs of the whole supply chain and also minimise non-flying time of the aircraft. (Cook 2007) presents mathematical models that help create an intelligent and reactive supply chain for helicopter maintenance programmes. This is achieved through implementing prognostic analysis of real-time mechanical health information from Health and Usage Monitoring Systems installed on the helicopters of the UK Ministry of Defence. (Zwas 2006) investigates the use of lean manufacturing techniques in bus and rail maintenance with a case study at the Chicago Transit Authority in Illinois, USA. Simulation results in the study indicate a possible reduction in inventory levels and elimination of double processing at the off-site warehouse through adopting lean principles.

2.6 Studies in Rolling Stock Maintenance

2.6.1 General Studies in Rolling Stock Maintenance

The body of knowledge regarding maintenance of rolling stock is still increasing with more work being done to explore the different facets that it entails. As with most other maintenance processes, the maintenance of rolling stock has traditionally been categorised into corrective and preventive maintenance (Cheng & Tsao 2010). However, with the passage of time, these two categories have proven to be inefficient, resulting in many problems that require maintenance optimisation strategies. Therefore, most of the work now focuses on determining optimisation strategies for carrying out maintenance work so that the reliability and safety of the rolling stock fleet is enhanced. It is evident from the existing literature that the most well-known and widely applied maintenance optimisation strategy is Reliability Centered Maintenance (RCM) (Rezvanizaniani, Valibeigloo, Asghari, Barabady, & Kumar 2008).

A typical application of RCM is found in (Tsang & Ho 2002) where RCM is applied to analyse and develop the preventive maintenance tasks for the electric multiple units of the East Rail of the Kowloon-Canton Railway Corporation. (Ross 2006) also mentions a case study were a RCM was performed on routine maintenance functions and the result was an overall increase in train availability. Other approaches have also been investigated and these include an enterprise modelling approach as carried out by (Monfared, West, Harrison & Lee 2007) in the train maintenance industry in the UK. Even more recent studies have investigated the possibility of using multi-criteria decision-making (MCDM) methods in order to improve maintenance strategy selection. (Cheng, Yang & Ma.2011) do one such study where MCDM is combined with spare part estimation and a replacement interval model to establish a new systematic approach to rolling stock maintenance strategy selection.

2.6.2 Lean Thinking in Rolling Stock Maintenance

From a look at literature in maintenance management, it is apparent that little has been covered in the way of lean thinking in rolling stock maintenance. This is confirmed by (Cheng et al. 2011) who state that in comparison with manufacturing system maintenance, studies on rolling stock maintenance are relatively rare. One such rare study is given by (Zwas 2006) which involves a case study at Chicago Transit Authority (CTA) in Illinois, USA. The initial hypothesis of the study was that CTA could significantly decrease costs by implementing lean. The study focused, as a pilot case, on the process of rehabilitating door operators for rail cars. Areas of waste were found in the system and one lean principle, with its accompanying methods, was recommended. (Schlake, Barkan & Edwards 2011) give a case where lean production principles were applied to railcar inspection and maintenance practices in order to determine the potential for direct and indirect cost savings.

2.7 Limitations of Lean Thinking

Although lean thinking has advanced considerably, as has been shown in the previous sections, various studies have concluded that there are limitations to its use. One such limitation is highlighted by (Chiarini 2012) who underlines the complications that arise when traditional accounting methods are used in a lean organisation. Financial savings brought about by continuous improvement (*kaizen*) only become visible after a long period and cannot be seen at micro, day-to-day and monthly levels. Various criticisms have also been made against the use of lean thinking in organisational supply chains. (Cox & Chicksand 2005) give one such study where they conclude that for most of the participants of the red meat supply chain in the UK, adoption of inter-organisational lean practices would result in a high level of dependency on buyers and low or declining levels of profitability. It has also been argued that there is a danger of taking lean thinking as a box of tools to be “cherry-picked” rather than an end-to-end value stream that delivers competitiveness (Bicheno 2004). Therefore, it can be concluded that unless management is able to consider the bigger picture and not overemphasise on a few lean tools, the organisation may never see the real potential of implementing lean thinking.

Alternative paradigms have been suggested to help overcome the limitations of lean thinking. Chief amongst those paradigms is that of Agile thinking which is mostly used in supply chain management and has the characteristic of reacting quickly to customer demand. (Martin & Towill 2002) goes further and states that rather than agility and leanness being opposing philosophies, they can work hand in hand under the “Leagile” paradigm which combines the best of both. This view is shared by other authors who include (Bottani & Rizzi 2006).

2.8 Summary

Lean thinking and its use in the maintenance environment has been the focus of this chapter. First, the foundations of the “traditional” use of lean thinking were investigated before exploring the advances that the concept has made into non-traditional areas such as mining, legal services and in the MRO industry. The concept of lean maintenance is then investigated starting with its use in the traditional area of manufacturing before exploring its expansion into non-manufacturing areas. It was found that lean maintenance practices were gaining acceptance in places such as municipal services and MRO industries. Lean thinking has even gone as far as into the maintenance supply chain with the aircraft MRO industry being its earliest and most frequent user to date. The study of the maintenance of rolling stock is still at its infancy although there has been a steady increase in this area of research in the last few years. There is a strong indication that organisations are moving away from a corrective/preventive maintenance approach to more of an optimised approach with reliability centered maintenance (RCM) being popular. A handful of examples are given where lean thinking has been applied in rolling stock showing that the subject area is still in its early years of research with much work still needing to be done. The chapter ends with a discussion of the limitations of lean thinking and the rise of alternative paradigms such as that of Agile and "Leagile" thinking.

CHAPTER THREE: LEAN THINKING TOOLS AND METHODOLOGIES

3.0 Introduction

The aim of this chapter is to give a literature review of the tools and methodologies used in lean thinking applications in general and more specifically, those used in lean thinking in the maintenance operations context. The review will start off by addressing the use of Maintenance Excellence models used to achieve maintenance best practices and the lean tools that have been used to get to the level of maintenance excellence. A closer look is given to the important lean tool of value stream mapping and the corresponding value stream management methodology. These lean tools and methodologies are used in conjunction with various decision-making approaches and these are discussed with particular attention being given to the Analytic Hierarchy Process (AHP) and Quality Function Deployment (QFD) approaches. Finally, the methods of measuring progress towards achieving lean thinking and maintenance best practices is then discussed by looking at the current state of lean performance metrics.

3.1 Maintenance Excellence and Corresponding Lean Tools

3.1.1 The Maintenance Excellence Criteria

According to (Smith & Hawkins 2004) Maintenance Excellence is when an organisation has achieved best maintenance practice standards, which are essentially a yardstick for the performance of industrial maintenance. According to them, an organisation that has adopted the principles of maintenance excellence will most likely achieve 30-50% reduction in maintenance spending within 3-5 years and also realise production volume increases. It can also be referred to as asset maintenance excellence which is essentially the balance of performance, risk, and cost to achieve an optimal solution (Campbell & Jardine 2010). Given in Figure 3.1 are some factors to consider for maintenance excellence.

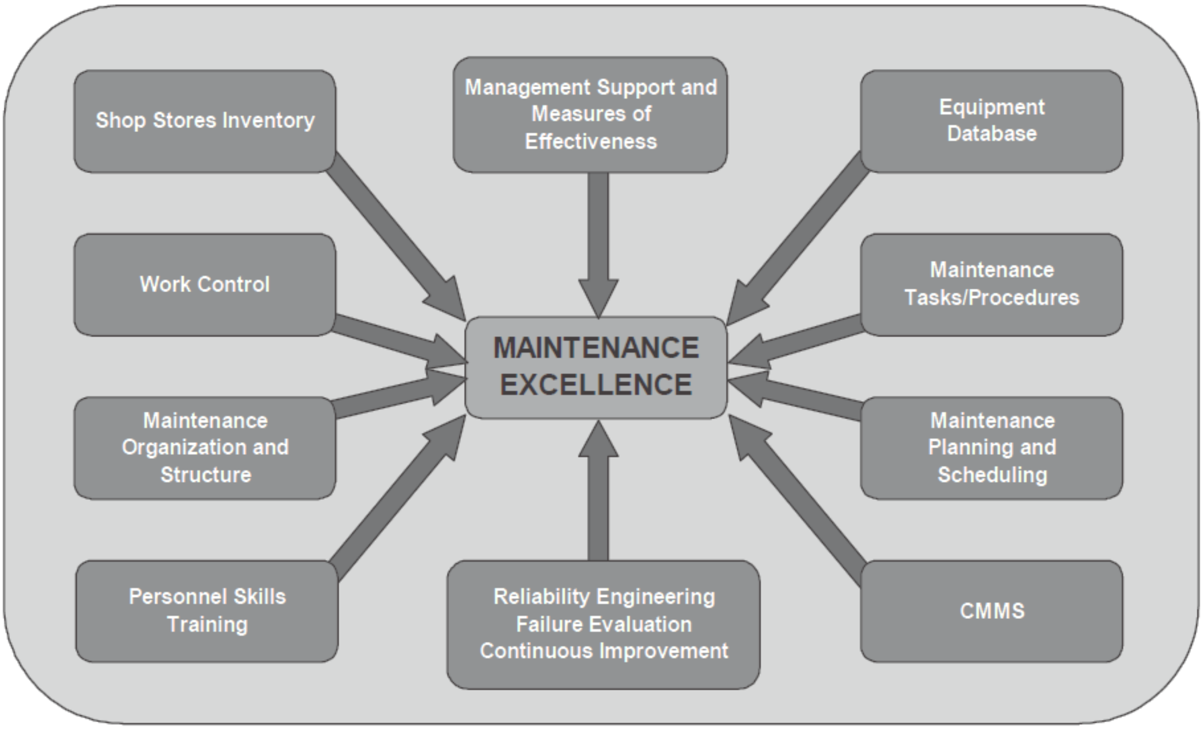

Figure 3.1 Factors to consider for Maintenance Excellence (Smith & Hawkins 2004)

(Lazreg & Gien 2009) give an alternative maintenance excellence model with ten distinctive areas, each representing a different aspect of the organisation as shown in Figure 3.2. The ten areas are subdivided into those concerned with *what* results have been achieved (Results) and areas concerned with *how* these results have been achieved (Enablers).

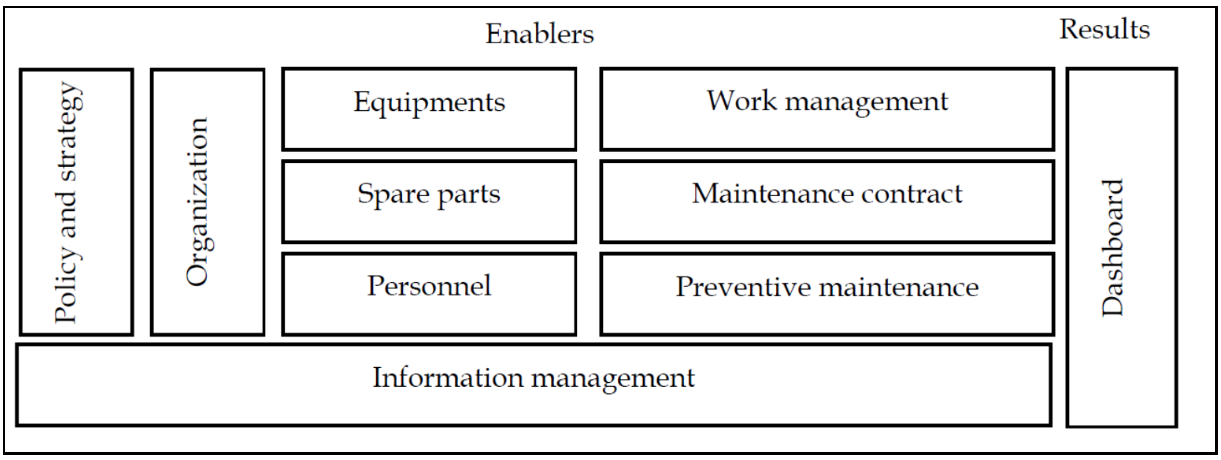

Figure 3.2: The Maintenance Excellence Model (Lazreg & Gien 2009)

A maintenance excellence pyramid developed by (Campbell & Reyes-Picknell 2006) is illustrated in Figure 3.3. The pyramid acts as an overall strategy or roadmap that can be used to guide choices on how maintenance is managed. Any company that has physical assets to maintain will, by default, apply at least some of the elements from the "Essentials" level to varying degrees of competence. More successful companies may achieve some level of excellence in executing the "Essentials". High performing companies will consciously and consistently attend to "Essentials" and add elements from "Choosing Excellence" as shown in the pyramid.

3.1.2 Lean Maintenance Enablers/Tools

Lean Enablers are the various tools that can be used to increase the leanness of a function. These enablers are designed in order to prepare for, plan and execute the function using lean thinking. And when referring to the maintenance function, these lean enablers will allow lean thinking to be applied with the end result that maintenance excellence is attained. (Davies & Greenough 2003) state that there is no clearly defined lean practice framework which can be referred to for the maintenance function. Table 3.1 gives a brief overview of tools that have been used or have been determined to be effective in performing lean thinking in the maintenance environment. As can be observed from the table, most of the lean enablers have been applied in a manufacturing context.

Figure 3.3: A maintenance excellence pyramid (Campbell & Reyes-Picknell 2006)

Identification and application of lean enablers in non-manufacturing maintenance environments is still developing. It is also apparent that most of the tools that are used in the manufacturing maintenance environment are also used in the non-manufacturing maintenance environment as can be observed from the one example given in the table.

Table 3.1 Lean Tools/Enablers Used in Maintenance Functions

Lean Tool (s)	Application/Industry	Author (s)
5S, TPM, OEE, Standards, Mapping, Inventory Management, Visual Management, Root cause problem solving, Continuous improvement, Kaizen Activities, Poka Yoke, Process Activity Mapping, Self-Audits, Story boarding, Kanban, Scenarios, Takt Time, Lead Time mapping, Value Focused Thinking, Supplier Associations, Open Book Management	General – Manufacturing Origins	(Davies & Greenough 2003)
5S, 7 Deadly Wastes, Standardised Work, Value Stream Mapping, Kanban, Jidoka, Poka Yoke, JIT	General – Manufacturing Origins	(Smith & Hawkins 2004)
Jidoka, Just-in-time, Heijunka, Kaizen	M.R.O	(Zwas 2006)
Value Mapping, Criticality Analysis, Hidden Lost Cost Model, Best Practice Development, Lean Maintenance Standards, Focused Improvement	Pharmaceutical Manufacturing	(Clarke et al. 2010)

3.2 Value Stream Mapping

3.2.1 Value Stream Mapping

Value stream mapping (VSM) is a pencil and paper tool that helps to understand the flow of material and information as a product makes its way through the value stream (Rother & Shook 2003). A typical value stream is a combination of value-adding and non-value-adding actions that are required to bring about a product or group of products from the raw material stage to the customer. VSM has been widely used in lean thinking efforts ever since its inception, especially in the manufacturing environment where it has its origins. A few examples of its use in manufacturing include (Abdulmalek & Rajgopal 2007), (Wee & Wu 2009), and (Boppana & George 2011). VSM has also found use in non-manufacturing environments, examples include:

- Ship repair and maintenance (Verma & Ghadmode 2004)
- Bus and rail maintenance operations (Zwas 2006)
- Streamlining of accounting systems (Chiarini 2012)

The mapping process uses several standard map symbols derived from manufacturing processes. A comprehensive list of the most commonly used symbols is given in APPENDIX D. A six-step waste identification and elimination process commonly used in VSM is described below (Kister & Hawkins 2006):

1) Select the process for assessment, and starting at its end point; carefully map out each stage/activity of the process.
2) Analyse the process map by examining each map symbol and continue until you are convinced that all steps of the process have been mapped. This results in the current state map.
3) Re-analyse the current state map to identify all non-value-adding activities. Remove the non-value-adding activities or develop value-adding alternatives and remap the process. Re-analyse the new map until convinced that the process is now workable and consists of only value adding activities and it is not feasible to remove the remaining non-value-adding activities. The resulting map constitutes the process' future state.
4) Create a listing of all the actions needed to remove the non-value-adding activities as well as any value added work-arounds developed. This constitutes the steps of an action plan for modifying (removing waste) the selected process.
5) Write-up an action plan that will be applied to the process' current state to move it to the (value added) future state. Submit the action plan together with both the current state and future state process maps, for approval and authorisation.
6) Execute the process' action plan in accordance with approval guidelines.

According to (Tapping 2002) when VSM is used in lean applications, there are three stages that the process has to go through, namely customer demand, flow and levelling stages.

1) **Customer Demand Stage** – this stage involves the customer's demand for your products, including quality characteristics, lead time and price. The following questions should be asked in an effort to steer the value stream in the lean direction:

- ✓ What is the demand? In other words, what is the takt time?
- ✓ Is the current process over producing, under producing, or meeting demand?
- ✓ Can you meet takt time (or pitch) with current production capabilities?
- ✓ Do you need to buffer stock? Where? How much?
- ✓ Do you need safety stock? Where? How much?

- ✓ Will you ship finished goods right after the final operation or use a finished goods supermarket?
- ✓ What improvement tools will you use to improve your ability to fulfil customer demand?

The various tools and concepts used for determining and meeting demand include:

- *Takt time* – the rate at which a company must produce a product to satisfy customer demand. The formula for calculating takt time is as follows:

$$Takt\ Time = \frac{Available\ Production\ Time}{Total\ daily\ quantity\ required} \tag{3.1}$$

Where $Available\ Production\ Time$ is the total available production time minus the regularly scheduled planned downtime occurrences such as lunch, breaks or meetings.

- *Pitch* – the amount of time- based on takt-time required for an upstream operation to release a predetermined pack-out quantity of work in process to a downstream operation. The formula for calculating pitch is as follows:

$$Pitch = takt\ time\ \times packout\ quantity \tag{3.2}$$

- *Buffer and safety inventories* – these are temporary measures that allow you to meet demand while you are planning and implementing improvements. Buffer inventory is used when customer demand suddenly increases and your production process is not capable of meeting a lower takt time. A safety inventory, on the other hand, protects you from internal problems such as equipment reliability problems that can prevent you from meeting demand.
- *Finished-goods Supermarket* – a system used in the shipping part of a value stream to store a set level of finished goods and replenish them as they are "pulled" to fulfil customer orders.

2) **Flow Stage** – this stage is for establishing a flow to ensure that customers receive the right parts at the right time in the correct amounts. The tools and concepts necessary to establish flow include:

- *Continuous Flow* – this means producing or conveying products according to three key principles namely, only what is needed, just when it is needed and in the exact amount that it is needed.
- *Work Cells* – a work cell is a self-contained unit that includes several value-adding operations. The cell arranges equipment and personnel in process sequence and includes all the operations necessary to complete a product or a major production sequence.
- *Line Balancing* – this is the process through which work elements within the value stream are evenly distributed in order to meet takt time. The best tool to perform this task is the operator balance chart which is a visual display of the work elements, time requirements, and operators at each work station. It is used to show improvement opportunities by visually displaying each operation's times in relation to takt time and total cycle time. Cycle time is the time that elapses from the beginning of an operation until its completion.
- *Standardised work* – this is an agreed-upon set of work procedures that establishes the best method and sequence for each process. This is done in order to ensure consistent flow within the value stream and that workers are able to produce to takt time and achieve consistent cycle times for the work elements assigned.
- *Autonomous Maintenance* – this is an element of total productive maintenance and its aim is to prevent equipment related losses through addressing abnormal conditions that lead to such losses. It focuses on maintaining optimal conditions to prevent such losses.
- *In-Process Supermarkets* – this system is used where obstacles to continuous flow exist and provides a way to keep work-in-process so as to ensure that flow is possible. As the flow improves, the need for supermarkets usually decreases.
- *Kanban System* – kanbans are cards attached to containers that store standard lot sizes. When the inventory represented by that card is used, the card acts as a signal to indicate that more inventory is needed. In this way, inventory is produced only when needed, in the exact amounts needed. There are three types of kanban, namely a production kanban, withdrawal kanban and a signal kanban.

3) **Levelling Stage** – this stage involves evenly distributing over a shift or day the work required to fulfil customer demand. The concepts and tools used to level production include *Paced Withdrawal*, *Heijunka*, *Heijunka Box* and *The Runner*.

- *Paced Withdrawal* – this is a system for moving small batches of product from one operation or process to the next, at intervals equal to the pitch. Paced withdrawal is used when you have no product variety in the value stream, meaning that all increments will be identical.
- *The Runner* – the runner ensures that pitch is maintained. He or she covers a designated route within the pitch period, picking up kanban cards, tooling, and components, and delivering them to their appropriate places.

3.2.2 Drawbacks of Value Stream Mapping

In spite of the relatively positive results that the application VSM has brought to many organisations implementing lean thinking, the approach is not fool-proof and has shown some inherent weaknesses or limitations. One such limitation is that unless the personnel on the floor are adequately trained on the various lean concepts used in VSM, there may be a large degree of hesitancy from them in adopting the recommendations put forward in the future state scenario. This was observed by (Lasa, Laburu, & De Castro 2008) who note from a case study carried out that the personnel expressed doubt in taking the decision to establish a pacemaker along the process they had not been sufficiently trained in VSM concepts. Another drawback of VSM is highlighted by (Abdulmalek & Rajgopal 2007) who state that sometimes a future state map is not easy to evaluate due to its static nature. They advocate for the use of a complementary tool to use with VSM which in their case was simulation. This claim is backed by (McDonald, Van Aken & Rentes 2002) who earlier on made the same recommendation from a different study.

3.2.3 The Value Stream Management Methodology

In order to address some of the problems encountered when using value stream mapping, a methodology called Value Stream Management (VSM) is discussed by (Hines, Rich, Bicheno & David 1998). It is a strategic and operational approach designed to help a company or complete supply chain, achieve a lean status. This approach has its origins still grounded in value stream mapping. It has been successfully used to implement lean manufacturing in

Fortune 500 companies (Tapping 2002). (Hines et al. 1998) break down the process into 20 individual and consecutive stages which start with understanding the broader company mission and end with measuring progress against the initial plan. VSM can also be performed in an alternative eight steps as described by (Tapping 2002), namely:

1. Commit to lean.
2. Choose the value stream.
3. Learn about lean
4. Map the current state
5. Determine lean metrics.
6. Map the future state
7. Create Kaizen plans.
8. Implement Kaizen plans.

3.3 Lean Decision-making Approaches

3.3.1 The Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a systematic decision-making approach that was first developed in 1971 by Thomas L Saaty (Saaty 1980). A very detailed literature review of the many applications of AHP is given by (Vaidya & Kumar 2006) who highlight just how broadly the process has been used. According to the study, AHP has been used in education, engineering, government, industry, management, manufacturing, finance sector and so forth. The reason why it has been so widely used is because of its simplicity, ease of use and flexibility (Ho 2008). The process does however have its critics with the earliest being (Belton & Gear 1983), who state that they discovered many instances where the addition of an alternative causes a change in the relative importance of criteria and thus overall preferences order. They recommend that the pairwise comparison questions be more specific than those advocated in the original method. This view is supported by other studies such as one carried out by (Ruan & Jinli 2010) who propose a new method of rank preservation based on what they call the judgement matrix consistency.

The technique can be summarised in the following steps (Saaty 1980):

1. Break down the decision-making problem into a hierarchy which is a particular type of system based on the assumption that the entities which are identified, can be grouped into

disjoint sets with the entities of one group influencing the entities of only one other group. Figure 3.4 shows a breakdown into three levels with the potential to have many more levels.

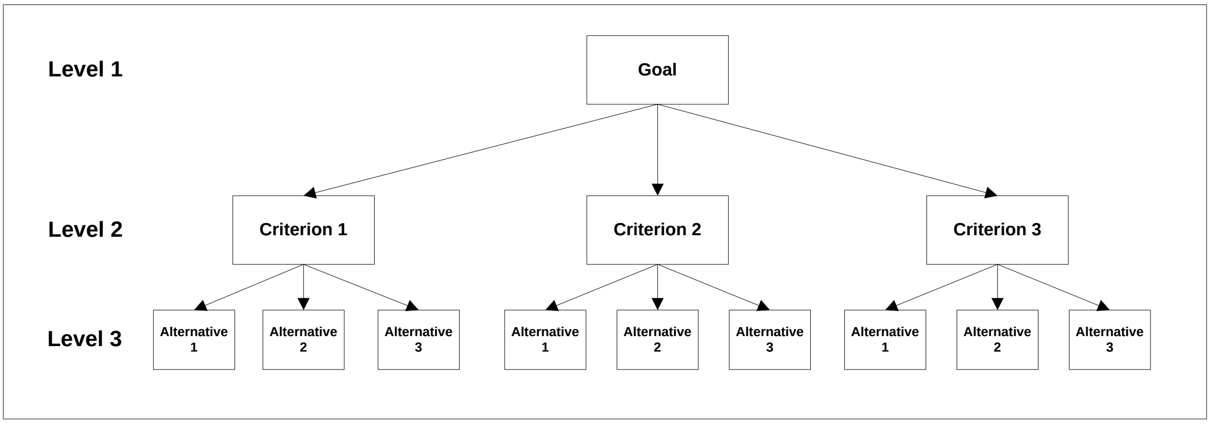

Figure 3.4 AHP Hierarchy Levels

2. Make pairwise comparisons and establish priorities among the elements in the hierarchy. This helps to determine the strengths or priorities of the elements in one level relative to their importance for an element in the next level. The procedure for doing this is as follows (Chuang 2001):

Complete a pairwise comparison matrix A for m objectives,

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix} \qquad (3.3)$$

Where, a_{ij} indicates how much more important the ith element is than the jth element for constructing the column vector of importance weightings. For all i it is necessary that a_{ii}=1 and $a_{ij} = 1/a_{ji}$. The possible assessment values of a_{ij} with the corresponding interpretation is shown in Table 3.2.

Table 3.2 Assessment of a_{ij}

Value of a_{ij}	**Interpretation**
1	Objective i and j are of equal importance.
3	Objective i is weakly more important than objective j.
5	Objective i is strongly more important than objective j.
7	Objective i is very strongly more important than objective j
9	Objective i is absolutely more important than objective j
2,4,6,8	Intermediate values

3. Normalise the resulting matrix. This is done by dividing each entry in column i of $\boldsymbol{A}$ by the sum of the entries in column I. This yields a new matrix $\boldsymbol{A_w}$, in which the sum of the entries in each column is 1, as shown below.

$$\boldsymbol{A_w} = \begin{bmatrix} \frac{a_{11}}{\sum_{i=1}^{m} a_{i1}} & \frac{a_{11}}{\sum_{i=1}^{m} a_{i2}} & \cdots & \cdots & \frac{a_{1m}}{\sum_{i=1}^{m} a_{im}} \\ \vdots & \vdots & & \cdots \quad \cdots & \vdots \\ \vdots & \vdots & \ddots & & \\ \vdots & \vdots & & \ddots & \vdots \\ \frac{a_{m1}}{\sum_{i=1}^{m} a_{i1}} & \frac{a_{m2}}{\sum_{i=1}^{m} a_{i2}} & \cdots & \cdots & \frac{a_{mm}}{\sum_{i=1}^{m} a_{im}} \end{bmatrix} \tag{3.4}$$

4. Compute c_i as the average of the entries in row i of $\boldsymbol{A_w}$ to yield column vector $\boldsymbol{C}$

$$\boldsymbol{C} = \begin{bmatrix} c_1 \\ \vdots \\ \vdots \\ c_m \end{bmatrix} = \begin{bmatrix} \dfrac{\frac{a_{11}}{\sum_{i=1}^{m} a_{i1}} + \frac{a_{12}}{\sum_{i=1}^{m} a_{i2}} + \cdots + \frac{a_{1m}}{\sum_{i=1}^{m} a_{im}}}{m} \\ \vdots \\ \dfrac{\frac{a_{m1}}{\sum_{i=1}^{m} a_{i1}} + \frac{a_{m2}}{\sum_{i=1}^{m} a_{i2}} + \cdots + \frac{a_{mm}}{\sum_{i=1}^{m} a_{im}}}{m} \end{bmatrix} \tag{3.5}$$

Where c_i represents the relative degree of importance for the ith criteria in the column vector of importance weightings.

5. Calculate and check the consistency of the pairwise comparison in the following manner:
   i. Compute $\boldsymbol{A} \cdot \boldsymbol{C}$:
   ii. Compute δ which is called the maximum or principal eigenvalue:

$$\boldsymbol{A}\cdot\boldsymbol{C}=\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mm} \end{bmatrix}\begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_m \end{bmatrix}=\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix} \tag{3.6}$$

The closer δ is to m, the more consistent is the result.

iii. Compute the consistency index ($\boldsymbol{CI}$) as follows:

$$\boldsymbol{CI}=\frac{\delta-m}{m-1} \tag{3.7}$$

iv. Compare $\boldsymbol{CI}$ to the random index ($\boldsymbol{RI}$) for the appropriate value of m to determine if the degree of consistency is satisfactory. After conducting some experiments at Oak Ridge National Laboratory (Saaty 1980), an average $\boldsymbol{RI}$ for matrices of the order 1-15 using a sample size of 100 was generated and is shown below.

m	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\boldsymbol{RI}$	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

If $\boldsymbol{CI}$ is sufficiently small, the decision-maker's comparisons are probably consistent enough to give useful estimates of the weights for the objective function. If the consistency ratio, given by $\boldsymbol{CI}/\boldsymbol{RI}$ is less than 0.10, the degree of consistency is satisfactory, but if it is greater than 0.10, serious inconsistences may exist, and the AHP may not yield meaningful results. In situations where that happens, it is necessary to revise judgements and in order to help that revision there are three methods that have been shown to work (Saaty 1980).

Method 1: Form a matrix of priority ratios w_i/w_j and consider the matrix of absolute differences $\left[\left|a_{ij}-\left(w_i/w_j\right)\right|\right]$ and attempt to revise the judgement on the element(s) or row sums with the largest such differences.

Method 2: Form the root mean square deviation using the rows of $\left(a_{ij}\right)$ and $\left(w_i/w_j\right)$ and revise the judgements for the row with the largest value. The procedure can then be repeated to note improvement.

Method 3: The procedure consists of replacing all a_{ij} in the row in question by the corresponding w_i/w_j and recalculating the priority vector. Repetition of this process has been noted to produce convergence to the consistent case.

3.3.2 Integrated AHP Approaches

The AHP process has been integrated with tools that include mathematical programming, Quality Function Deployment (QFD), meta-heuristics, SWOT analysis, and data envelopment analysis, as opposed to using it as a stand-alone method. This is according to a literature survey carried out by (Ho 2008) for the period 1997 to 2006. It was found that the combined AHP-GP (Goal Programming) and AHP-QFD approaches were the most commonly used methods and that logistics and manufacturing are the two application areas to which the integrated AHPs were most frequently applied. Others have even gone further in the integration of AHP with other tools by adding a third tool. One such example is the addition of the Analytic Network Process (ANP) which results in the creation of the QFD-ANP-AHP approach (Partovi 2004). In this example, where the objective is to develop an analytical technique for process selection and evaluation for manufacturing systems, the ANP is used to determine the intensity of synergy effects among the column variables of the AHP matrix.

3.3.3 The Quality Function Deployment Technique

Quality Function Deployment (QFD) was first proposed and used by Mitsubishi Heavy Industry's Kobe shipyards to design super tankers (ReVelle 1998). It is a widely used customer-driven, design and manufacturing tool, and is commonly used in the new product development field to translate customer requirements (WHATs) into appropriate engineering characteristics (HOWs) (Zarei, Fakhrzad & Paghaleh 2011). Toyota Auto Body developed a quality table that had a "roof" on top, which was later passed on as the House of Quality (HOQ). The HOQ is essentially a matrix that is used to display the relationship between the WHATs and the HOWs and demonstrates how quality characteristics satisfy the customer requirements. The general outline of the HOQ is as shown in Figure 3.5. The QFD technique tends to be used in conjunction with other techniques in order to enhance its effectiveness and applicability. It is also combined with other techniques in order to deal with the subjective linguistic judgements that arise when expressing relationships and correlations required in the HOQ. One such adaptation is through the use of Fuzzy Logic (Bottani 2009), which is used to minimise the vagueness frequently represented in decision data. Another approach that is gaining wide acceptance is that of combining QFD with the Analytic Hierarchy Process.

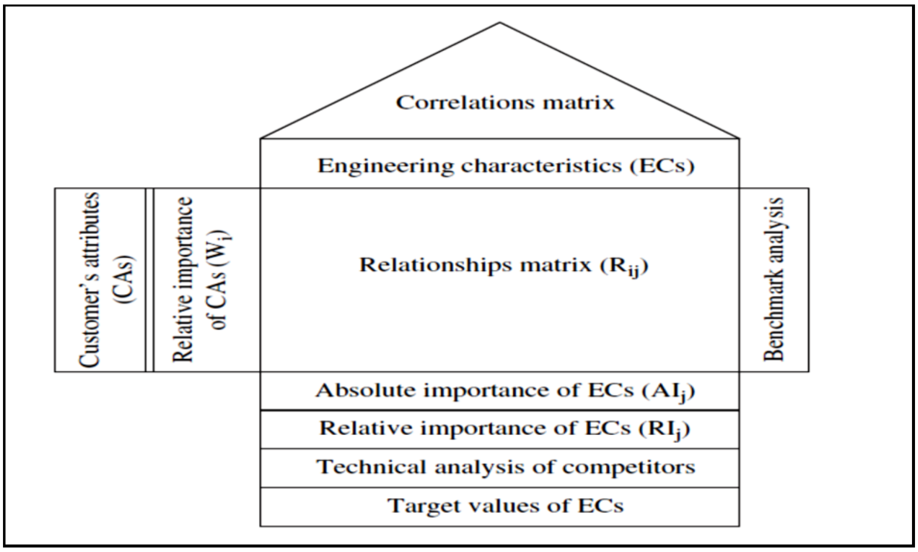

Figure 3.5: The House of Quality (Bottani & Rizzi 2006)

The HOQ can be built by following an eight step process (Bottani & Rizzi 2006):

Step 1: Identify the customer's needs and requirements, in other words, the customer's attributes (CAs). These are listed in row in the HOQ.

Step 2: The CAs are weighted in order to express their relative importance and the weight of each CA is inserted in a column in the matrix.

Step 3: Establish how the product performs against competing products through benchmark analysis. The results of this step are added to the right side of the matrix.

Step 4: Translate the CAs into engineering characteristics (ECs). The ECs are measurable attributes concerning a firm's product or service and are listed in columns in the HOQ.

Step 5: Construct the relationship matrix by first determining the relationships between customer needs and the firm's ability to meet those needs. The relationships are expressed with graphic symbols that indicate how and to what extent each engineering characteristic meets each customer's attribute. Usually, symbols express three degrees of strength (weak, medium, strong), which are translated into a rating scale such as 1-3-9 or 1-5-9.

Step 6: Establish the correlations matrix which is used to express how ECs affect each other. A positive relationship indicates that two ECs can complement or improve each other whilst a negative one suggests that trade-offs are required. Symbols are also used for this matrix with a 1-3-7-9 or 1-3-5-9 (strong negative, negative, positive, strong positive) scale.

Step 7: Carry out a quantitative benchmark analysis of competitors' ECs and the results are added in a row in the lower part of the matrix.

Step 8: Introduce a target measure which translates the customer's expectations into numerical values for each EC in the matrix. Either the absolute and/or relative importance of each EC against customer's requirements is quantitatively evaluated. The absolute importance $\boldsymbol{AI}_j, j = 1, \dots m$ of each EC can be calculated as

$$\boldsymbol{AI}_j = \sum_{i=1}^{\boldsymbol{n}} W_i R_{ij}, \qquad j = 1, \dots, m \tag{3.8}$$

Where:

W_i is the relative importance of the ith CA,

R_{ij} expresses the relationship between the ith CA and the jth EC with a numerical scale.

The relative importance $\boldsymbol{RI}_j$ can be derived from the absolute importance $\boldsymbol{AI}_j$**,** through the following equation:

$$\boldsymbol{RI}_j = \frac{\boldsymbol{AI}_j}{\sum_{j=1}^{m} \boldsymbol{AI}_j}, \quad j = 1, \dots, m \tag{3.9}$$

3.3.4 The AHP-QFD Approach

As has been discussed in the previous section, Quality Function Deployment (QFD) has been used extensively in conjunction with AHP to give better solutions. (Partovi 2004) carries out one such combination where instead of using a stand-alone AHP approach, an AHP-QFD approach is used for evaluating decision alternatives in a facility location problem. Another QFD-AHP study used in a facility location problem is found in (Chuang 2001). AHP is used to measure the relative importance weighting for each location requirement and also to assess the evaluating score for each candidate location for a particular set of location criterion. (Dziadak & Michalski 2010) use QFD and AHP in the evaluation of hardware for a mobile station and find that the results of these methods are better than those obtained using quality/price ranking method. (Ho 2008) gives many another examples where the AHP-QFD approach has been used including amongst others:

- Improving the education quality for a higher learning institution.

- Project selection.
- Determining the composition of an army deployment.
- New product development.

3.4 Lean Performance Metrics

Performance measurement, as a field of study, is receiving ever-increasing attention because of its relevance to the success or failure of the overall organisation. Performance measures in general, provide a mechanism for relating product or process improvement policies developed by senior management to action at a local organisation level (Bond 1999).

3.4.1 Maintenance Performance Metrics

Measuring for maintenance performance has not developed as fast as other parts of the organisation with both academics and practitioners failing to recognise maintenance management as a full-grown business. However, due to changes in the way manufacturing companies operate, maintenance is now recognised as a major contributor to the performance and profitability of manufacturing systems (Kutucuoglu, Hamali, Irani & Sharp 2001). Maintenance output is difficult to measure because of the following reasons, amongst others: (Pintelon & Van Puyvelde 1997).

- Maintenance activity is closely related to production activity which in turn is affected by other functions which have their own performance measures.
- Performance of the maintenance function is perceived differently depending on the perspective applied. For example accountants will think of maintenance in terms of cost whilst production will think of maintenance in terms of equipment availability.
- Maintenance managers often have access to a lot of data but hardly ever receive the information they need to make informed decisions.

Maintenance performance measures can be divided into two categories, namely leading indicators and lagging indicators. The former are indicators that measure performance before a problem arises and the latter are measures that indicate that a problem has occurred and a reactive action needs to be taken. A list of mostly leading and a few lagging key performance indicators (KPIs) is illustrated in Table 3.3. KPIs are a combination of several metrics and indicators to yield an assessment of critical or key processes (Smith & Hawkins 2004).

Table 3.3: Leading and Lagging KPIs (Smith & Hawkins 2004)

Reliability/Maintainability ➢ MTBF (mean time between failures) by total operation and by area and then by equipment. ➢ MTTR (mean time to repair) maintainability of individual equipment. ➢ MTBR (mean time between repairs) equals MTBF minus MTTR. ➢ OEE (overall equipment effectiveness) Availability × Efficiency (slow speed) × Quality (all as a percentage). **Preventive Maintenance** (includes predictive maintenance) ➢ PPM labor hrs. divided by Emergency labor hrs. ➢ PPM WOs (work orders) #s divided by CM (corrective maintenance, planned/scheduled work) WOs as a result of PM inspections. **Planning and Scheduling** ➢ Planned/Schedule Compliance—(all maintenance labor hours for all work must be covered and not by "blanket work orders"). This a percentage of all labor hours actually completed to schedule divided by the total maintenance labor hours. ➢ Planned work—a % of total labor hours planned divided by total labor hours scheduled.	**Materials Management** ➢ Stores Service Level (% of stock outs)—Times a person comes to check out a part and receives a stock part divided by the number of times a person comes to the storeroom to check out a stocked part and the part is not available. ➢ Inventory Accuracy as a percentage. **Skills Training** (NOTE: A manager must notify maintenance craft personnel about the measurement of success of skills training.) ➢ MTBF. ➢ Parts Usage—this is based on a specific area of training such as bearings. **Maintenance Supervision** ➢ Maintenance Control—a % of unplanned labor hours divided by total labor hours. ➢ Crew efficiency—a % of the actual hours completed on scheduled work divided by the estimated time. ➢ Work Order (WO) Discipline—the % of labor accounted for on WOs. **Work Process Productivity** ➢ Maintenance costs divided by net asset value. ➢ Total cost per unit produced. ➢ Overtime hours as % of total labor hours.

Table 3.4 is a list of performance indicators that are applicable in maintenance operations and also shows different aspects of the activities that can be evaluated at the same time. Table 3.5 shows a classification of maintenance measurement indices under four categories. (Kutucuoglu et al. 2001) observes that although the measures form a balanced view of the maintenance system, they are yet limited to operational and tactical aspects. They argue instead, that a good maintenance performance measurement system should have the following five categories:

1. Equipment related performance
2. Task related performance
3. Cost related performance
4. Immediate customer impact related performance
5. Learning and growth related performance

Table 3.4 Performance Indicators Applicable In Maintenance Operations

Topic	Focus	Measurement
Maintenance Efforts (inputs)	Department	Manpower
		Work orders
		Costs
	Service	Operations
		Maintenance Intensity
		Costs
Maintenance impact (outputs)	Plant condition	MTTR (mean time to repair)
		MTBF (mean time between failures)
	Plant performance	Machine utilisation
		Output quality
Global evaluation (global process)	Cost reduction index	
	Maintenance intensity index	
	Cost/service index	

Table 3.5 Classification Of Maintenance Measurement Indices Adapted from (Coetzee 2004)

Performance Measurement Categories			
Machine/Facility Maintenance Efficiency	**Task Efficiency**	**Organisational Efficiency**	**Profit/Cost Efficiency**
Total Production Time	Number of Tasks completed.	Time planned for scheduled tasks	Total maintenance cost
Number of Breakdowns	Number of tasks received.	Time planned for overdue scheduled tasks	Cost of lost production
Production	Number of tasks overdue	Time spent on scheduled tasks	Value of stock at the end of the period
	Clocked time	Time spent on breakdowns	Plant investment value
	Time allowed on tasks	Cost of breakdowns	
	Time spent on tasks	Total direct maintenance costs	

3.4.2 Lean Performance Metrics

Table 3.6 lists some of the more commonly used metrics for measuring lean implementation. Most of these metrics are derived from the manufacturing context. They can generally be placed under the umbrella of four families of measures, namely quality, cost, delivery, and safety (Brown, Collins & McCombs 2006). This list is of course not exhaustive and is rather just a snapshot of what academics and practitioners look at improving when employing lean thinking. The list is also diverse and this is because lean manufacturing, and subsequently lean thinking, does not have a universally accepted standard of evaluation as observed by (Miller et al. 2010).

Table 3.6 Metrics for Measuring Lean Implementation

(Shah & Ward 2003)	(Brown et al. 2006)
• Scrap and Removal costs • Manufacturing cycle time • First pass yield • Labour productivity • Unit manufacturing cost • Customer lead time	• Defects per unit, • First time yield, • Overall equipment effectiveness • Productivity • Lead-time • Set-up/ changeover time. • Scrap • WIP • Lost time injury.
(Aulakh & Gill 2008)	(Boppana & George 2011)
• On time delivery • Process lead time • Total cost • Quality yield • Inventory • Space utilisation • Travel distance • Productivity	• Non-value added time, • Total cycle time, • Number of workforce, • WIP inventory • Floor space

3.4.3 Lean Maintenance Performance Metrics

(Davies & Greenough 2003) present a list of maintenance performance indicators that are used to measure the impact of lean techniques upon the maintenance function. This list is illustrated in Table 3.7, which contains only four out of eleven performance indicators that were used at a particular case study. As has been discussed in Section 2.3.3, TPM is considered to be a prerequisite for establishing lean maintenance. One of the major themes of TPM is maximising equipment effectiveness through overall equipment effectiveness (OEE) (Nakajima 1988). In order to achieve OEE, a set of performance measures need to be set in place and calculated. This is illustrated by the example given in Figure 3.6 which shows that availability, performance efficiency, and rate of quality products are important performance measures to be considered. The rest of the lean maintenance performance measures are essentially a mixture of general maintenance metrics and lean thinking performance metrics as discussed in the previous two sections.

Table 3.7 Some Maintenance Performance Indicators (Davies & Greenough 2003)

	Performance indicator	Indicator calculation	Description	Desired outcome
I	Utilisation	Standard hours / Total clock time	Percentage index used to identify non-productive time. "Periodic studies show how well a remedy is working"	Trend increase
II	Breakdown repair hours	Number of Hours spent on breakdowns / Total direct M'tance hours	Index used to guage effectiveness of M'Tance program. In particular, preventative maintenance	Trend decrease
III	Length of running	Total production output in units or hours / Qty repairs during same period	Index to show whether added service in hours, parts or frequency would give noticeable results	Value increase
IV	Emergency and other unscheduled tasks	Man-hours emergency, unscheduled jobs / Total direct M'tance hours worked	One of four indicators used for overall maintenance effectiveness indices. Focus on unscheduled tasks	Trend decrease

3.4 Summary

Maintenance organisations have adopted a set of best maintenance practices through the use of maintenance excellence models. Lean enablers/tools that have been used successfully in the manufacturing context are increasingly being used to achieve the level of maintenance excellence desired by an organisation. The most important and most widely used tool in lean thinking thus far has been value stream mapping which has been found to be applicable in non-manufacturing as well as in manufacturing environments where most of its underlying concepts are found. However, some drawbacks have been found to exist with this tool and the methodology of value stream management, which is a holistic approach to value stream mapping, has been found to be useful in addressing the shortcomings. Amongst the various decision-making approaches that exist for optimising and executing lean thinking in maintenance environments, the combined approach of using the Analytic Hierarchy Process (AHP) together with Quality Function Deployment (QFD) has great potential. Metrics for measuring performance in maintenance functions and in measuring attainment of lean thinking in manufacturing environments abound. This is however, not the case for measuring the effect of lean thinking in maintenance environments, where there are no independent performance measures with almost all of them being borrowed from lean manufacturing and TPM.

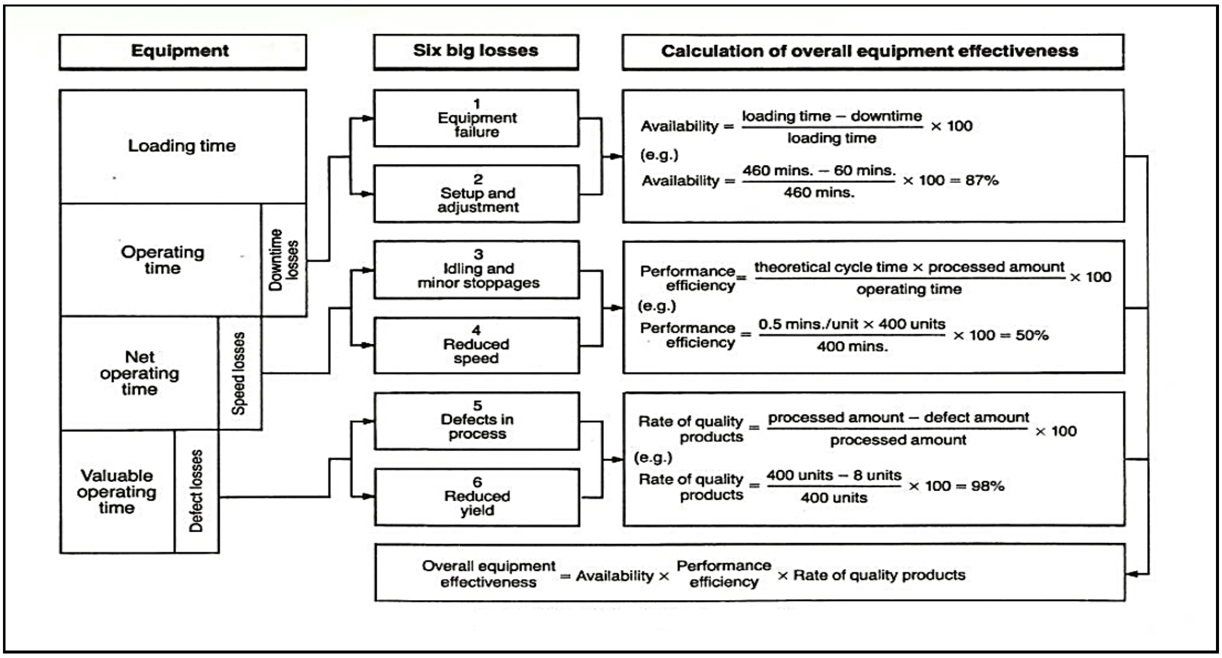

Figure 3.7 Calculation of OEE (Nakajima 1988)

CHAPTER FOUR: CASE STUDY

4.0 Introduction

A case study was chosen for the purposes of developing and testing a framework that can be used to apply lean thinking in a "non-traditional" maintenance environment. The organisation chosen for this purpose is the Rolling Stock division of the Metrorail, Salt River depot. A brief background of Metrorail is given before providing an over-view of the Rolling Stock division of the Salt River depot together with its core operations namely the maintenance, repair and overhaul of traction motors. The supply chain that supports these operations is also described in some detail.

4.1 Company Background

Metrorail is owned by the Passenger Rail Agency of South Africa (PRASA), which in turn is a wholly State-Owned Enterprise (SOE). Metrorail transports over 1.7 million passengers on weekdays in major Metropolitans made out of five regions of South Africa. According to (Metrorail 2012), these five regions combined occupy about 478 stations with a fleet of over 270 train sets making up to 3100 coaches with each coach carrying more than 100 people. Metrorail has the custodianship of all commuter and passenger rail assets such as land in and around stations, infrastructure and rolling stock. Most of its rolling stock is over 35 years old, making it very old and considerably harder to maintain with a large number of failures occurring (PRASA 2010). Most of the failures have been as a result of faulty electronic systems and traction motors. However there were efforts to upgrade the rolling stock through the Accelerated Rolling Stock Investment Programme which should have seen a total of 2000 coaches being upgraded (PRASA 2010).

4.2 Case Study Overview

The case study is carried out at the Rolling Stock division of the Salt River depot which is in the Western Cape region. The site was chosen mainly because of its convenient geographical proximity allowing for frequent visits to gather information for the research study.

4.2.1 Organisation and Structure

Figure 4.1 shows the current management structure at the case study in question. It should be mentioned that this structure is still going through changes as the organisation restructures its operations.

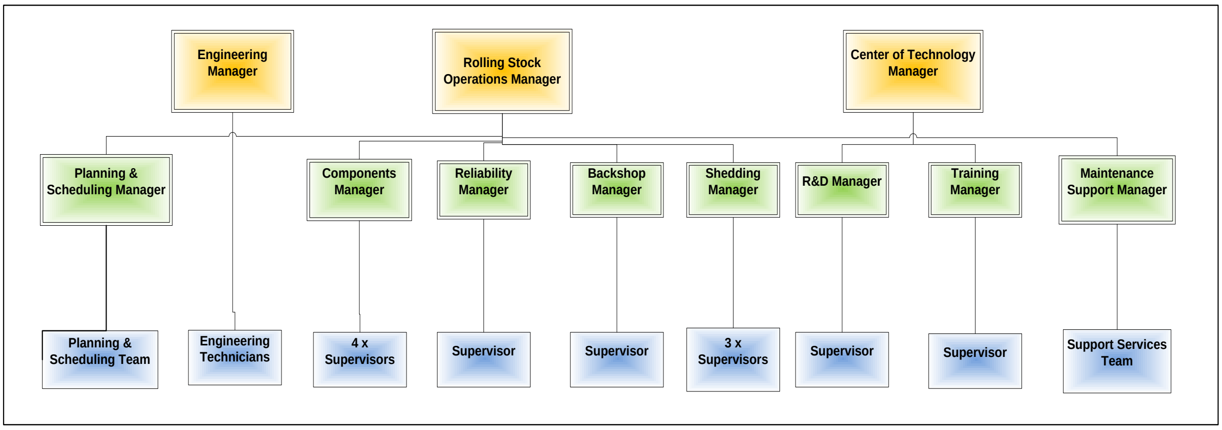

Figure 4.1 Salt River Rolling Stock Organogram

4.2.2 Current Maintenance Policy and Strategies

According to a recent study carried out by (Rommelspacher 2012), the current overall maintenance policy is shared between time directed maintenance (TDM) and run to failure (RTF). TDM is a maintenance policy that uses the hazard function of part failure to determine when a part is replaced based on the organisation's definition of allowable risk (Wessels 2010) and RTF is a maintenance policy that allows a machine to run until it breaks down before repairing it. There is currently a shift within the organisation to move from TDM to Condition Directed maintenance/Predictive maintenance which is a more tactical maintenance policy.

4.3 Traction Motor Workshop

The focus of the study is narrowed down and the maintenance processes in the traction motor workshop are chosen. In this workshop, the motor is stripped and washed and the armature is sent to the winders and the carcass is put in the Hi-Pot area for testing.

4.3.1 General Traction Motor Movements

Movement of the motor from the time that it comes from the lifting shop can be summarised in the following steps:

Step 1: The motor is received with a repairable ticket.

Step 2: At the strip bay the motor is examined and the decision is made whether or not to strip.

Step 3: When stripped, the armature and carcass are sent to the steam generator for cleaning.

Step4: The cleaned components are then sent to the oven for drying.

Step 5: The armature is sent to the armature winders and the carcass is put in the Hi-Pot area for testing.

Step 6: If a fault is found on the carcass, it is sent to the re-fielding bay and repaired and sent back to the Hi-Pot area for testing.

Step 7: The carcass is then sent to the spray booth for insulating.

Step 8: After insulating, the carcass is placed at the assembly area.

Step 9: The assembled motor is placed on the testing stand. Tested and run.

Step 10: The tested motor is either dispatched to a demarcated area in the lifting road or placed in the dispatched area for Transnet.

4.3.2 Armature Repair

Figure 4.2 shows the general process flow for repairing 5M2A motor armatures that are sent to the armature winding section. The times given in the different stages of the process were estimated with the help of experienced technicians on the shop floor since no time studies exist to this regard. Points to note from the process include the following:

- Drying time in the oven is much less during the summer and can be as low as 14 hours.
- If the armature is significantly out of balance, it can take up to half a day to balance it.
- Rewinding is only 1.5 weeks when done internally otherwise it can take much longer when it is outsourced.

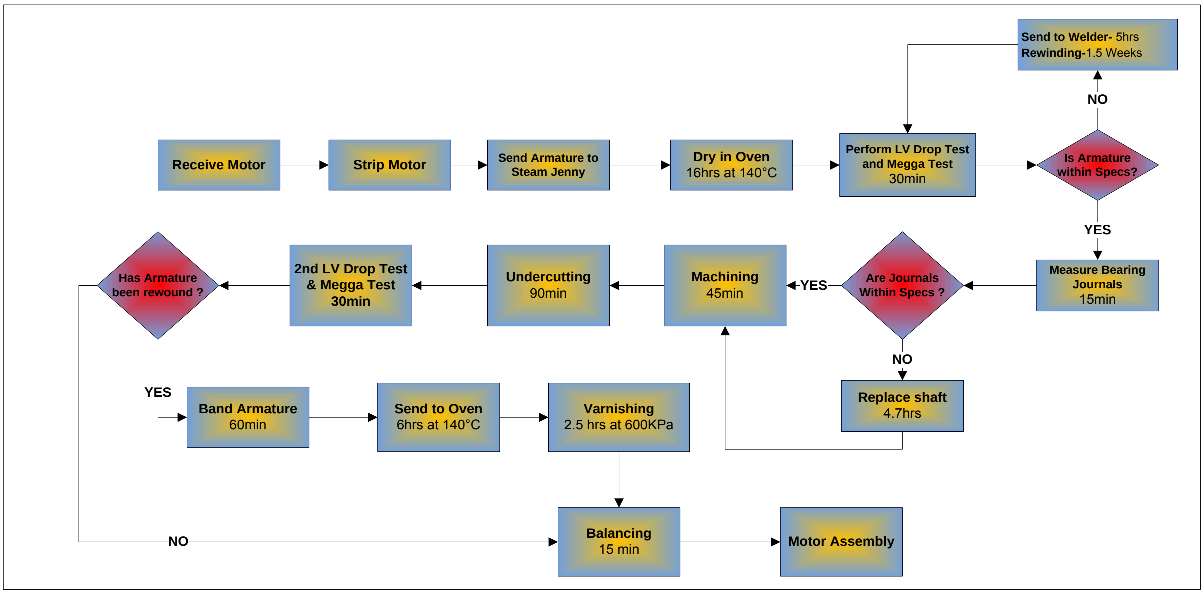

Figure 4.2 General Process Flow for 5M2A Armature Repair

4.3.3 Hi-Pot Testing and Repair

Figure 4.3 shows the general process flow for the hi-pot testing and repair process for the 5M2A motor carcass. Points to consider from this process are:

- Hi-Pot testing is highly dangerous as it involves high voltages and because of this, it is done in a designated area with strict admittance procedures.

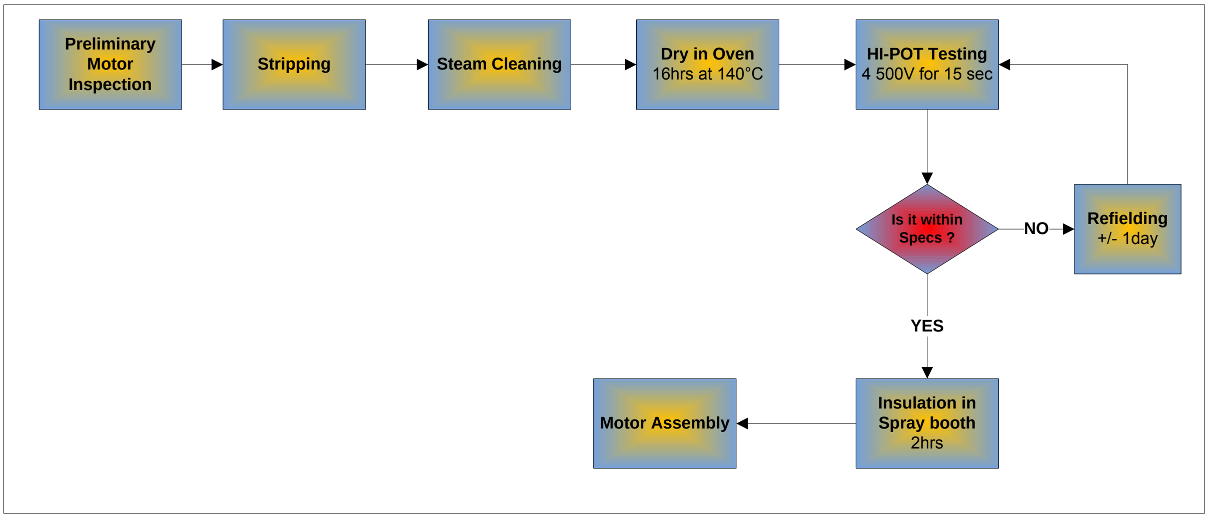

Figure 4.3 General Process Flow for Hi-Pot Testing & Repair of 5M2A Carcass

4.3.4 Assembling Stage

The rewound armature and the tested carcass are brought to the assembly area together with other parts of the motor that have either been washed and refurbished or have been completely replaced. This process is heavily dependent on the availability of the crane as almost all the parts have to be lifted to the assembly area at the exact time that they are needed. For example, the end shields which are heated in the oven have to be lifted to the assembly area when they are still hot and in an expanded state so that bearings can be fitted in. After assembly, the motor has to be tested before it is dispatched. This is done under the following parameters:

Duration: 2 hours at 110V

Speed: 500 rpm

Starting Current: 7 - 12 Amps.

The two main deviations that occur are excessive vibrations and any unusual sounds.

4.4 The Maintenance Supply Chain

4.4.1 Supply Chain Overview

The supply chain of the rolling stock maintenance division at Salt River can be summarised as shown in Figure 4.4.

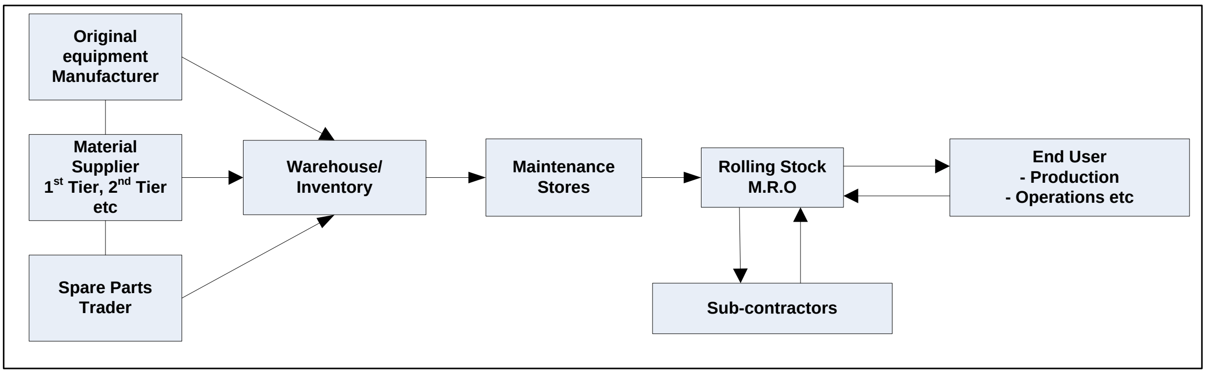

Figure 4.4: Salt River Rolling Stock Supply Chain

4.4.2 Integrated System Procurement Procedure

Figure 4.5 shows the integrated procurement procedure used at the rolling stock division for purchases of between R4001 and R350 000. A separate procedure exists for purchases of between R350 001 and R5 Million and it is shown in APPENDIX B. These procurement procedures are heavily influenced by regulatory frameworks that control how these procedures are to be conducted. An example of a current regulatory framework that Metrorail is abiding by is that of the Preferential Procurement Regulations drafted by the National

Treasury (National Treasury 2009). This particular framework is based on the aims of the Broad Based Black empowerment act and its codes of Good Practice.

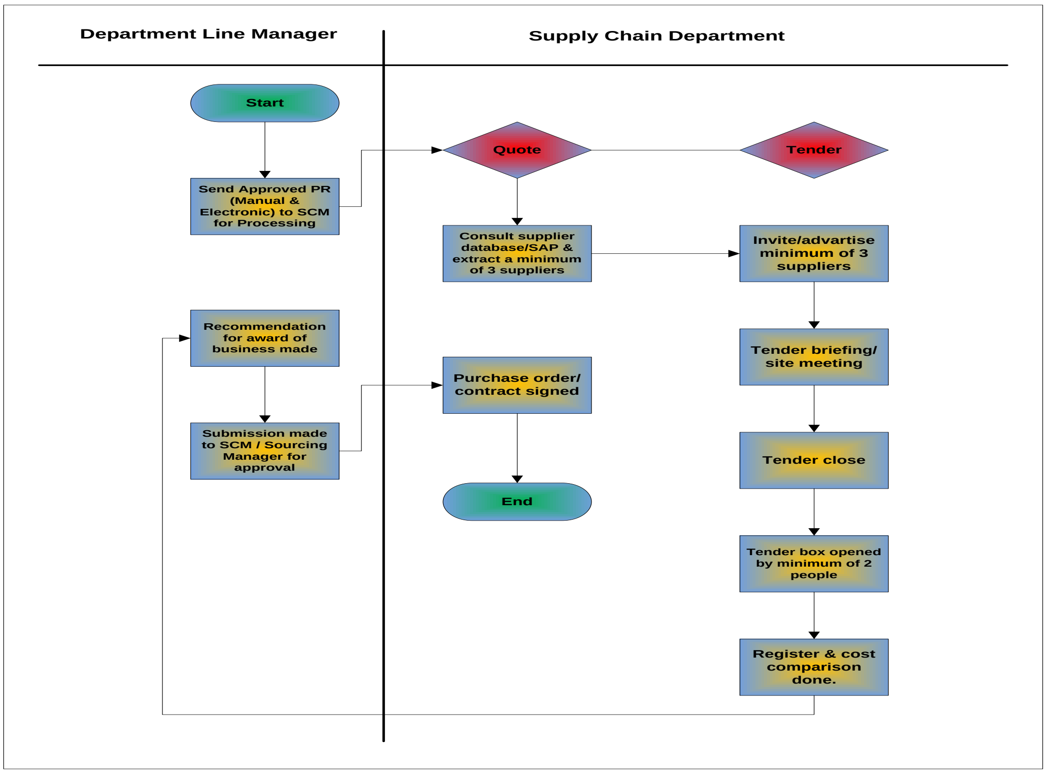

Figure 4.5: Procurement Procedure for Purchases between R4001 and R350 000

4.4.3 Quality Inspection Procedures for Incoming Material

Figure 4.6 shows the procedure for controlling purchasing processes to ensure that the product conforms to requirements. All material is inspected for quality and checked for conformance to prescribed specifications with a criterion for quality assurance having been defined. The Receiving clerk does the initial check for correctness of material and after that, further inspection is done by the materials Quality Management Representative (QMR). The QMR will inspect and employ a sampling method for high volume goods such as bolts, nuts, O-rings, seals generally in excess of 10 items. This sampling involves taking 10% of the quantity received. If 1% or more of the sample quantity does not conform to specified requirements, the order will be rejected.

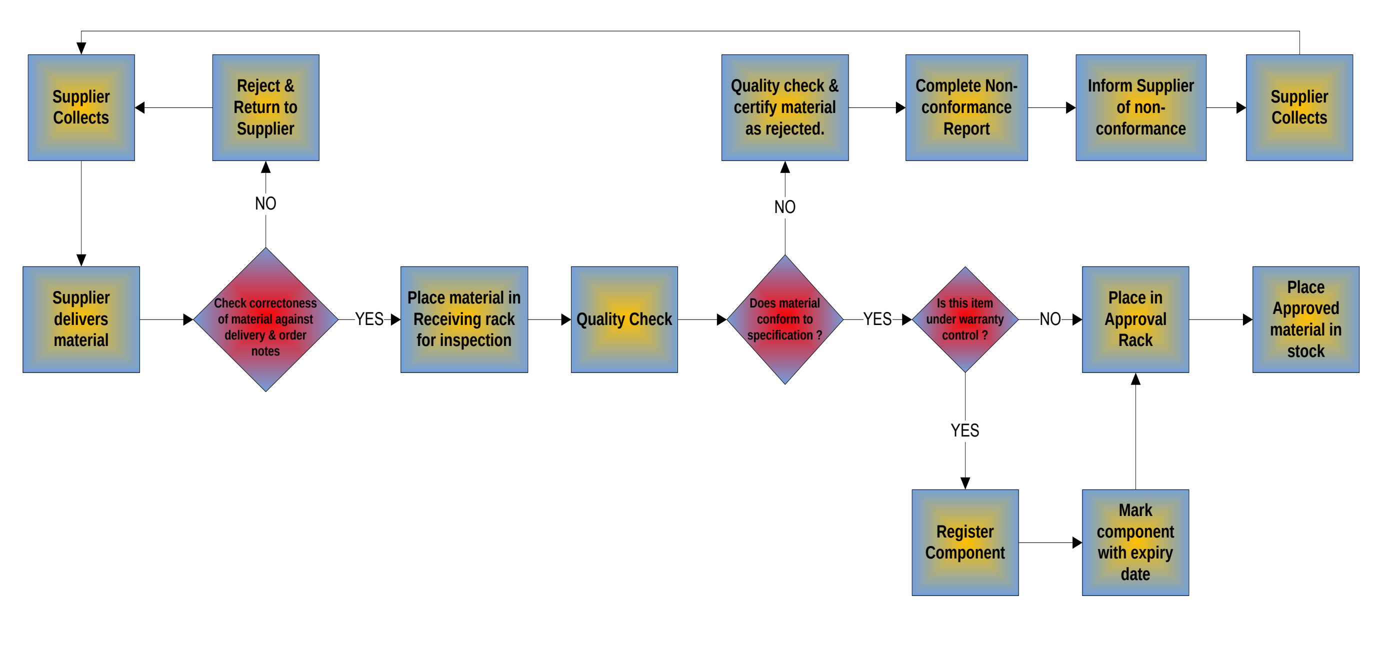

Figure 4.6: Procedure for Controlling Purchasing Processes

A list of components and material essential for the maintenance and repair of the 5M2a motor is given in Table 4.1. This list was still under development by the time of conducting this research and was being drafted by one of the supervisors. It is based largely on his experience of recent problems that they have faced in having these components and material delivered on time to the workshop.

Table 4.1 5M2a Traction Motor List of Essential Components & Material

5M2a Traction Motor List Essential Components & Material		
Pinion End	**Commutator End**	**General**
Bearing inner cap	Arc horn End shield	Saf Power
Pinion end wiper bearing	Bearing inner cap	Grease
Pinion end seal ring	M16 x 35	
Locking plate washer	M16 spring washer	
M30 x 48 bolt	M30 x 48 special bolt	
M12 spring washer	Locking plate washer	
M12 x 30 hex screw		

4.4.4 Contracted Work

The organisation contracts a large portion of its work to contractors and has a set of procedures for carrying out the job. The general procedure involves receiving quotations from potential contractors, creating the order and approving job execution and finally providing feedback on the job performed. APPENDIX B shows detailed procedures for each of these steps where the main players in the various processes are the supply chain manager, maintenance manager and supervisors and the finance manager.

4.5 Current Maintenance Management System

The organisation currently uses a combination of Facility Maintenance Management System (FMMS) and SAP® enterprise software for its management operations. FMMS is currently used for providing and capturing maintenance work orders and for providing a scheduling facility for planned preventive work on major equipment and assets on the one hand. SAP® is used mostly for procurement and inventory management purposes on the other hand. An illustration of how FMMS is integrated into the organisation's operations is shown in APPENDIX B which also shows the general overhaul, heavy repair and contracted repair procedure.

4.6 Summary

An overview of the case study used for the research has been given in this chapter. Firstly, the background of Metrorail is given before focusing on the actual case study which was carried out at the rolling stock division of the Salt River depot. The case study was further narrowed down to focus on the traction motor workshop within the rolling stock division and the traction motor repair process was explained. The supply chain that supports the rolling stock operations is also considered with particular attention being given to the procurement, quality inspection of incoming material and contracting procedures. Finally a brief consideration is given to the computerised maintenance management systems used to manage operations, namely the Facilities Maintenance Management System (FMMS) and SAP® enterprise software. The next chapter focuses on developing a framework that can be used to apply lean thinking in a maintenance environment similar to that in the case study.

CHAPTER FIVE: FRAMEWORK DEVELOPMENT

5.0 Introduction

It has been established from the previous chapters, that not much work has been done in finding ways to implement lean thinking in a non-traditional maintenance environment similar to that found at the Metrorail case study. In light of this knowledge, this chapter focuses on developing a framework that can be used to implement lean thinking in one such context. The Quality Function Deployment (QFD) approach, together with the Analytic Hierarchy Process (AHP) technique, is used to develop and verify certain key elements of the framework. This is done after having conducted a survey, coupled with interviews and physical observations on the shop floor of the case study. The chapter ends by proposing a supporting framework to apply lean thinking in the case study's maintenance supply chain.

5.1 Maintenance Excellence Survey

A Maintenance excellence survey, which is found in APPENDIX A, was carried out in order to provide input (WHATs) for the QFD model that was used to develop the framework. The survey constituted of a set of questions derived from maintenance excellence practices in literature and also from observations at the case study involved (see Chapters 3 and 4). Management and supervisors of the relevant sections were asked to fill out the questionnaires giving an indication of where they perceived the organisation to be; in as far as each maintenance excellence practice is concerned.

Table 5.1 shows the results of the survey conducted at the Rolling Stock division of Metrorail, Salt River with Table 5.2 showing the sample of respondents together with their respective sections. The Priority Scores were obtained by first assigning weights of 1, 2, 3, 4, and 5 for the reactions "Excellent", "Good", "Average", "Poor" and "Bad" respectively. These weights were then multiplied by the number of responses and then added together to give the final score. An example of such a calculation is given below for the weighting of "Spare Parts and Material Availability":

$$\text{"Excellent"} \times 1 + \text{"Good"} \times 2 + \text{"Average"} \times 3 + \text{"Poor"} \times 4 + \text{"Bad"} \times 5$$
$$= 0 \times 1 + 1 \times 2 + 2 \times 3 + 10 \times 4 + 4 \times 5$$
$$\underline{\mathbf{= 68}}$$

Table 5.1 Respondents' Results and Weighting

		Number of Responses						
Serial Number	ME Practice	Excellent	Good	Average	Poor	Bad	Priority Scores	Rank
1	**CI**		6	8	3		48	**11**
2	**FMMS**	1	1	5	8	2	60	**2**
3	**SC**	3	9	4	1		37	**15**
4	**DOP**	3	6	7	1		40	**14**
5	**MGT**		5	8	4		50	**9**
6	**SP**		1	2	10	4	68	**1**
7	**WO**		2	10	4		50	**9**
8	**MAINT**		5	8	5		54	**6**
9	**SKILLS**		4	10	1	1	47	**13**
10	**POL**		2	10	5		54	**6**
11	**CONTR 1**		3	13	3		57	**4**
12	**CONTR 2**	1	6	7	5		54	**6**
13	**KPI**		3	4	9	1	59	**3**
14	**WI**		2	8	5		48	**11**
15	**QUAL**		6	8	3		48	**11**

Table 5.2 Survey Sample Profile

Section	Respondents
Components Shop	1 Manager & 2 Supervisors
Reliability Shop	1 Manager & 2 Supervisors
Engineering	1 Manager
Support Services	1 Manager & 2 Supervisors
Research & Development	1 Manager & 2 Supervisors
Lifting Shop	1 Manager & 2 Supervisors
Training	1 Manager

In order to determine the consistency of the results of the survey, a Pairwise comparison based on the Priority Scores was made using the Analytic Hierarchy Process (AHP). Figure 5.1 shows a pairwise comparison matrix constructed according to Eqn. (3.3) for these scores.

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL
CI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
FMMS	7	1	9	7	5	1/5	5	5	7	5	3	5	3	7	7
SC	1/7	1/9	1	1/3	1/7	1/9	1/7	1/7	1/5	1/7	1/7	1/7	1/9	1/7	1/7
DOP	1/5	1/7	3	1	1/5	1/9	1/5	1/7	1/5	1/7	1/7	1/7	1/7	1/5	1/5
MGT	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
SP	7	5	9	9	7	1	7	7	9	7	7	7	5	7	7
WO	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
MAINT	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
SKILLS	1/3	1/7	5	5	1/3	1/9	1/3	1/5	1	1/5	1/5	1/5	1/7	1/3	1/3
POL	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
CONTR 1	5	1/3	7	7	5	1/7	5	3	5	3	1	3	1/3	5	5
CONTR 2	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
KPI	7	1/3	9	7	5	1/5	5	3	7	3	3	3	1	7	7
WI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
QUAL	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1

KEY:

CI	Continuous Improvement Efforts
FMMS	Use of FMMS/SAP
SC	Schedule Compliance
DOP	Detailed Operating Procedures
MGT	Management Support
SP	Spare Parts and Material Availability
WO	Work Orders/ Job Cards
MAINT	Maintenance Organisation & Structure
SKILLS	Personnel Skills Training
POL	Maintenance Policy & Strategy
CONTR 1	Maintenance Contracting 1
CONTR 2	Maintenance Contracting 2
KPI	Key Performance Indicators
WI	Workforce Involvement
QUAL	Conformance Quality

Figure 5.1 ME Pairwise Comparison Matrix

This matrix is then normalised and gives the new Matrix according to Eqn. (3.4) as shown in Figure 5.2.

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL
CI	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02
FMMS	0.14	0.12	0.09	0.09	0.14	0.07	0.14	0.22	0.12	0.22	0.18	0.22	0.26	0.14	0.14
SC	0.00	0.01	0.01	0.00	0.00	0.04	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00
DOP	0.00	0.02	0.03	0.01	0.01	0.04	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00
MGT	0.06	0.02	0.07	0.06	0.03	0.05	0.03	0.01	0.05	0.01	0.01	0.01	0.02	0.06	0.06
SP	0.14	0.59	0.09	0.11	0.20	0.33	0.20	0.31	0.15	0.31	0.42	0.31	0.43	0.14	0.14
WO	0.06	0.02	0.07	0.06	0.03	0.05	0.03	0.01	0.05	0.01	0.01	0.01	0.02	0.06	0.06
MAINT	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10
SKILLS	0.01	0.02	0.05	0.06	0.01	0.04	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01
POL	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10
CONTR 1	0.10	0.04	0.07	0.09	0.14	0.05	0.14	0.13	0.08	0.13	0.06	0.13	0.03	0.10	0.10
CONTR 2	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10
KPI	0.14	0.04	0.09	0.09	0.14	0.07	0.14	0.13	0.12	0.13	0.18	0.13	0.09	0.14	0.14
WI	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02
QUAL	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02

Figure 5.2 Normalised ME Comparison Matrix

The importance weighting of each ME criterion is then derived from this matrix according to Eqn. (3.5) and the consistency measures according to Eqn. (3.6). These are displayed in Table 5.3 where they are ranked from the one with the highest ranking to the one with the lowest.

The Consistency Index is calculated from Eqn. (3.7) where δ is given by Eqn. (3.6) and is equal to 17.45 and $m = 15$, thus giving:

$$\boldsymbol{CI} = \frac{17.45 - 15}{15 - 1}$$
$$= \mathbf{0.175}$$

Table 5.3 Importance Weighting of ME Criterion

ME Criterion	Importance Weighting	Consistency Measure	Rank
Spare Parts and Material Availability	0.26	19.33	**1**
Use of FMMS/SAP	0.15	19.54	**2**
Key Performance Indicators	0.12	19.12	**3**
Maintenance Contracting 1	0.09	19.01	**4**
Maintenance Organisation & Structure	0.06	18.00	**6**
Policy and Strategy	0.06	18.00	**6**
Maintenance Contracting 2	0.06	18.00	**6**
Management Support	0.04	17.06	**9**
Comprehensive Work Orders	0.04	17.06	**9**
Continuous Improvement Efforts	0.03	15.89	**11**
Workforce Involvement	0.03	15.89	**11**
Conformance Quality	0.03	15.89	**11**
Personnel Skills Training	0.02	15.85	**13**
Detailed Operating Procedures	0.01	16.29	**14**
Schedule Compliance	0.01	16.85	**15**

For m = 15, we have $\boldsymbol{RI}$ given by 1.59. This gives a Consistency Ratio of:

$$\frac{0.18}{1.59}$$
$$\underline{= \mathbf{0.11}}$$

The value of 0.11 is just outside the scope of the acceptable threshold value of 0.10. There is therefore a need to revise the judgements made so that they fall within the acceptable limits and to do that, Method 3 from Section 3.3.1 is used. This yields the results shown in Table 5.4

Table 5.4 Revised ME Importance Weightings

ME Criterion	Importance Weighting	Consistency Measure	Rank
Spare Parts and Material Availability	0.17	16.96	1
Key Performance Indicators	0.15	18.05	2
Maintenance Contracting 1	0.12	18.06	3
Use of FMMS/SAP	0.11	17.30	4
Maintenance Organisation & Structure	0.08	17.33	5
Policy and Strategy	0.08	17.33	6
Maintenance Contracting 2	0.08	17.33	7
Comprehensive Work Orders	0.06	15.19	8
Management Support	0.04	16.47	9
Continuous Improvement Efforts	0.03	15.77	10
Workforce Involvement	0.03	15.77	11
Conformance Quality	0.03	15.77	12
Personnel Skills Training	0.02	15.88	13
Detailed Operating Procedures	0.01	15.09	14
Schedule Compliance	0.01	14.73	15

Figure 5.3 shows the difference between the values of the original importance weightings and the revised ones.

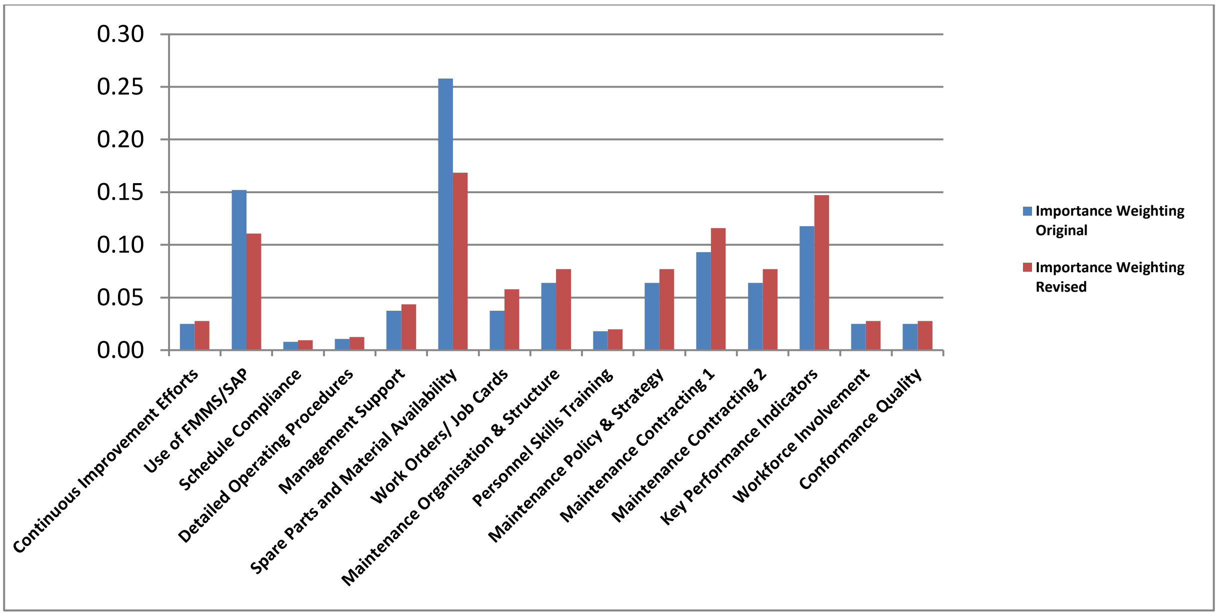

Figure 5.3 Revised vs. Original Importance Weightings

The Consistency Index is calculated from Eqn. (3.7) where δ is given by Eqn. (3.6) and is equal to 16.47 and $m = 15$, thus giving:

$$\boldsymbol{CI} = \frac{16.47 - 15}{15 - 1}$$

$$= \mathbf{0.105}$$

For m = 15, we have $\boldsymbol{RI}$ given by 1.59. This gives a Consistency Ratio of:

$$\frac{0.105}{1.59}$$

$$\underline{= \mathbf{0.07}}$$

The new value for the consistency ratio is below the threshold of 0.10 hence giving acceptability to our pairwise comparison.

5.2 AHP-QFD Implementation

5.2.1 H.O.Q for M.E. vs. Lean Enablers

After having identified a set of maintenance excellence criteria that are imperative if a maintenance organisation is to achieve best maintenance standards, the next step is to identify lean enablers (LEs) that would allow the organisation to meet those standards in a manner that eliminates waste and adds value. The LEs are identified from literature and are then used as input (HOWs) in an HOQ that had the ME criteria as the WHATs as shown in Figure 5.4. The importance degree of the LEs is calculated according to Eqn. (3.8) where the numerical scale of the relationships between the LE and the ME Criteria is 1-3-9 for the Weak, Strong and Medium relationships respectively and the importance weightings of ME criteria are taken from Table 5.4. The normalised importance degree is calculated from Eqn. (3.9) and the results are ranked from the one with the highest degree to the one with the lowest.

	Kaizen	Kanban	Visual Management	Just In Time	Variability Reduction/Standardisation	Hoshin	Balanced Scorecard	Jidoki/ Poka-Yoke	5S	Importance Weighting of ME Practice
Continuous Improvement Efforts	●		□		●	●	●	●	●	0.03
Use of FMMS/SAP	□	□	○	○			○	○	□	0.15
Schedule Complaince	○	●	□	●	○	□	●	□	□	0.01
Detailed Operating Procedures			●		●	○		□	●	0.01
Management Support			□			●	□		□	0.04
Spare Parts and Material Availability	○	●	○	●	□		○		□	0.26
Comprehensive Work Orders	○	□	□		□	○		□	●	0.04
Maintenance Organisation & Structure	○		□			●	□		□	0.06
Personnel Skills Training	●		○		□	□	●	○	□	0.02
Policy and Strategy	□		●		□	●	□		●	0.06
Maintenance Contracting	○	○		●	○		□	□	□	0.08
Key Performance Indicators	●		●		●	□	●	□	□	0.12
Workforce Involvement	●		●		○	●	●		□	0.03
Conformance Quality	●		○	□	●	○	●	●	●	0.03
Importance Degree of Lean Approach	2.99	3.04	2.93	3.33	2.85	2.45	3.11	1.35	3.74	
Normailsed Importance Degree	0.12	0.12	0.11	0.13	0.11	0.09	0.12	0.05	0.14	
Rank	5	4	6	2	7	8	3	9	1	

Key

- ○ Weak relationship
- □ Medium relationship
- ● Strong Relationship

Figure 5.4 ME Criteria vs. LE HOQ Matrix

5.2.2 Lean Tools Pairwise Comparison

A Pairwise comparison of each of the LEs was then made using AHP in order to see if there would be any consistency in the judgements of the importance degrees derived from the HOQ. Table 5.1 is once again used to determine the scale of importance of the LEs with respect to each other. Figure 5.5 shows a pairwise compassion matrix constructed according to Eqn. (3.3) for these scores. Microsoft Excel 2010 ® was used to perform these calculations and some of the key cell formulae can be found in Appendix F.

	KAI	KAN	VIS	JIT	STA	HOS	BAL	PKY	5S
KAI	1	1/3	3	1/3	3	5	1/3	7	1/5
KAN	3	1	3	1/3	3	5	1/3	7	1/5
VIS	1/3	1/3	1	1/3	3	3	1/3	7	1/5
JIT	3	3	3	1	3	5	3	7	1/3
STA	1/3	1/3	1/3	1/3	1	3	1/3	7	1/5
HOS	1/5	1/5	1/3	1/5	1/3	1	1/5	7	1/7
BAL	3	3	3	1/3	3	5	1	7	1/5
PKY	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1	1/7
5S	5	5	5	3	5	7	5	7	1

KEY:

KAI	Kaizen
KAN	Kanban
VIS	Visual Management
JIT	Just In Time
STA	Standardisation
HOS	Hoshin
BAL	Balanced Scorecard
PKY	Poka-Yoke
5S	5S

Figure 5.5 LE Pairwise Comparison Matrix

This matrix is then normalised and gives the new Matrix according to Eqn. (3.4) as shown in Figure 5.6.

	KAI	KAN	VIS	JIT	STA	HOS	BAL	PKY	5S
KAI	0.06	0.02	0.16	0.06	0.14	0.15	0.03	0.12	0.08
KAN	0.19	0.07	0.16	0.06	0.14	0.15	0.03	0.12	0.08
VIS	0.02	0.02	0.05	0.06	0.14	0.09	0.03	0.12	0.08
JIT	0.19	0.22	0.16	0.17	0.14	0.15	0.28	0.12	0.13
STA	0.02	0.02	0.02	0.06	0.05	0.09	0.03	0.12	0.08
HOS	0.01	0.01	0.02	0.03	0.02	0.03	0.02	0.12	0.05
BAL	0.19	0.22	0.16	0.06	0.14	0.15	0.09	0.12	0.08
PKY	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.02	0.05
5S	0.31	0.37	0.27	0.50	0.23	0.21	0.47	0.12	0.38

Figure 5.6 Normalised LE Pairwise Comparison Matrix

The importance weighting of each LE is then derived from this matrix according to Eqn. (3.5) and the consistency measures according to Eqn. (3.6). These are displayed in Table 5.5 in order of rank from the one with the highest importance weighting to the one with the lowest.

Table 5.5 LE Importance Weightings

Lean Enabler	Importance Weighting	Consistency Measure	Rank
5S	0.32	10.96	**1**
Just In Time	0.17	11.24	**2**
Balanced Scorecard	0.13	11.32	**3**
Kanban	0.11	10.93	**4**
Kaizen	0.09	10.45	**5**
Visual Management	0.07	10.04	**6**
Standardisation	0.05	9.87	**7**
Hoshin	0.04	9.52	**8**
Poka-Yoke	0.02	9.59	**9**

The Consistency Index is calculated from Eqn. (3.7) where δ is given by Eqn. (3.6) and is equal to 10.43 and $= 9$, thus giving:

$$\boldsymbol{CI} = \frac{10.43 - 9}{9 - 1}$$
$$= \mathbf{0.179}$$

For m = 9, we have $\boldsymbol{RI}$ given by 1.45. This gives a Consistency Ratio of:

$$\frac{0.179}{1.45}$$
$$\underline{= \mathbf{0.12}}$$

The value of 0.12 is a little over the acceptable threshold of 0.10 but by following a procedure similar to that revising the judgements for the ME Criteria, the value can be reduced to 0.04 with the importance weightings as shown in Table 5.6:

Table 5.6 Revised LE Importance Weightings

Lean Enabler	Importance Weighting	Consistency Measure	Rank
Balanced Scorecard	0.25	10.40	**1**
Visual Management	0.18	10.59	**2**
5S	0.15	11.28	**3**
Kaizen	0.15	10.03	**4**
Standardisation	0.10	9.69	**5**
Hoshin	0.08	9.66	**6**
Just In Time	0.04	7.74	**7**
Kanban	0.04	8.50	**8**
Poka-Yoke	0.02	7.04	**9**

The changes that occur in this revised judgement are illustrated in the chart shown in Figure 5.7.

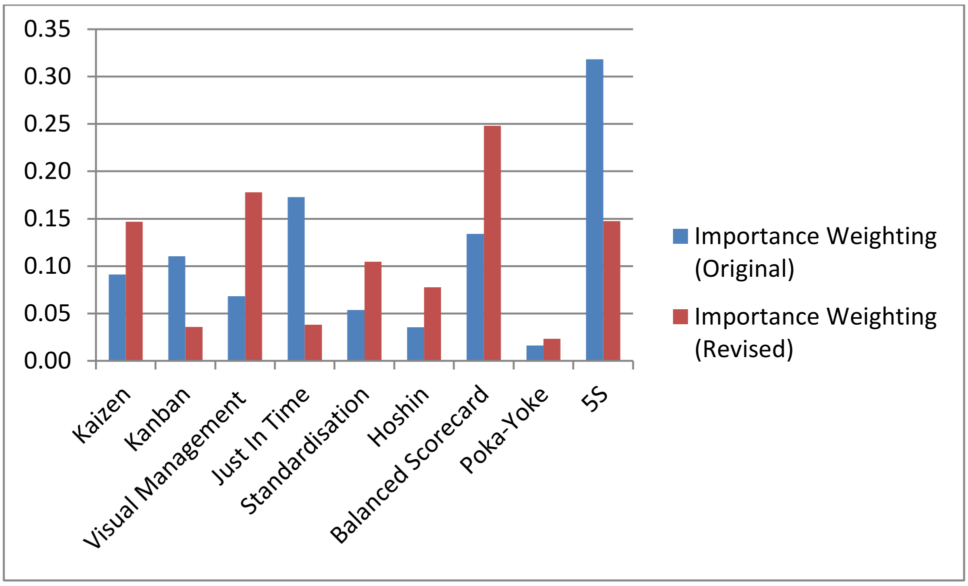

Figure 5.7 Revised vs. Original LE Weightings

5.3 Framework

The framework presented in this section addresses the question of how lean thinking can be used in a non-traditional maintenance environment. It is loosely based on the five lean principles as given by (Womack & Jones 2003), emphasised by (Bicheno 2004) and many others and it is adapted to fit within the non-traditional maintenance environment.

5.3.1 Framework Variables

Given in Figure 5.8 is a diagrammatic representation of the proposed framework and what follows is a discussion of the various elements within the framework.

Maintenance Excellence Criteria

A set of MEs are selected based on theoretical evidence and are verified through the combined QFD-AHP approach as has been discussed in the previous sections. The QFD-AHP approach also helped to rank these MEs in order to determine which are more relevant and urgent in the organisation's context. This set of criteria acts as the baseline on which any intervention is going to be carried out.

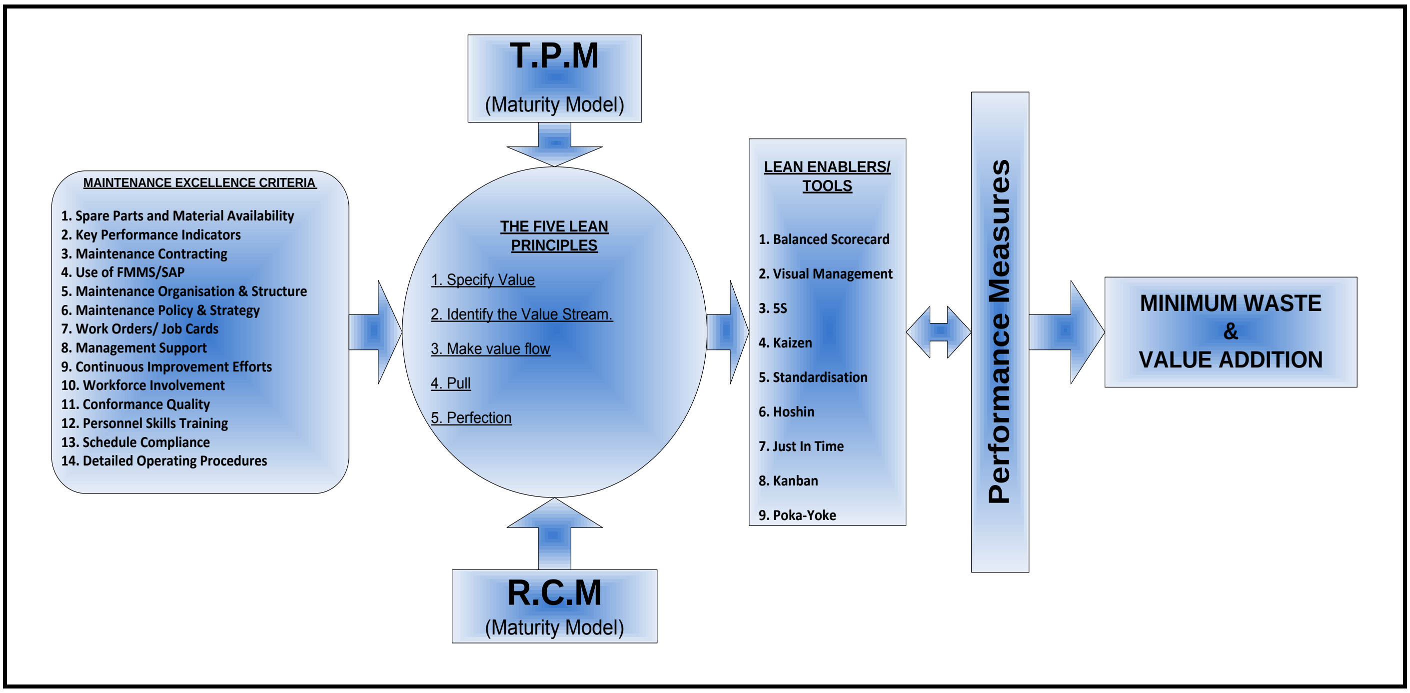

Figure 5.8: Framework for Lean Thinking in Maintenance

The Five Lean Principles

The Five Lean Principles act as the intervention that will go towards implementing lean thinking within an organisation. These lean principles are:

1. *Specify Value*

Value has to be specified from the view-point of the customer, which can be the next process, or next company along the chain, or the customer's customer.

2. *Identify the Value Stream*

This is the sequence of processes all the way from raw material to final customer, or from product concept to market launch. This should be seen from the view-point of the customer and not the view-point of the process. This value stream should then be mapped.

3. *Make Value Flow*

This principle is meant to avoid or continuously reduce batches and queues so that value-adding steps are not delayed by non-value-adding steps.

4. *Pull*

This means developing short-term response to the customer's rate of demand, and not over producing. This needs to take place along the whole demand flow network.

5. *Perfection*

Perfection means producing exactly what the customer wants, exactly when, at a fair price and with minimum waste.

TPM and RCM

As has been discussed earlier (Chapter 2), the very foundation of lean maintenance is Total Productive Maintenance (TPM) and in order to 'fine-tune' TPM, there is need to initiate Reliability Centred Maintenance (RCM). In order to determine the level of maturity in as far as the implementation of TPM is concerned, a maturity table as shown in Table 5.7 is proposed. This is based on the four developmental stages of TPM as determined by (Nakajima 1988). And for TPM to be successfully implemented, eight "pillars" were formulated by the Japan Institute for plant technology and these are namely (Ahuja & Khamba 2007):

1) Autonomous Maintenance – fostering operator skills.
2) Individual improvement – systematic identification and elimination of losses.
3) Planned maintenance – planning efficient and effective preventive maintenance systems.
4) Quality maintenance-achieving zero defects.

5) Education and training – imparting technological, quality control and interpersonal skills.
6) Safety health and environment – ensure safe and appropriate working environment.
7) Office TPM – improve synergy between various business functions.
8) Development management/5S – maintenance improvement initiatives.

Table 5.7 Developmental Stages of TPM (Nakajima 1988)

Stage #	Name	Description
I	**Breakdown Maintenance**	Maintenance personnel take action only if the machine or equipment is broken and production has stopped.
II	**Preventive Maintenance**	Maintenance work is programmed on a regular basis to inspect equipment, uncover potential problems and make necessary repairs so that the system does not fail during normal operations.
III	**Productive Maintenance**	A maintenance plan for the equipment's entire lifespan is established. It includes maintenance prevention during the equipment design stages and repairing or modifying equipment to prevent breakdowns and facilitate ease of maintenance during the equipment's latter stages.
IV	**TPM**	A team of maintenance staff re-design and reconfigure equipment to make it more reliable and easier to maintain and operators perform basic equipment repairs.

(Hauge & Mercier 2003) present a RCM Maturity Level Roadmap which is based on the Carnegie Mellon University Software engineering Institute Capabilities Maturity Model® (CMM®). The roadmap consists of five levels ranging from *Initial (Level I)* to *Continuous Improvement (Level V)* as illustrated in Figure 5.9. This roadmap is proposed as part of the overall framework being developed. What follows is a description of each of these levels:

Initial (Level I) – maintenance processes are considered ad-hoc and occasionally chaotic. The processes are poorly defined and success depends upon individual effort and heroics. Basic RCM training is in place and trainees have a basic understanding of RCM concepts, fundamentals, and existing analysis documentation methods.

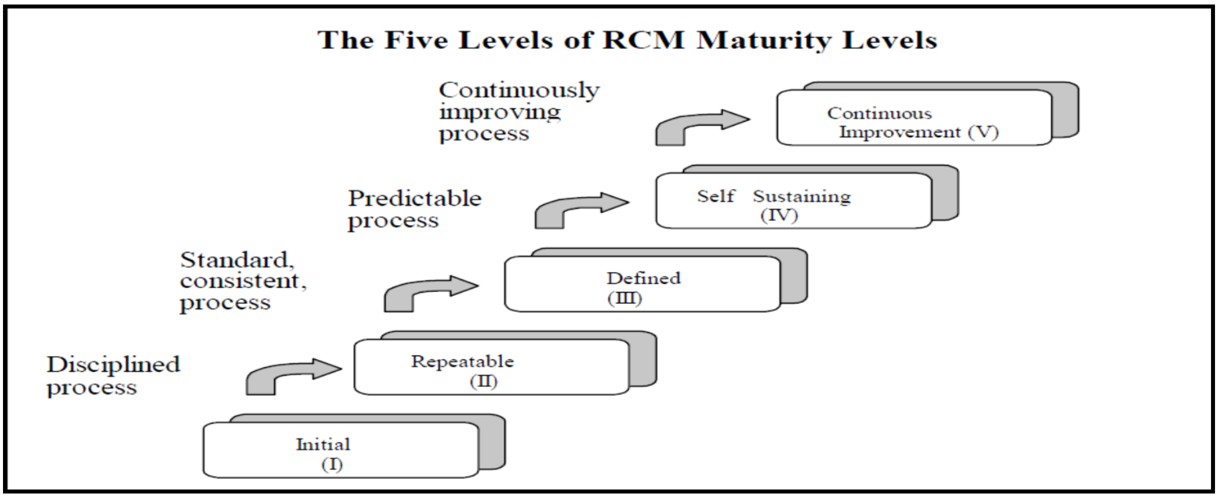

Figure 5.9 Five Levels of RCM Maturity (Hauge & Mercier 2003)

Repeatable (Level II) – Basic RCM management processes are established to track analysis, training, mentoring and facilitation, analysis documentation, metrics and living process. The necessary process discipline is in place to repeat previous successes on RCM projects. Analysis results are contained in a searchable electronic database, which supports metrics, audits and feedback process.

Defined (Level III) – the RCM process for managers, engineers and maintainers is documented, standardised, integrated and practised by the organisation. All RCM projects use an approved version of the organisation's standard RCM process for developing and maintaining maintenance procedures. The analysis documentation is contained in a relational database format.

Self-Sustaining (Level IV) – it is characterised by having detailed measures of the RCM process and product quality collected. Both the RCM process and the product are quantitatively and qualitatively understood and controlled. The training and audit infrastructure is in place and effective at all levels of the organisation. The RCM analysis documentation data systems are integrated.

Continuous Improvement (Level V) – this level is enabled by quantitative and qualitative feedback from the process. Improvements are energised through innovation and technology. There is also use of web enabled enterprise systems, integrating analysis, financial, maintenance, and logistics data systems.

The Society of Automotive Engineers developed a standard that defines the RCM process as asking seven basic questions (Kister & Hawkins 2006):

1) What are the functions and associated performance standards of the asset in its present operating context?
2) In what ways can it fail to fulfil its functions?
3) What causes each functional failure?
4) What happens when each failure occurs?
5) In what ways does each failure matter?
6) What can be done to predict or prevent each failure?
7) What should be done if a suitable proactive task cannot be found?

Lean Enablers/ Tools

These have been discussed in Chapter 3 and emanate from the five lean principles. They are the instruments through which lean thinking will be applied in the organisation. They are ranked according to order of importance or relevance to the context of the case study.

Performance Measures

Specific performance measures linked to lean thinking must be used in order to gauge progress that the organisation is making towards achieving leanness. This is a process that will require constantly referring back to the lean Tools depending on the lean goals that the organisation has set for itself

5.3.2 Assigning Performance Measures

In this section performance measures are assigned to the various Maintenance Excellence criteria and their associated lean tools. Table 5.8 shows each set of ME criteria with the lean tools that are relevant to it and the performance measures that are used to monitor progress towards achieving it. The table also ranks the MEs according to the importance weightings obtained from the previous sections. A description of the various performance measures and their respective calculations is given in APPENDIX C**.**

5.3.3 Developing a Lean Maintenance Supply Chain

In the top five most important ME criteria, there is “Spare Parts and Material Availability” which is ranked 1st, and “Maintenance Contracting”, which is ranked 4th. These two criteria are a direct result of the organisation’s supply chain management efforts. This means that there is a need to execute the whole supply chain and using the concepts of lean thinking if the organisation will truly become lean. This is a view shared by (Kister & Hawkins 2006) who state that lean is a comprehensive package that must include a lean supply chain.

5.4.4.1 Supply Chain Maturity

According to (Poirier 2004), an organisation goes through five levels of supply chain development until it has the optimal business supply chain model. These five levels are:

Level 1: Internal/functional – this level focuses on sourcing and logistics, concentrating on internal needs and business unit efficiency, while neglecting organisational synergies.

Level 2: Internal/Cross-functional – this level focuses on internal excellence, breaking down the internal walls and beginning intra-enterprise integration. The organisation starts to move away from a functional organisational structure and begins building a foundation for an optimised internal supply chain.

Level 3: External Network Formation – this level focuses on the customer through collaboration with selected partners. The company begins to link its processes with selected customers via the previous market segmentation, whilst eliciting the help of a few key suppliers to make sure that orders are fulfilled.

Table 5.8 Assigning Performance Measures to ME Criteria

Rank	Maintenance Excellence Criteria	Lean Tool(s)	Performance Measures
1	Spare Parts and Material Availability	Kaizen, Kanban, Visual Management, Just In Time, Standardisation, Balanced Scorecard, 5S	Stores service level, Inventory accuracy, Breakdown repair hours, Equipment availability
2	Key Performance Indicators	Kaizen, Visual Management, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	OEE
3	Use of FMMS/SAP	Kaizen, Kanban, Visual Management, Just In Time, Balanced Scorecard, Poka-Yoke, 5S	OEE, Equipment Availability
4	Maintenance Contracting	Kaizen, Kanban, Just In Time, Standardisation, Balanced Scorecard, Poka-Yoke, 5S	Perfect customer order rates, Equipment availability, Maintenance hours applied, Contractor Cost as Percent of Maintenance Cost Total Maintenance Cost
5	Maintenance Policy & Strategy	Kaizen, Visual Management, Standardisation, Hoshin, Balanced Scorecard, 5S	PPM Work orders vs. CM Work orders, Degree of Scheduling
5	Maintenance Organisation & Structure	Kaizen, Visual Management, Hoshin, Balanced Scorecard, 5S	Cost of maintenance hours, Crew efficiency
7	Work Orders/ Job Cards	Kaizen, Kanban, Visual Management, Just In Time, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	Overdue Tasks, Work orders turnover, PPM Work orders vs. CM Work orders.
8	Management Support	Visual Management, Standardisation, Hoshin, Balanced Scorecard, 5S	Manpower Efficiency, Maintenance control
9	Continuous Improvement Efforts	Kaizen, Visual Management, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	OEE, Breakdown frequency, Equipment availability, Cost of Maintenance hours
9	Conformance Quality	Kaizen, Visual Management, Just In Time, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	MTBF, MTTR, MTBR, OEE
9	Workforce Involvement	Kaizen, Visual Management, Standardisation, Hoshin, Balanced Scorecard, 5S	Crew efficiency
12	Personnel Skills Training	Kaizen, Visual Management, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	Manpower Efficiency, Overtime
13	Detailed Operating Procedures	Visual Management, Standardisation, Hoshin, Poka-Yoke, 5S	Manpower Efficiency, Maintenance hours applied, Emergency man hours, Work order discipline
14	Schedule Compliance	Kaizen, Kanban, Visual Management, Just In Time, Standardisation, Hoshin, Balanced Scorecard, Poka-Yoke, 5S	Manpower efficiency, Degree of Scheduling, Planned work,

Level 4: External Value Chain – this level focuses on the consumer with partners and establishes inter-enterprise synchronisation. The organisation is now part of constellation of companies that represent the end-to-end value chain, with all of its complexities understood and under an overall improvement effort.

Level 5: Full Network Connectivity – this level focuses on cyber technology as the value chain enabler to achieve network optimisation. Supply chain visibility is achieved, inventories are viewed on a real time basis, and forecasting error is reduced to workable levels or banished in favour of direct linkage to consumption.

Figure 5.10 shows an overview of the major business applications matched with the five levels of supply chain maturity. The changes in roles and activities that take place in these business applications are matched to the various levels of progress.

Progression / Business Applications	Levels 1 & 2 Internal Supply Chain Optimization	Level 3 External Network Formation	Level 4 Value Chain Constellation	Level 5 Full Network Connectivity
	Supply Chain Optimization	Advanced Supply Chain Management	e-Commerce	e-Business
Design, Development Product/Service Introduction	Internal Only	Selected External Assistance	Collaborative Design – Enterprise Integration and PIM-Linked CAD/CAM	Business Functional View – Joint Design and Development
Purchase, Procurement, Sourcing	Leverage Business Unit Volume	Leverage Full Network Through Aggregation	Key Supplier Assistance, Web-Based Sourcing	Network Sourcing Through Best Constituent
Marketing, Sales, Customer Service	Internally Developed Programs, Promotions	Customer-Focused, Data-Based Initiatives	Collaborative Development for Focused Consumer Base	Consumer Response System Across the Value Chain
Engineering, Planning, Scheduling, Manufacturing	MRP MRPII DRP	ERP – Internal Connectivity	Collaborative Network Planning – Best Asset Utilization	Full Network Business System Optimization Shared Processes and Systems
Logistics	Manufacturing Push – Inventory-Intensive	Pull System Through Internal/External Providers	Best Constituent Provider	Total Network, Virtual Logistics Optimization
Customer Care	Customer Service Reaction	Focused Service – Call Centers	Segmented Response System, Customer Relationship Management	Matched Care – Customer Care Automation and Remediation
Human Resources	Regulatory Issues/Hiring, Recruiting, Training	New Work Models, Training	Inter-Enterprise Resource Utilization, Training	Full Network Alignment and Capability Provision
Information Technology	Point Solutions Internal Silos	Linked Intranets Corp Strategy/Architecture	Internet-Based Extranet Shared Capabilities	Full Network Comm. System Shared Architecture Planning

Figure 5.10 Levels of Supply Chain Maturity (Poirier 2004)

5.4.4.2 Lean Maintenance Supply Chain Framework

Given in Figure 5.11 is a diagrammatic representation of a proposed framework developed by the authors (Tendayi & Fourie 2012) and can be used to execute a lean maintenance supply chain. What follows is a general description of some of the terms used in the framework:

Supply Chain Components

Supply Chain components in maintenance environments differ from those in manufacturing-oriented environments which typically consist of raw material suppliers, 1st tier and 2nd tier suppliers, wholesalers, retailers and the end customer. For the MSC it typically involves Original Equipment Manufacturers, material suppliers, sub-contractors, the main contractor or maintenance organisation and the end-user.

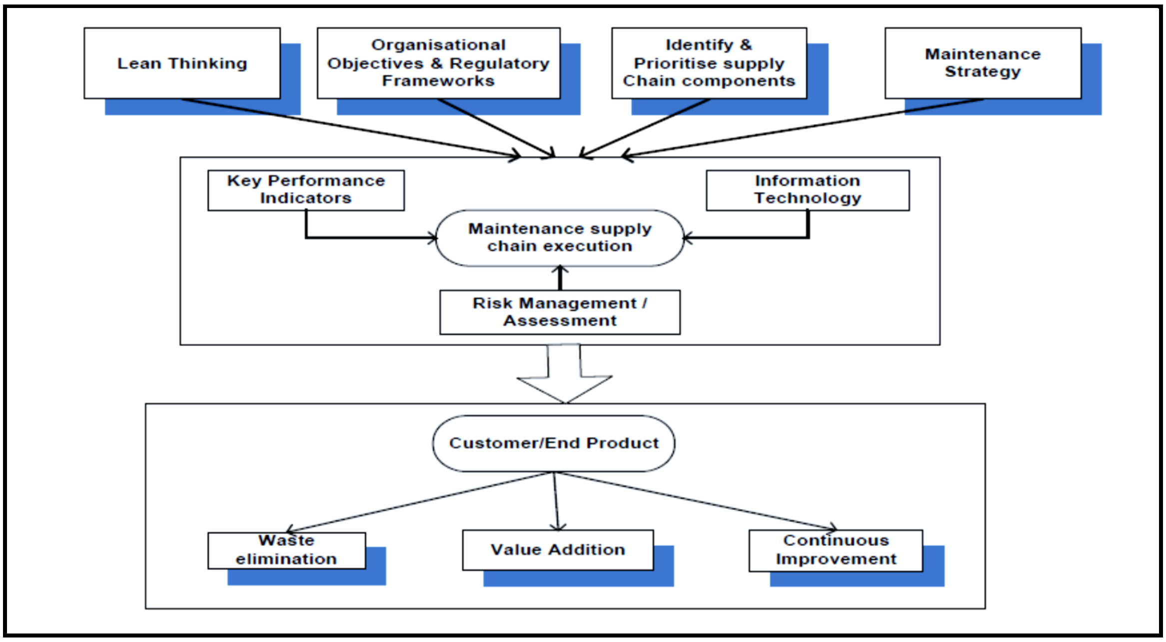

Figure 5.11 Lean Maintenance Supply Chain Framework

Maintenance Strategies

Maintenance strategies range from non-tactical, such as breakdown or corrective maintenance, to tactical such as condition-based maintenance. More mature maintenance organisations will also have optimisation strategies such as Reliability Centred Maintenance or Total Productive Maintenance (TPM) as their maintenance strategy.

Organisational Objectives and Regulatory Frameworks

An organisation’s objectives consist of the overall purpose, mission and goals that it aims to achieve while regulatory frameworks are a system of regulations and the means to enforce them, usually established by a government to regulate a specific activity.

Performance Measurement

After the maintenance organisation has established its maintenance strategy, taken account of the overall business objectives, identified and prioritised all components of its Supply Chain and factored in its lean objectives, there arises a need to put performance measures in place. This is achieved through Key Performance Indicators (KPIs) which combine several metrics and indicators to yield an assessment of critical or key processes. Table 5.9 gives useful metrics that guide an organisation in evaluating its performance in as far as lean thinking in the supply chain is concerned.

Information Technology

Information Technology (IT) is very important for the support of maintenance and maintenance support operations within the supply chain. For an effective enterprise-wide transformation of lean, the IT group should be actively pursuing continuous improvement of the support efforts that they provide for the maintenance operation. IT solutions have evolved with time from the days of computerised maintenance management systems (CMMS), to Enterprise Asset Management (EAM), to customised CMMS/EAM and now to enterprise resource planning (ERP) systems. This evolution has been necessitated by the need to address the multiplicity of business functions within the supply chain. Most ERP vendors initially chose not to offer maintenance management modules although this has changed with time with vendors like SAP and JD Edwards being major players in the market (Singer 2002).

Risk Management/ Assessment

Risk management is an integral part of a supply chain and it takes on an even more important role when lean thinking is applied. For instance, having fewer total suppliers or purchasing of smaller quantities on a more frequent basis has risks attached to it. There are also risks involved with outsourcing (McIvor 2000). There are even risks associated with implementing enterprise software to support organisational objectives. There is therefore a need to incorporate risk assessment before and during execution of the supply chain.

Improvement Models

After having measured and established the MSC’s position in the road to becoming lean, there is a need to put in place improvement models. (Poirier 2004) gives examples of models that can be used to reach higher levels of achievement in the supply chain. He includes models for purchasing, procurement and strategic sourcing, forecasting, demand management and capacity planning and models for order management and inventory management. These and other improvement models will be on-going since lean-thinking calls for continuous improvement and they will exist for the lifetime of the organisation.

Table 5.9 Metrics for Lean Supply Chain Measurements. (Trent 2008)

Supply Chain Area	Measures	Comments
Lean Supply	Supplier Scorecard Measures Procurement overhead as a percent of total sales	Includes regular reports of supplier performance, including performance areas that support lean objectives. Reflects the efficiency of the procurement organisation.
Lean Transportation	Percent of receipts delivered on a just-in-time (JIT) basis	Reflects the maturity of a JIT delivery network.
Lean Operations	Percent of inbound receipts that do not move to storage Overall equipment effectiveness	Reflects the amount of material that downstream entities within a facility require immediately. Measures the availability, efficiency, quality performance, and nonplanned downtime for equipment.
Lean distribution	Perfect cutomer order rates Order fill rates	The percent of orders that ship to customers with zero defects. Unfilled orders due to lack of stock create supply chain waste, costs, and lost sales.
Planning and control	Inventory record accuracy Raw material, work-in-process, and finished goods inventory turnover.	Reflects the differences between physical and computer records for inventory across the supply chain Reflects how often inventory moves across the supply chain.
Customer value satisfaction	Customer repurchase rate	When everything comes together, repurchase rates should be higher than industry averages.

5.4 Summary

In this chapter, a framework is developed, through the combined QFD-AHP approach, to support lean thinking in a non-traditional maintenance environment. The framework consists of a set of ranked Maintenance Excellence criteria, prioritised lean tools and relevant key performance measures. Judgements used to develop and rank elements in the framework are tested for consistency and it is found that they generally meet the accepted limits with only slight deviations that can be adjusted using prescribed methods. The next chapter investigates possible ways in which this framework can be applied in the case study. Proposals were also made on how the organisation can go about developing a lean maintenance supply chain.

CHAPTER SIX: FRAMEWORK IMPLICATIONS

6.0 Introduction

With a framework to support lean thinking in a non-traditional maintenance environment having been developed in the previous chapter, the next step is to find out how to implement it. In order to do this, the case study used in chapter four and five is referred to again. First of all, the maturity of the organisation with regards to its use of Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) is ascertained. Next, one maintenance process is selected from the case study and the principles of value stream management are used in order to determine what changes the framework would potentially have on its operations. The maintenance supply chain of this process is also explored and the implications of applying the framework on its current state are also investigated.

6.1 TPM/RCM Maturity

6.1.1 TPM Maturity of the Organisation

According to the development stages of TPM discussed in Section 5.3.1, the organisation currently stands at Stage II which is the Preventive maintenance stage meaning that maintenance work is programmed on a regular basis to inspect and repair equipment. The maintenance operations are yet to move to the Productive maintenance stage and finally to the TPM stage.

In addition to determining the organisation's overall stage in as far development towards TPM is concerned, the author went further and determined the organisations current state with regard to the specific areas of the eight pillars of TPM (Section 5.3.1). The results of this comparison are shown in Table 6.1 where descriptions of the various pillars are taken from (Rogers 1998) and (Ahuja & Khamba 2007). Information on the current state is based on general observations made and also having discussions with management, workers on the shop floor and a consultant who is part of a team implementing improvement plans across the organisation. As can be seen from the table, the organisation seems to be quite some way in attaining the eight pillars required to have a fully-fledged TPM program in place.

Table 6.1 Current State of TPM Maturity

TPM Pillar	Ideal State	Current State
Autonomous Maintenance	Operators can perform many of the "in-operation" maintenance requirements efficiently.	Good - Train operators are generally good at per- forming general maintenance procedures in order to reduce minor stoppages and delays.
Individual Kaizen	Personnel take personal responsibility to pursue continuous improvement in small steps.	Bad - Most of the initiatives for continuous improvement come from management and supervisors.
Planned Maintenance	Maintenance of equipment is as natural as any other job in the area. Guess work is eliminated, and equipment is maintained to schedule.	Poor – a generally reactive maintenance strategy currently exists.
Quality Maintenance	There is good understanding of the relationship between proper maintenance of equipment and the quality of product that the equipment produces.	Average – Quality control measures are in place for maintenance equipment, spare parts and material.
5S	The following 5-step programme is in place throughout the organisation: Pre-cleaning, developing a storage location for everything & keeping everything in its place, establishing procedures to maintain cleaning, developing the discipline to do the cleaning, and creating the eventual natural expectation that the workplace be clean.	Bad – the organisation has realised a need for this and is in the process if introducing the programme across the organisation.
Education & Training	There is an investment in people's time to construct a truly efficient, meaningful, and lasting training programme.	Poor – there is mostly just an initial training conducted without much follow up on skills improvement especially towards problem solving techniques.
Office TPM	Non-production areas carry out the basic tenets of preventive maintenance.	Poor – supporting structures are not yet fully in sync with maintenance operations resulting in parts and material shortages and long lead times for critical processes.
Safety & Environment	There is a good understanding of the relationship between safety and preventive maintenance and the impact on the environment.	Poor – basic safety procedures exist although on the whole, there is no evidence of good awareness of SHE issues.

6.1.2 RCM Maturity of the Organisation

According to the ranking and description of RCM maturity levels as discussed in Section 5.3.1, the organisation currently stands at the Repeatable level as shown in Figure 6.1. This means that there are basic RCM management practices in place but they are not sufficiently documented, standardised and integrated. There is need therefore, to put measures in place to ensure that the maintenance organisation reaches *Level V* of the maturity grid. A starting point would be to subject all the major maintenance equipment to the seven basic questions (Section 5.3.1) and then take appropriate action.

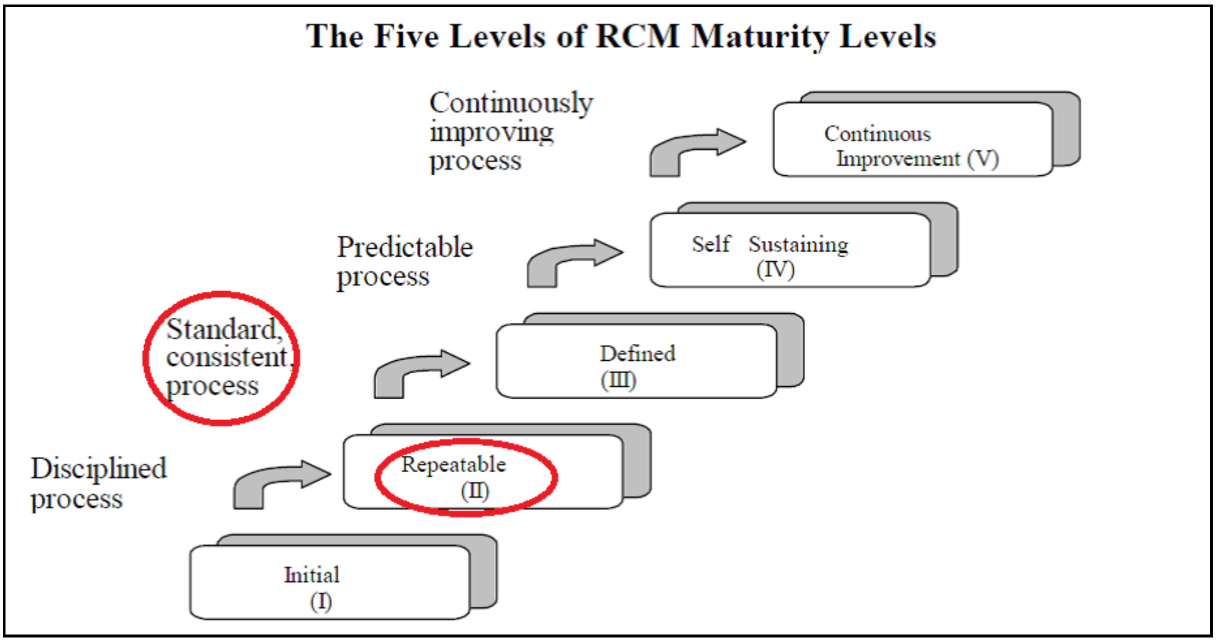

Figure 6.1 Current State of RCM Maturity

6.1.3 Rotating Armature Repair Current State

Figure 6.2 shows a Value Stream Map (VSM) derived from the process flow of the 5M2 rotating armature repair procedure described in Section 4.3.2. For a complete description of the various icons used in the map, refer to APPENDIX D. The VSM represents a snapshot of the current state of the process and as such it is called a Current State VSM. The following is to be noted from this map:

- The Stores icon represents the place where materials and parts are drawn by the maintenance crew in order to repair the rotating armatures. Maintenance crew regularly visit the stores not only at the beginning of the repair but also during all the other stages of the repair process.
- The Operations icon represents the end user of the traction motors which in this case is the train operations section.
- The Planning Control icon represents the Maintenance Planning office which acts as the centre of communication using the FMMS and SAP systems. Communication takes place

both manually and electronically between the office, stores, operations and the maintenance supervisors.

The following non-lean conditions were identified in the current-state value stream:

- The flow of parts in the workshop is inhibited by the floor layout which results in extra movements. One case in point is the Washing process which is located outside the main workshop meaning that material has to be moved out of the workshop to the washing site after stripping and brought back into the workshop for the drying process.
- There is generally a push system in place when it comes to moving the armature from an upstream process to a downstream process.
- Armatures are moved in small batches rather than in the ideal lean state of one-piece flow.
- None of the processes are working according to the takt time which is currently set at 8600 seconds.
- Not much of the material and parts is neatly sorted out on the shop floor resulting in a relatively disorderly environment.
- Possible causes of waste along the current value stream included:
  - ✓ Waiting for material
  - ✓ Shared equipment, especially of the overhead crane.
  - ✓ Unbalanced workload.
  - ✓ Waiting for the armatures to dry which could take up to 16 hours.

Table 6.2 gives a summary of the metrics and baseline measurements of the current state. The table also includes a column for the proposed measurements which are to be determined (TBD). Total value stream WIP inventory is calculated by totalling the amount of WIP inventory on-hand between each operation. Total value stream lead time is the total of daily WIP divided by the daily customer requirements, which in this case is 3 armatures per day. On-time delivery is the processes' schedule compliance and this is a cumulative percentage. The current state value stream has generated the baseline measurements and now there is a need to propose, through lean thinking, a future state that closes the gaps discovered in the current system.

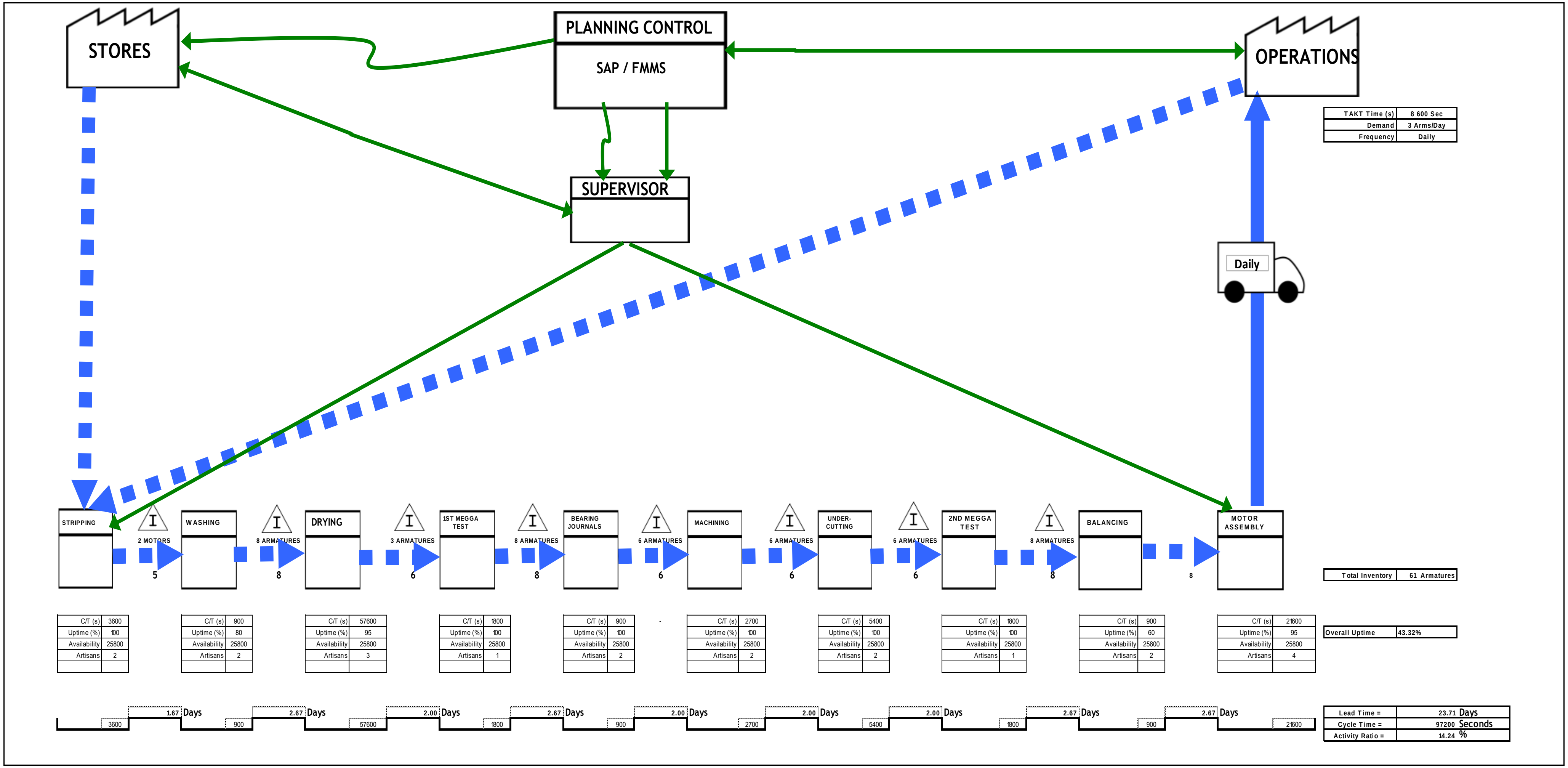

Figure 6.2 Current State Value Stream Map of Rotating Armature Repair

Table 6.2 Current Sate Metrics & Measurements

Metric	Baseline	Proposed
Total Value Stream WIP inventory	47 Units	TBD
Total process cycle time	9700 seconds	TBD
Total value stream lead time	11.21 days	TBD
On-time delivery	100%	TBD
Uptime	100%	TBD

6.1.4 Rotating Armature Repair Future State

Now that the current state has been determined, opportunities are identified that will be used to design a more efficient and waste free value stream which will become our proposed future state. Using the tools and concepts discussed in Section 5.4.2, the following steps are taken in order to develop the future state value stream:

Step 1: Takt Time and Pitch

Takt time is calculated using Eqn. 5.9 where:

$Avalable\ Production\ Time = 25\ 800\ Seconds$

$Total\ daily\ quantity\ required = 3\ Armatures$

Therefore:

$$Takt\ Time = \frac{25800}{3} Seconds = 8\ 600\ Seconds$$

Maintenance operations usually dispatch 6 armatures at a time, as and when it is needed to do so. And so pitch will be calculated as follows according to Eqn. 5.10:

$$Pitch = 8600\ Seconds\ \times 6 = 51\ 600\ Seconds$$

Step 2: Ability to meet demand

The value stream's capacity in the current state is given by the following equation:

$$Capacity = \frac{Available\ Production\ Time}{Cycle\ Time\ for\ the\ slowest\ operation} \quad (6.1)$$

Where:

$Available\ Production\ Time = 25\ 800\ seconds$

$Cycle\ Tme\ for\ the\ slowest\ operation = \ 57\ 600\ seconds\ (Drying)$

Therefore:

$$Capacity = \frac{25800}{57600} = 0.448\ Units$$

And because the overall uptime is only 44.78%, the process capability is adjusted to:

$$0.448 \times 0.4478 = 0.201\ Units\ per\ day$$

This figure is less than the required capacity of 3 Units per day.

Step 3: Buffer and safety inventories

In order to hedge against uncertainty caused by the low overall uptime, buffer and safety inventories of one day's worth of finished armatures must be put in place. Ideally, these inventories will be done away with as *kaizen* plans are put in place.

Step 4: Finished Goods Supermarket

It is also necessary, in the short term, to create a finished-goods supermarket with one day's worth of inventory. This is because it is not possible to establish a continuous flow in the system due to the erratic nature of demand for armatures by operations. The demand is erratic because armatures are only required when a breakdown has occurred and these breakdowns occur erratically.

Step 5: Line Balancing

In order to redesign the line for better flow, the current state data is reviewed in order to determine opportunities for balancing the line. Table 6.3 shows the current state data after which an operator balance chart is created in order to compare the cycle times of each process to takt time as shown in Figure 6.3. The balance chart shows that the line is out of balance with none of the processes producing according to takt time.

Table 6.3 Current State Process Data of Each Process

	Stripping	Washing	Drying	1st Megger Test	Bearing Journals	Machining	Undercutting	2nd Megger Test	Balancing	Motor Assembly
Cycle Time	3600 Sec.	900 Sec.	57600 Sec.	1800 Sec.	900 Sec.	2700 Sec.	5400 Sec.	1800 Sec.	900 Sec.	21600 Sec.
Operators	2	2	3	1	2	2	2	1	2	4
Uptime	100 %	80 %	95%	100%	100%	100%	100%	100%	60%	95%
Availability	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec	25800 Sec

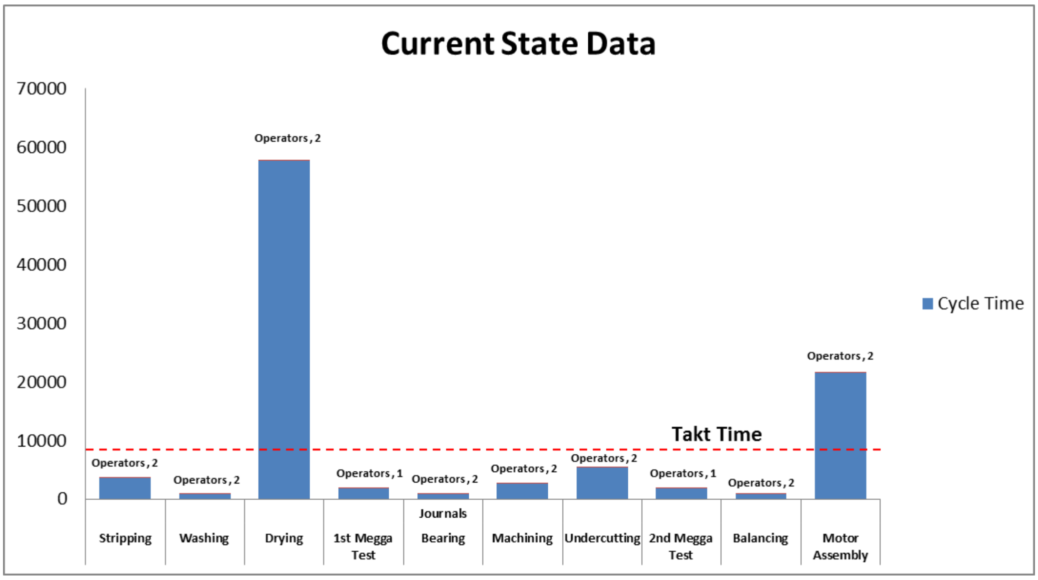

Figure 6.3 Operator Balance Chart

In order to determine the number of operators needed to achieve Takt time, the following formula is used:

$$Number\ of\ Operators = \frac{total\ cycle\ time}{takt\ time} \quad (6.2)$$

Therefore, for the current state:

$$Number\ of\ Operators = \frac{97200}{8600} = 11.3$$

This means that takt time can be ideally met by 12 operators as compared to the current 18 operators. Table 6.4 shows the proposed future state data with Figure 6.4 showing the proposed operator balance chart.

Table 6.4 Future State Process Data of Each Process

	Stripping	Washing	Drying	1st Megger Test, Bearing Journals, Machining	Undercutting, 2nd Megger Test, Balancing	Motor Assembly
Cycle Time	3600	900	57600	5400	8100	21600
Operators	2	1	1	3	3	2
Uptime	100%	80%	95%	100%	100%	95%
Availability	25800	25800	25800	25800	25800	25800

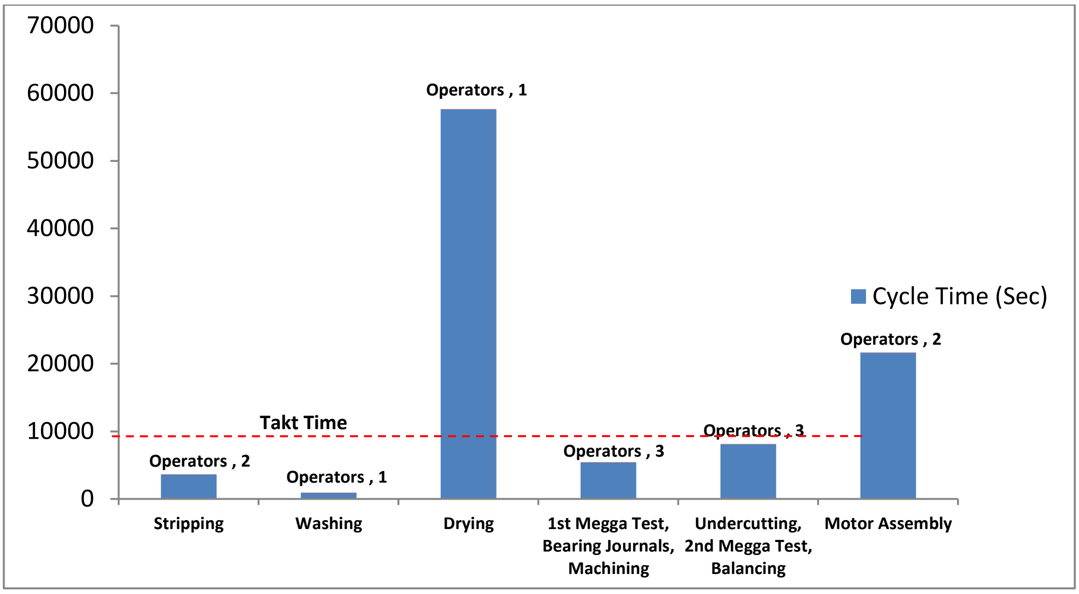

Figure 6.4 Future State Operator Balance Chart

As can be seen from the future state data and operator balance chart, six of the processes have been grouped into work cells with combined cycle times within the takt time. The first two processes, that is Stripping and Washing, cannot be combined into one work cell due to physical restrictions on the location of the processes with the latter being performed outside the workshop. The Drying cycle time will continue to be significantly above the takt time because of equipment restrictions caused by the ovens used to dry the armatures. The cycle time for the Motor Assembly process has been revised downwards assuming successful implementation of the improvement tools discussed in the section which follows.

Figure 6.5 shows the Future state map of the rotating armature repair process. A description of the icons used in the map can be found in APPENDIX D. The following can be noted from the map:

- It shows the six processes that have been combined into two successive work cells with a finished goods supermarket at the end. The finished armatures are then "pushed" from the finished goods supermarket to the final Assembly process.
- For the other processes that are not in work cells, in-process supermarkets are used with parts being "pulled" from one process to the next.
- Potential improvement methods are identified and they are shown within the "kaizen burst" icons at the appropriate places on the map. These include 5S, Standardisation, Visual Management, Kanban and Poka-Yoke. These are discussed in Section 5.2.2.
- The future state also employs the services of a Runner or Material Handler. Upon receiving a signal from Planning Control, the runner takes a Withdrawal Kanban to the finished goods supermarket. The runner then pulls parts from the finished goods supermarket and makes them ready for Motor Assembly. A production kanban is then created by Motor Assembly and is sent to the Undercutting/2nd Megger Test/Balancing work cell by the runner. Finished armatures are then taken from the work cell to the finished goods supermarket. After the runner transfers finished armatures to the finished-goods supermarket, he/she then goes with a withdrawal kanban back to the initial process.
- A supermarket is also created just before the Stripping process and the stripping operators are responsible for pulling signal kanbans from Operations and placing them on a kanban post. An appointed person will be responsible for collecting the signal kanbans and taking them to Operations.

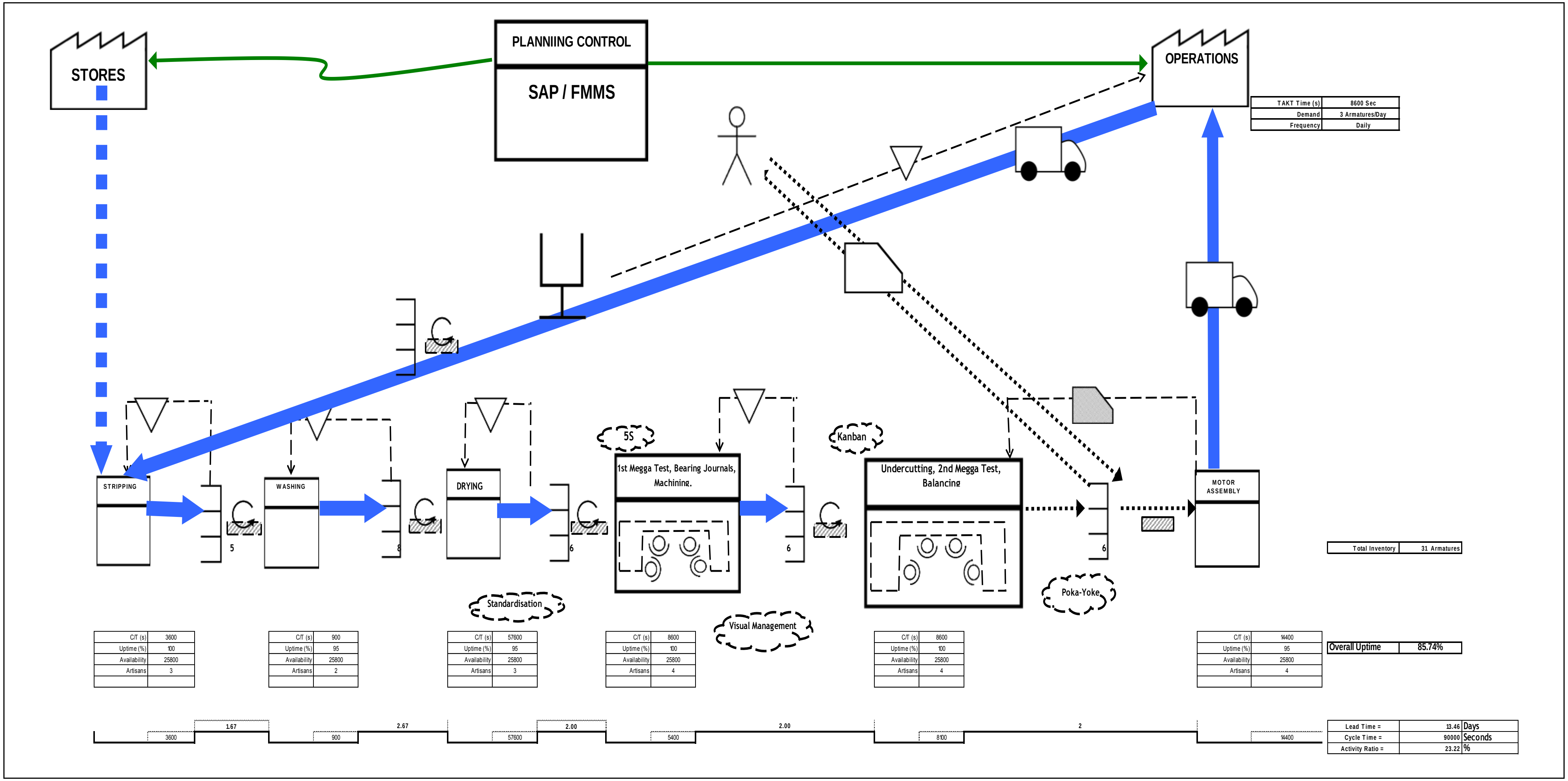

Figure 6.5 Future State Value Stream Map of Rotating Armature Repair

6.1.5 Rotating Armature Repair Process Current state vs. Future State

Table 6.5 gives a comparative summary of the metrics and baseline measurements of the current state compared to the proposed future state. The results show that the proposed future state will produce notable improvements all round with the highest improvement being realised in the overall uptime of processing equipment. Another significant improvement is the Activity Ratio which is beneficial because the core idea of implementing lean is to reduce non-value-adding time.

Table 6.5 Metrics & Measurements of Current State vs. Future State

Metric	Current State	Future State	Improvement
Total Value Stream WIP inventory	61 Units	31 Units	49.18 %
Total process cycle time	97200 seconds	90000 seconds	7.41%
Total value stream lead time	23.71 days	13.46 Days	43.23%
Overall Uptime	43.32%	85.74 %	97.92%
Activity Ratio	14.24%	23.22%	63.06%

6.2 Implications for the Supply Chain

6.2.1 Supply Chain Maturity of Case Study

According to the maturity scale discussed in Section 5.4.4.1, the case study is best described using Figure 6.6 which is a modification of Figure 5.10 highlighting the most appropriate description for the current supply chain. From the diagram, it is observed that most of its business application attributes fall within Level 3 which is the External Network formation level. As explained in Section 5.4.4.1, at this level the organisation focuses on the customer who in our case is the train operations section. The organisation elicits the help of a few key suppliers to make sure that maintenance processes are completed on time. As can be seen in the highlighted matrix, the Logistics operations which involve a mainly "push" system and are inventory intensive, fall within Levels 1&2 and are the only exception. The Marketing, Sales, customer service and customer care business applications do not apply to our present context and hence have been left without being highlighted

Progression / Business Applications	Levels 1 & 2 Internal Supply Chain Optimization	Level 3 External Network Formation	Level 4 Value Chain Constellation	Level 5 Full Network Connectivity
	Supply Chain Optimization	Advanced Supply Chain Management	e-Commerce	e-Business
Design, Development Product/Service Introduction	Internal Only	Selected External Assistance	Collaborative Design – Enterprise Integration and PIM-Linked CAD/CAM	Business Functional View – Joint Design and Development
Purchase, Procurement, Sourcing	Leverage Business Unit Volume	Leverage Full Network Through Aggregation	Key Supplier Assistance, Web-Based Sourcing	Network Sourcing Through Best Constituent
Marketing, Sales, Customer Service	Internally Developed Programs, Promotions	Customer-Focused, Data-Based Initiatives	Collaborative Development for Focused Consumer Base	Consumer Response System Across the Value Chain
Engineering, Planning, Scheduling, Manufacturing	MRP MRPII DRP	ERP – Internal Connectivity	Collaborative Network Planning – Best Asset Utilization	Full Network Business System Optimization Shared Processes and Systems
Logistics	Manufacturing Push – Inventory-Intensive	Pull System Through Internal/External Providers	Best Constituent Provider	Total Network, Virtual Logistics Optimization
Customer Care	Customer Service Reaction	Focused Service – Call Centers	Segmented Response System, Customer Relationship Management	Matched Care – Customer Care Automation and Remediation
Human Resources	Regulatory Issues/Hiring, Recruiting, Training	New Work Models, Training	Inter-Enterprise Resource Utilization, Training	Full Network Alignment and Capability Provision
Information Technology	Point Solutions Internal Silos	Linked Intranets Corp Strategy/Architecture	Internet-Based Extranet Shared Capabilities	Full Network Comm. System Shared Architecture Planning

Figure 6.6 Current Supply Chain Maturity

6.2.2 Current Sate Supply Chain Waste

In the case study's supply chain, the following areas of waste were observed:

1) Procurement procedures are too lengthy and as a result there is delay in securing material and parts that may be urgently required.
2) Some of their original equipment manufacturers have to wait for material coming from overseas before they can produce and deliver urgently required components to them.
3) Suppliers sometimes provide incorrect material and parts which then have to be returned and in a number of those cases, it involves third party suppliers which further delays replacement.
4) Cases of redundant or obsolete stock that is repeatedly ordered by the maintenance department were observed.

5) Generally, a "push" system exists in as far as delivery of critical components is concerned with the organisation aiming to have a safety margin of +/- 20 % to cover unforeseen circumstances.
6) It was noted from the case study that there is a tendency to overlook the role of the sub-contractor as an important member of the supply chain. Situations where it would have been better for the maintenance organisation to do the job in-house rather than outsourcing (e.g. winding of armatures), were observed.
7) For the case study, the fact that it is a State-Owned Enterprise means that it is heavily influenced by government policy which prioritises affordability, safety and reliability of its services. There are also legislative frameworks such as the Preferential Procurement Regulations Act (National Treasury 2009) that weigh heavily on the efficient and timely execution of the supply chain.
8) It was observed that no formal performance measures were in place with one of the few exceptions being a Supplier Evaluation form.
9) Related to the issue of performance measures is the issue of quality inspections which are performed on selected items that have been supplied. Unfortunately, this does not extend to critical parts like traction motor bearings where no quality inspections are in place making it difficult to trace a faulty bearing back to the supplier.
10) There is also a general lack of risk management/assessment procedures in place along the supply chain.

6.2.3 Proposed Supply Chain Improvements

Table 6.6 shows possible solutions to minimise the supply chain wastes identified in the previous section. These solutions are adapted from the metrics for lean supply chain measurements developed by (Trent 2008) and discussed in Section 5.4.3. They can be used to address waste and streamline the current supply chain operations to make them lean. The "Focus of Improvement" section in the table is simply the supply chain area where the waste in question is found. These supply chain areas include supply, transportation, operations, distribution, planning and control and finally the customer side. The "Supply Chain Measure" is a metric which, by careful observation and improvement, can minimise the waste in question.

Table 6.6 Solutions to Supply Chain Waste

Current Supply Chain Waste	Focus of Improvement	Supply Chain Measure	Comments
Lengthy Procurement Procedures	Supply	Procurement overhead as a percent of total sales	Reflects the efficiency of the procurement organisation.
Long lead times	Distribution	Order Fill rates	Unfilled orders due to lack of stock create supply chain waste, costs, and lost sales
Non-conformance of material and parts	Distribution	Perfect Customer Order Rates	The percentage of orders that slip to customers with zero defects.
Redundant/Obsolete Stock	Planning & Control	Inventory carrying charges as a percent of sales	Reflects the true cost of holding inventory.
"Push System" for delivery of critical components	Supply	Percentage of suppliers producing from a buyer's pull signals	Reveals how well a major lean objective is accomplished upstream.
Inefficient Contracting Procedure	Supply	Supplier Scorecard measures	Includes regular reports of supplier performance, including performance areas that support lean objectives.
Restrictive Legislative Frameworks	Supply	Return on investment from supplier development activities	A financial perspective showing the relevancy of development efforts
Lack of comprehensive risk management/ assessment procedures.	Distribution	Distribution quality indicators	Includes indicators of wrong parts picked, wrong quantities, missed deliveries, and damage

6.3 Summary

In this chapter, the implications of applying the framework developed in Chapter five to the Metrorail case study have been explored. First of all, the maturity of the organisation with regards to the use of TPM and RCM were explored. The organisation displayed considerable room for improvement when its current maintenance operations were compared to the eight pillars of TPM. As for its RCM maturity, it was determined that the organisation still has to advance three levels up before it can get to full maturity. Value stream management was carried out on the rotating armature repair process as a way of applying elements of the framework. The current state was mapped and it was determined that there is waste, as defined by lean thinking, in the system. A future state, with lean improvements suggested through the framework, was then proposed, designed and measured. It showed that if this design was implemented successfully, it would result in a significant reduction in waste and an increase in efficiency of the rotating armature repair process. Waste within the supply chain was also addressed by adapting a set of supply chain metrics that are designed to streamline the current supply chain operations of the case study.

CHAPTER SEVEN: CONCLUSION AND RECOMMENDATIONS

7.1 General Overview

The overall aim of this research was to investigate the applicability of lean thinking in an operational maintenance environment which is out of the traditional scope of the manufacturing environment. This was done by developing a framework applicable to a real life situation involving a non-traditional maintenance set-up. First of all, it was established from literature that lean thinking as a field of study, has been gaining acceptance within maintenance operations, mostly within the manufacturing context. Advances have been made outside of this traditional domain although studies in that area have been few and far between. There have been even less studies of this kind carried out in rolling stock maintenance within the rail industry.

The next step was to explore the tools and methodologies that have been used to implement lean thinking in general and more specifically within the maintenance context. The idea was to identify the most appropriate ones for the study at hand. The maintenance excellence criteria were identified as a useful way to gauge adherence to maintenance organisational objectives. Maintenance excellence criteria were therefore used in the current study as a means of finding appropriate lean tools that could help the maintenance organisation meet its objectives in a "lean way". From the many lean tools that have been successfully used, the value stream management methodology was found to be the most important and the most overarching of them all. Of the many lean thinking methodologies that exist especially in the line of decision-making, the AHP and QFD approaches, used separately and also together, were found to be particularly useful. Lastly within the context of finding the right lean tools and methodologies, performance metrics were found to be necessary in determining the success or lack thereof of lean thinking efforts.

The rolling stock division of the Salt River depot of PRASA, Metrorail was chosen as the case study to use for the purposes of the present study. A maintenance excellence survey was carried out and findings from the survey were verified through the AHP process which found slight inconsistences in the pairwise judgements of the responses. This anomaly was rectified using prescribed AHP methods in order to give more consistent judgements and hence importance rankings of the various maintenance criteria when compared to each other. Next, the AHP-QFD approach was used to assign lean tools to each of the maintenance excellence criteria, determine the strength of their relationships, determine consistencies of those judgements and then finally rank the various lean tools. The ranked maintenance excellence criteria and lean enablers/tools then formed the core of the framework. The other variables included the TPM and RCM maturity models, the five lean principles and a set of chosen performance measures. Elements that comprise a lean maintenance supply chain were also investigated and a set of metrics for lean supply chain measurement was proposed.

The final step was to now determine what implications the framework would have on the current operations. The rotating armature workshop repair process was chosen as a pilot case study. The overall maturity of the organisation with regard to TPM and RCM was determined using maturity models from literature which showed that the maintenance operations of the organisation had not yet matured to ideal levels. A value stream map was then drawn based on physical observations on the shop-floor and interviews with key personnel. Waste, as defined by lean thinking, was inherently evident in the process. A future state map was proposed, based on the five lean principles and lean tools derived from the framework. The future state map showed potential improvements in key waste areas such as WIP inventory, lead time and activity ratios. Relevant performance measures were then proposed for each of the maintenance excellence criteria. The supply chain maturity of the organisation was also determined using a maturity model and it was determined that the organisation's supply chain was not in its ideal state with a lot of wasteful practices being observed. Solutions to address these supply chain wastes were proposed through the use of supply chain performance measures that allow management to see how the organisation is advancing with regards to streamlining its supply chain operations.

7.2 Attainment of Research Questions and Hypothesis

The following questions were asked at the beginning of the study:

1) "*What is likely to happen when lean thinking principles that have worked so well in manufacturing oriented maintenance environments, are applied in an environment in which there is no lean manufacturing as the successor?*"

The answer to that question is that there is likely to be noticeable improvements in the overall operations of the maintenance function in as far as waste elimination and value-addition is concerned. In other words, there is likely to be the realisation of more value-adding activities as compared to non-value-adding activities as was shown from the results of the value stream mapping approach used in the case study.

2) *"What lean thinking tools are relevant to such an environment and what corresponding performance measures can be used to determine the success or otherwise of such an initiative?"*

From the foregoing discussion, it can be concluded that most of the tools that have been used in manufacturing-oriented organisations can be translated into the non-manufacturing context. They may probably have to be prioritised differently depending on the overall objectives of the organisation, as was shown by the ranking of tools depending on their relationship to the maintenance excellence criteria. As for the performance measures, most of them focus on the context of the core operations of the organisation. For example, in our case study, maintenance and repair of motors was the core objective and so most of the performance measures were maintenance related, rather than production related if the core activities had been in the manufacturing environment.

3) *"What does a supply chain in a non-manufacturing maintenance environment consist of and what are the necessary constituents in order to create a lean maintenance supply chain?"*

The main difference between a manufacturing supply chain and a non-manufacturing supply chain is that there is no transfer of ownership of goods. There is rather, a transfer of information between the various constituents of the supply chain. Therefore in a non-manufacturing industry similar to that found in MRO, Key Performance Indicators, information technology and comprehensive risk management practices are very important factors to consider in developing a successful supply chain framework.

The following hypothesis was made at the beginning of the study:

> *"Lean thinking, that has worked relatively well in manufacturing-oriented maintenance organisations, can also be applicable to non-manufacturing-oriented maintenance organisations."*

From the findings made throughout the research, this hypothesis can safely be concluded as accurate although it has to be added that this will be subject to a careful selection of tools and performance measures based on specific organisational objectives. The only issue that still needs to be addressed is the level of success of such initiatives. This still needs to be adequately quantified and compared to that in manufacturing-oriented organisations so that no doubt can be left in the mind of management that such an initiative is worth it.

7.3 Contribution to Body of Knowledge and the 'Real World'

It was established from the outset, that few frameworks have been developed to test the applicability of lean thinking in non-manufacturing maintenance operations similar to that in rolling stock maintenance. This has been the biggest motivation for undertaking this project, so that more light can be shed into that subject area and hence further increase the scope of lean thinking. The novel use of the AHP-QFD approach within this context is also important and increases the scope of this decision-making approach. Another useful contribution is in the definition of a lean maintenance supply chain for use in the rolling stock environment. A study of literature shows little, if any, of other studies that have been done in that subject area and to such depth.

In terms of the contribution of this study to the 'real world', this study forms part of the efforts of the PRASA Chair in Maintenance and Engineering Management to improve maintenance operations at PRASA, Metrorail facilities across South Africa. This study, and in particular the framework, will go a long way in helping the organisation to streamline its operations through the implementation of lean thinking.

7.4 Recommendations for Future Work

- As was highlighted in Section 3.2.2, value stream mapping sometimes requires a complimentary tool due to its static nature. One such tool would be that of simulation. This however requires that enough data be made available to provide input for the simulation parameters. This was not possible in the present study because of the lack of historical data in key parameters. Maintenance organisations, including Metrorail, are therefore encouraged to keep relevant historical data which can later be referred back to for decision-making purposes.

- It would be useful to compare the results of the AHP-QFD approach against other integrated AHP approaches as discussed in Section 3.3.2. This would help determine which results provide a more accurate representation of the real world scenario. The use of appropriate meta-heuristics algorithms would especially be recommended as it allows for effective optimisation of multiple conflicting objectives.
- In addition to the maintenance excellence criteria carried out at the case study, it would be useful to go back to the same respondents and gauge their feelings in as far as the applicability of the framework within their organisation is concerned. However, before this can be done, there is need to embark on an extensive education exercise to make the people aware of the aims and objectives of lean thinking.
- The implications of using the framework were determined using only one pilot case study which was in the rotating armature repair process. It is therefore recommended that in any future work, the study must be expanded to other key processes within the rolling stock workshop and see if the same conclusions could be reached.

7.5 Closing Remarks

Due to the far-reaching nature of this subject area, it is not possible to accurately and numerically predict all the outcomes of using the proposed framework to prove the usefulness of lean thinking in an operational maintenance environment similar to the one given in the case study. However, it is hoped that through application of scientific methods that include the maintenance excellence survey, AHP-QFD approach and also through the value stream management methodology carried out on the pilot case study, sufficient evidence has been given to suggest that the conclusions reached in this study can indeed be trusted. It would definitely be a worthwhile initiative to look at other non-traditional environments other than rolling stock maintenance and determine if the same conclusions obtained in this study can be found in those scenarios as well.

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APPENDIX A: Maintenance Excellence Criteria Survey

Appendix A outlines the maintenance excellence criteria survey that was carried out at the rolling stock division of the Salt River depot of PRASA, Metrorail.

"An Investigation into the Applicability of Lean Thinking in an Operational Maintenance Environment"

by

Tendayi, T.G.

Department of Industrial Engineering, Faculty of Engineering, Stellenbosch University

Supervisor: Prof C.J Fourie

The student is currently researching on the topic mentioned above, and as part of the study, would like to know the current operating conditions of the maintenance organisation by conducting a survey on Maintenance Excellence criteria.
May the respondent please indicate, by clicking or marking in the appropriate checkbox, ranging from Excellent, if the organisation is fully compliant with the criteria in question, to Bad, if the organisation still has a lot of work to do in that area.

Maintenance Excellence Criteria

1) **Continuous Improvement Efforts –** to what extent is the organisation engaged in on-going efforts to improve maintenance processes?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

2) **Use of FMMS/SAP –** to what extent are the current FMMS/SAP systems helping the organisation do its work more effectively e.g. in determining which machines require maintenance, optimising stock levels of material and spare parts and allocation of resources?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

3) **Schedule compliance –** is maintenance work generally completed according to schedule?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

4) **Detailed Operating Procedures (DOPs) –** do the current DOPs clearly document maintenance tasks so that workers have no trouble following them?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

5) **Management Support –** to what extent is top and middle level management supportive of day to day maintenance activities?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

6) **Spare Parts and Material Availability –** are materials and parts ordered and delivered on time so as to avoid stock-outs during planned maintenance activities and emergency breakdowns?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

7) **Comprehensive Work Orders/ Job Cards –** are work orders/job cards completely and accurately filled in and contain clear and descriptive comments that can be used for future reference?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

8) **Maintenance Organisation Structure –** is the maintenance organisation structure clear and divisions between roles, responsibilities and authorities well defined?

Excellent	Good	Average	Poor	Bad

☐ ☒ ☐ ☐ ☐

9) **Personnel Skills Training –** are the skills improvement and training programmes providing real value to the maintenance operation in terms of a well-qualified and knowledgeable workforce?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

10) **Policy and Strategy –** are the current maintenance policies and strategies well understood by all maintenance workers and does it guide them in making day-to-day decisions?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

11) **Maintenance Contracting –** in terms of a cost-benefit analysis perspective, do the decisions to contract work significantly out-weigh doing it in-house?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

12) **Maintenance Contracting –** are the contractor's responsibilities and expectations clearly spelt out before awarding the contract so that jobs are timely performed according to agreed specifications?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

13) **Key Performance Indicators (KPIs) –** do all key maintenance processes have KPIs and are these KPIs regularly reviewed for decision-making processes?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

14) **Workforce involvement** – does management encourage the maintenance workforce to make independent decisions on-site and also contribute to the overall decision-making process?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

15) **Conformance Quality –** are skilled and qualified maintenance personnel directly supervising maintenance work including inspection of material and parts for conformance to quality?

Excellent	Good	Average	Poor	Bad
☐	☐	☐	☐	☐

Comments

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For any further information and to return this form, please contact:
Tinashe G Tendayi on Email: 16873890@sun.ac.za , Cell: +277152882019 or,
Prof C.J Fourie on Email: cjf@sun.ac.za , Tel: +27 808 4237

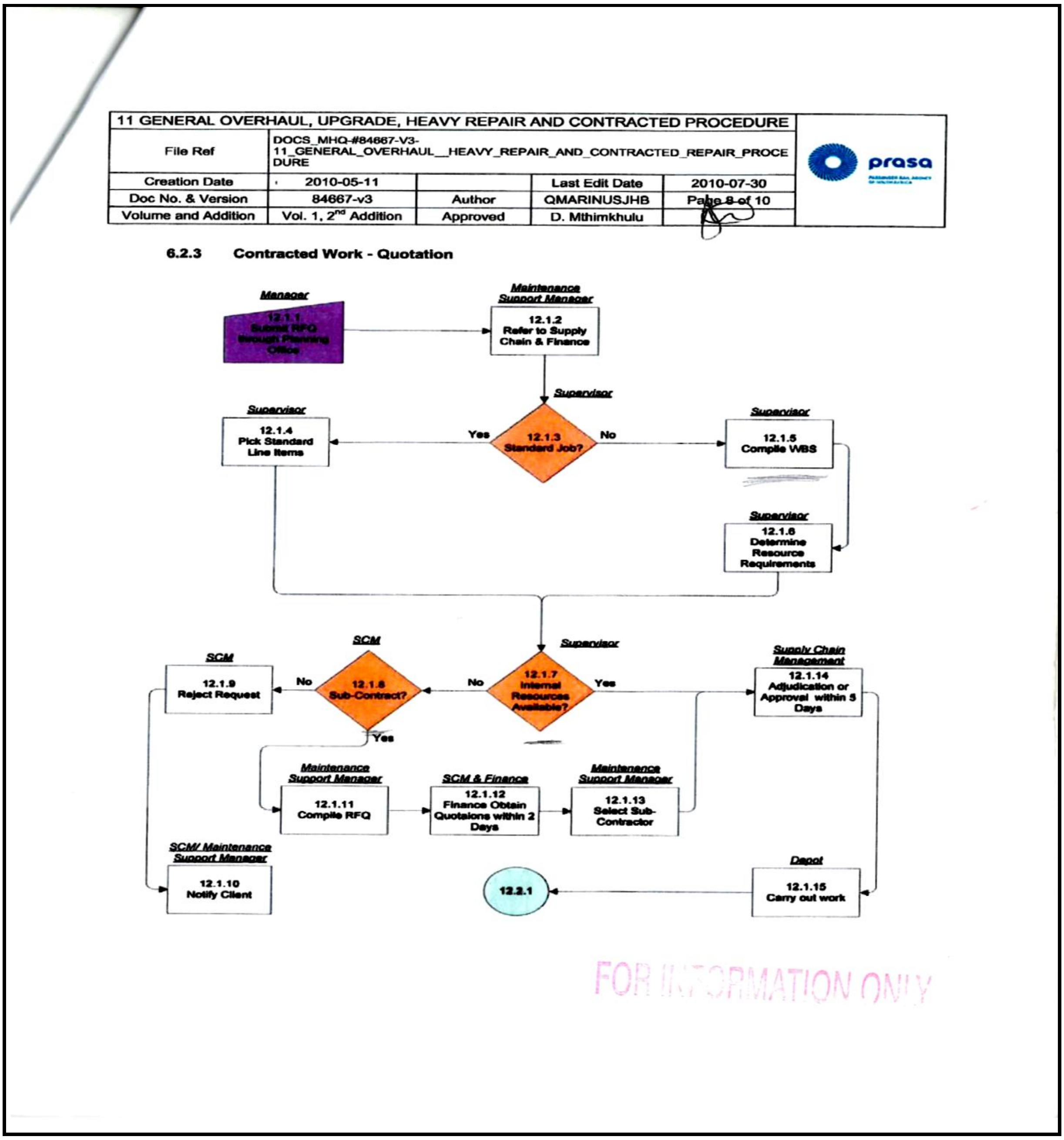
Your time and opinion is greatly appreciated.

Kind Regards,
Tinashe

APPENDIX B: Detailed Operating Procedures

Quotations for Contracted Work

The detailed procedure for assessing quotations for outsourced jobs is given below. Amongst the major decisions that are made, personnel have to decide whether it is a standard job, whether internal resources are available and finally whether or not to subcontract. The main actors in this stage are the Supply Chain Manager, Finance Manager and the Maintenance Support Manager.



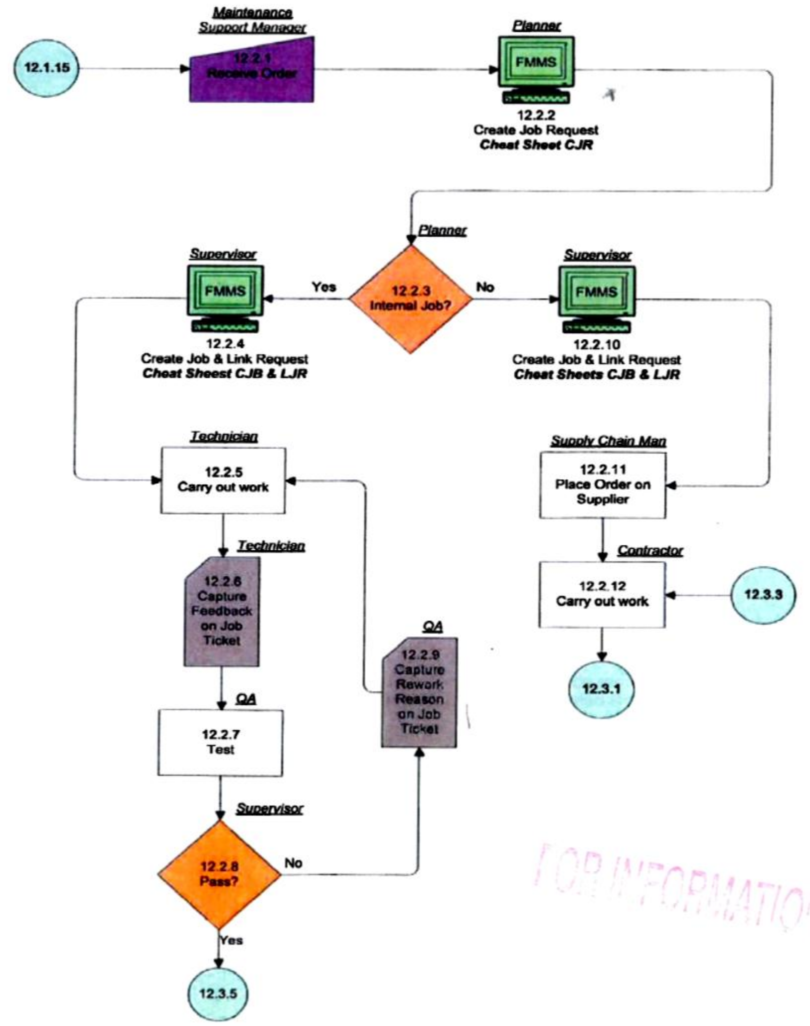
11 GENERAL OVERHAUL, UPGRADE, HEAVY REPAIR AND CONTRACTED PROCEDURE				
File Ref	DOCS_MHQ-#84667-V3-11_GENERAL_OVERHAUL__HEAVY_REPAIR_AND_CONTRACTED_REPAIR_PROCEDURE			
Creation Date	2010-05-11		Last Edit Date	2010-07-30
Doc No. & Version	84667-v3	Author	QMARINUSJHB	Page 8 of 10
Volume and Addition	Vol. 1, 2nd Addition	Approved	D. Mthimkhulu	

6.2.3 Contracted Work - Quotation

A detailed procedure for ordering and executing a contracted job is given below. The main actors in this process are the Planner who has to decide whether it is indeed an external job and enter it in to the FMMS. The SCM places the order on the Contractor who in turn carries out the work.

11 GENERAL OVERHAUL, UPGRADE, HEAVY REPAIR AND CONTRACTED PROCEDURE					prasa
File Ref	DOCS_MHQ-#84667-V3-11_GENERAL_OVERHAUL__HEAVY_REPAIR_AND_CONTRACTED_REPAIR_PROCEDURE				
Creation Date	2010-05-11		Last Edit Date	2010-07-30	
Doc No. & Version	84667-v3	Author	QMARINUSJHB	Page 9 of 10	
Volume and Addition	Vol. 1, 2nd Addition	Approved	D. Mthimkhulu		

6.2.3 Contracted Work - Ordering & Job Execution

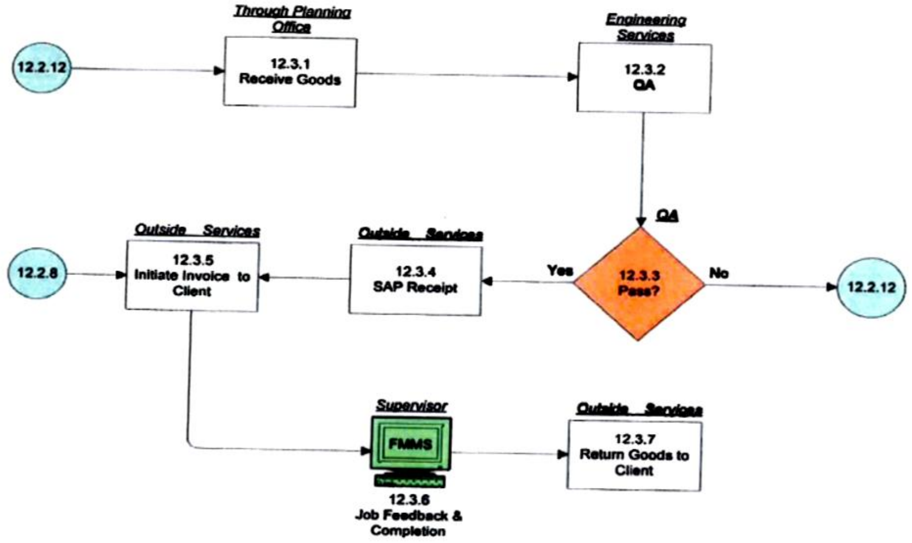


Feedback on Contracted Work

A detailed procedure for receiving the job from the contractor and providing feedback on the quality of the work is given below. The main actors in this procedure are the Planning office who receive the job and the section supervisors who give the actual job feedback and confirm if the order has been completed..

11 GENERAL OVERHAUL, UPGRADE, HEAVY REPAIR AND CONTRACTED PROCEDURE					
File Ref	DOCS_MHQ-#84667-V3-11_GENERAL_OVERHAUL__HEAVY_REPAIR_AND_CONTRACTED_REPAIR_PROCEDURE				prasa
Creation Date	2010-05-11		Last Edit Date	2010-07-30	
Doc No. & Version	84667-v3	Author	QMARINUSJHB	Page 10 of 10	
Volume and Addition	Vol. 1, 2nd Addition	Approved	D. Mthimkhulu		

6.2.3 **Contracted Work - Feedback**



7. RECORDS RETAINED

All completed job tickets and attachments (invoices, delivery notes, etc.) are required to be kept on file for reference for all General Overhauls, Upgrades, Heavy Repair and Contracted Repair Work.

The contractor to provide the following documentation:

- Test Bench Reports
- Commissioning Report that covers all sub systems
- Data Books

8. ATTACHMENTS

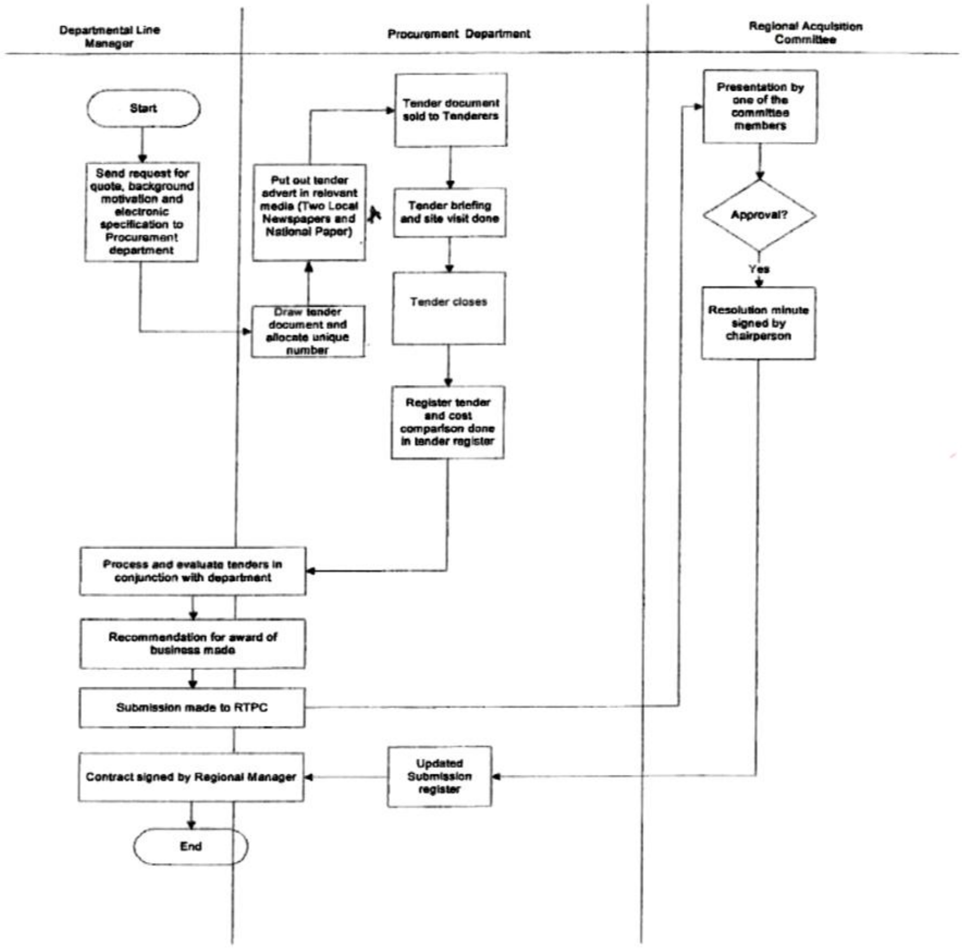
None

MATION ONLY

Integrated System Procedure for Procurements of R350 001 to R5 million.

File Ref:	IMS_O / QUAL_MAN / QMS	
Effective Date:	03/01/2011	**INTEGRATED SYSTEM PROCEDURE**
Title:	**PROCUREMENT**	

R350 001 – R5M purchases



Doc. No & Version:	14846 – v6	Page 4 of 5	
Author:	Departmental QMR	Last Edit Date:	2011/06/06 08:49:20 AM
Approved by:	Head of Department	Last Print Date:	2011/06/06 08:49:20 AM

APPENDIX C: Maintenance Performance Measures

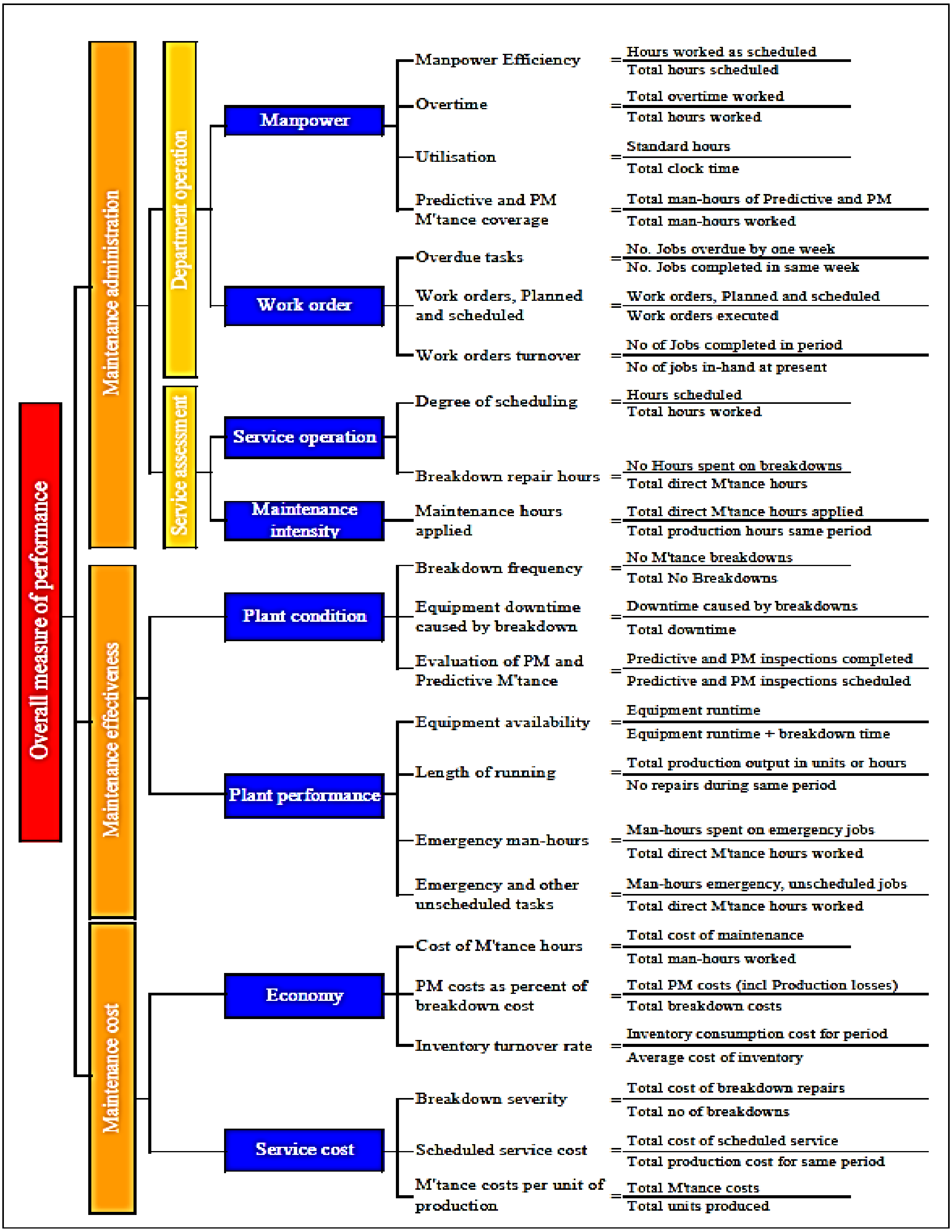


Figure C2: Typical Maintenance Performance Measures (Davies, Greenough 2003a)

Table C8: Primary Measures Related to Maintenance Quality (Smith, Hawkins 2004)

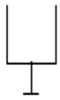
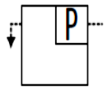
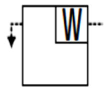
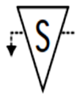
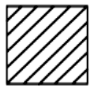
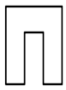
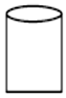
Measure	Essential Data Sources	Goal
Maintenance Downtime by Equipment (Uptime)		
As Percent of Scheduled Run Time	Shop Floor Data Collection	0.5 to 2.0%
Mean Time Between Failures	Equipment History	Increasing Trend
Percent of Failures Addressed by Root Cause Analysis	Equipment History	>75%
PPM Schedule Compliance	PPM Schedule of the Work Order System	>95%
PPM Delinquency by Weeks Delinquent	PPM Schedule of the Work Order System	<5% past due 1 to 4wks.
Ratio of Corrective Work Orders to PPM Inspections	Work Order System	1:6*
Call-In Frequency	Payroll System	Trend
Maintenance Overtime Percentage	Payroll System	5 to 15%*
Annual Training Per Mechanic, measured in:	Personnel Records	
Hours		>100/yr.
Dollars		$2 to $3K/yr.
Percent of Maintenance Labor Budget		5 to 10%*
Average Number of PMs per Thousand Occupied Sq. Ft. per Year	Engineering Calculation from Work Order System Data	Var.
Average PM Hours per Thousand Sq. Ft. per Year	Engineering Calculations from Work Order System Data	Var.

* Indicates Generally Accepted Industrial Best Practice Benchmarks.

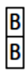
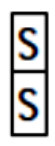
These are the primary measures related to maintenance quality. They also impact internal as well as External Customer Satisfaction and might, therefore, also be added to the preceding list.

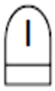
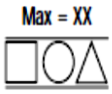
APPENDIX D: Value Stream Mapping Icons

Given below is a list of some of more commonly used value stream mapping icons used to add continuous flow to the future state map (Tapping 2002).

Purpose	Icon
Kanban Post	
Production Kanban	
Withdrawal Kanban	
Signal Kanban	
Supermarket Parts	
U-shaped Cell	
Computer-assisted (MRP)	
Physical Material Pull	

Given below are value stream mapping icons used to map the demand focus.

Purpose	**Icon**
Buffer Inventory	
Safety Inventory	
Supermarket	

Meaning of Icon	Icon
Customer or Supplier	
Attribute Fields	
Production Control	
Dedicated Process Box	
Truck Shipment	
Material Push	
Electronic Information Flow	
Manual Information Flow	
Operator Location	
Kaizen Focus	
Kaizen Flow (must flow form Kaizen Focus)	
Shared Process Box	
Inventory WIP Stagnation	
First-In, First-Out (FIFO)	

APPENDIX E: Calculation of Pairwise Comparisons

The following diagrams show how Microsoft Excel 2010 ® formulae were manipulated in order to calculate values in key cells used to create the AHP pairwise comparison matrices. Not all the formulae are shown and what are given below are only snapshots of some of the key formulae.

Book	Cell	Value	Formula
HOQ M...	D22	1/7	`=IF(L4=0,1,IF(AND(0<L4,L4<=5),3,IF(AND(5<L4,L4<=10),5,IF(AND(10<L4,L4<=20),7,IF(L4>20,9,IF(AND(-5<=L4,L4<0),1/3,IF(AND(-10<=L4,L4<5),1/5,IF(AND(-20<=L4,L4<-10),1/7,IF(L4<-20,1/9)))))))))`
HOQ M...	E22	7	`=IF(M4=0,1,IF(AND(0<M4,M4<=5),3,IF(AND(5<M4,M4<=10),5,IF(AND(10<M4,M4<=20),7,IF(M4>20,9,IF(AND(-5<=M4,M4<0),1/3,IF(AND(-10<=M4,M4<5),1/5,IF(AND(-20<=M4,M4<-10),1/7,IF(M4<-20,1/9)))))))))`
HOQ M...	F22	5	`=IF(N4=0,1,IF(AND(0<N4,N4<=5),3,IF(AND(5<N4,N4<=10),5,IF(AND(10<N4,N4<=20),7,IF(N4>20,9,IF(AND(-5<=N4,N4<0),1/3,IF(AND(-10<=N4,N4<5),1/5,IF(AND(-20<=N4,N4<-10),1/7,IF(N4<-20,1/9)))))))))`
HOQ M...	G22	1/3	`=IF(O4=0,1,IF(AND(0<O4,O4<=5),3,IF(AND(5<O4,O4<=10),5,IF(AND(10<O4,O4<=20),7,IF(O4>20,9,IF(AND(-5<=O4,O4<0),1/3,IF(AND(-10<=O4,O4<5),1/5,IF(AND(-20<=O4,O4<-10),1/7,IF(O4<-20,1/9)))))))))`
HOQ M...	H22	1/7	`=IF(P4=0,1,IF(AND(0<P4,P4<=5),3,IF(AND(5<P4,P4<=10),5,IF(AND(10<P4,P4<=20),7,IF(P4>20,9,IF(AND(-5<=P4,P4<0),1/3,IF(AND(-10<=P4,P4<5),1/5,IF(AND(-20<=P4,P4<-10),1/7,IF(P4<-20,1/9)))))))))`
HOQ M...	I22	1/3	`=IF(Q4=0,1,IF(AND(0<Q4,Q4<=5),3,IF(AND(5<Q4,Q4<=10),5,IF(AND(10<Q4,Q4<=20),7,IF(Q4>20,9,IF(AND(-5<=Q4,Q4<0),1/3,IF(AND(-10<=Q4,Q4<5),1/5,IF(AND(-20<=Q4,Q4<-10),1/7,IF(Q4<-20,1/9)))))))))`

N44 *fx*

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL
CI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
FMMS	7	1	9	7	5	1/5	5	5	7	5	3	5	3	7	7
SC	1/7	1/9	1	1/3	1/7	1/9	1/7	1/7	1/5	1/7	1/7	1/7	1/9	1/7	1/7
DOP	1/5	1/7	3	1	1/5	1/9	1/5	1/7	1/5	1/7	1/7	1/7	1/7	1/5	1/5
MGT	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
SP	7	5	9	9	7	1	7	7	9	7	7	7	5	7	7
WO	3	1/5	7	5	1	1/7	1	1/3	3	1/3	1/5	1/3	1/5	3	3
MAINT	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
SKILLS	1/3	1/7	5	5	1/3	1/9	1/3	1/5	1	1/5	1/5	1/5	1/7	1/3	1/3
POL	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
CONTR 1	5	1/3	7	7	5	1/7	5	3	5	3	1	3	1/3	5	5
CONTR 2	5	1/5	7	7	3	1/7	3	1	5	1	1/3	1	1/3	5	5
KPI	7	1/3	9	7	5	1/5	5	3	7	3	3	3	1	7	7
WI	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
QUAL	1	1/7	7	5	1/3	1/7	1/3	1/5	3	1/5	1/5	1/5	1/7	1	1
	50.68	8.49	99.00	82.33	34.68	3.02	34.68	22.75	59.40	22.75	16.49	22.75	11.56	50.68	50.68

	CI	FMMS	SC	DOP
CI	0.02	0.02	0.07	0.06
FMMS	0.14	0.12	0.09	0.09
SC	0.00	0.01	0.01	0.00
DOP	0.00	0.02	0.03	0.01
MGT	0.06	0.02	0.07	0.06
SP	0.14	0.59	0.09	0.11
WO	0.06	0.02	0.07	0.06
MAINT	0.10	0.02	0.07	0.09
SKILLS	0.01	0.02	0.05	0.06
POL	0.10	0.02	0.07	0.09
CONTR 1	0.10	0.04	0.07	0.09
CONTR 2	0.10	0.02	0.07	0.09
KPI	0.14	0.04	0.09	0.09
WI	0.02	0.02	0.07	0.06
QUAL	0.02	0.02	0.07	0.06
	1.00	1.00	1.00	1.00

Book	Cell	Value	Formula
HOQ M...	AH27	0.14	=P27/$P$37
HOQ M...	AI27	0.14	=Q27/$Q$37
HOQ M...	AJ27	0.26	=AVERAGE(U27:AI27)
HOQ M...	AK27	19.33	=MMULT(C27:Q27,$AJ$22:$AJ$36)/AJ27
HOQ M...	T28	WO	
HOQ M...	U28	0.06	=C28/$C$37

AL31 *fx*

	CI	FMMS	SC	DOP	MGT	SP	WO	MAINT	SKILLS	POL	CONTR 1	CONTR 2	KPI	WI	QUAL	Importance Weighting	Consistency Measure
CI	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.03	15.89
FMMS	0.14	0.12	0.09	0.09	0.14	0.07	0.14	0.22	0.12	0.22	0.18	0.22	0.26	0.14	0.14	0.15	19.54
SC	0.00	0.01	0.01	0.00	0.00	0.04	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	16.85
DOP	0.00	0.02	0.03	0.01	0.01	0.04	0.01	0.01	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01	16.29
MGT	0.06	0.02	0.07	0.06	0.03	0.05	0.03	0.01	0.05	0.01	0.01	0.01	0.02	0.06	0.06	0.04	17.06
SP	0.14	0.59	0.09	0.11	0.20	0.33	0.20	0.31	0.15	0.31	0.42	0.31	0.43	0.14	0.14	0.26	19.33
WO	0.06	0.02	0.07	0.06	0.03	0.05	0.03	0.01	0.05	0.01	0.01	0.01	0.02	0.06	0.06	0.04	17.06
MAINT	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10	0.06	18.00
SKILLS	0.01	0.02	0.05	0.06	0.01	0.04	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	15.85
POL	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10	0.06	18.00
CONTR 1	0.10	0.04	0.07	0.09	0.14	0.05	0.14	0.13	0.08	0.13	0.06	0.13	0.03	0.10	0.10	0.09	19.01
CONTR 2	0.10	0.02	0.07	0.09	0.09	0.05	0.09	0.04	0.08	0.04	0.02	0.04	0.03	0.10	0.10	0.06	18.00
KPI	0.14	0.04	0.09	0.09	0.14	0.07	0.14	0.13	0.12	0.13	0.18	0.13	0.09	0.14	0.14	0.12	19.12
WI	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.03	15.89
QUAL	0.02	0.02	0.07	0.06	0.01	0.05	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.02	0.02	0.03	15.89
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		

```
Book      Cell  Value  Formula
HOQ M...  H16   1/3    =IF(G4=0,1,IF(AND(0<G4,G4<=0.5),3,IF(AND(0.5<G4,G4<=1),5,IF(AND(1<G4,G4<=3),7,IF(G4>3,9,IF(AND(-0.5<=G4,G4<0),1/3,IF(AND(-1<=G4,G4<-0.5),1/5,IF(AND(-3<=G4,G4<-1),1/7,IF(G4<-3,1/9)))))))))
HOQ M...  I16   3      =IF(H4=0,1,IF(AND(0<H4,H4<=0.5),3,IF(AND(0.5<H4,H4<=1),5,IF(AND(1<H4,H4<=3),7,IF(H4>3,9,IF(AND(-0.5<=H4,H4<0),1/3,IF(AND(-1<=H4,H4<-0.5),1/5,IF(AND(-3<=H4,H4<-1),1/7,IF(H4<-3,1/9)))))))))
HOQ M...  J16   5      =IF(I4=0,1,IF(AND(0<I4,I4<=0.5),3,IF(AND(0.5<I4,I4<=1),5,IF(AND(1<I4,I4<=3),7,IF(I4>3,9,IF(AND(-0.5<=I4,I4<0),1/3,IF(AND(-1<=I4,I4<-0.5),1/5,IF(AND(-3<=I4,I4<-1),1/7,IF(I4<-3,1/9)))))))))
HOQ M...  K16   1/3    =IF(J4=0,1,IF(AND(0<J4,J4<=0.5),3,IF(AND(0.5<J4,J4<=1),5,IF(AND(1<J4,J4<=3),7,IF(J4>3,9,IF(AND(-0.5<=J4,J4<0),1/3,IF(AND(-1<=J4,J4<-0.5),1/5,IF(AND(-3<=J4,J4<-1),1/7,IF(J4<-3,1/9)))))))))
HOQ M...  L16   7      =IF(K4=0,1,IF(AND(0<K4,K4<=0.5),3,IF(AND(0.5<K4,K4<=1),5,IF(AND(1<K4,K4<=3),7,IF(K4>3,9,IF(AND(-0.5<=K4,K4<0),1/3,IF(AND(-1<=K4,K4<-0.5),1/5,IF(AND(-3<=K4,K4<-1),1/7,IF(K4<-3,1/9)))))))))
HOQ M...  M16   1/5    =IF(L4=0,1,IF(AND(0<L4,L4<=0.5),3,IF(AND(0.5<L4,L4<=1),5,IF(AND(1<L4,L4<=3),7,IF(L4>3,9,IF(AND(-0.5<=L4,L4<0),1/3,IF(AND(-1<=L4,L4<-0.5),1/5,IF(AND(-3<=L4,L4<-1),1/7,IF(L4<-3,1/9)))))))))
```

D14 *fx*

KEY

KAI	Kaizen
KAN	Kanban
VIS	Visual Management
JIT	Just In Time
STA	Standardisation
HOS	Hoshin
BAL	Balanced Scorecard
PKY	Poka-Yoke
5S	5S

	KAI	KAN	VIS	JIT	STA	HOS	BAL	PKY	5S
KAI	1	1/3	3	1/3	3	5	1/3	7	1/5
KAN	3	1	3	1/3	3	5	1/3	7	1/5
VIS	1/3	1/3	1	1/3	3	3	1/3	7	1/5
JIT	3	3	3	1	3	5	3	7	1/3
STA	1/3	1/3	1/3	1/3	1	3	1/3	7	1/5
HOS	1/5	1/5	1/3	1/5	1/3	1	1/5	7	1/7
BAL	3	3	3	1/3	3	5	1	7	1/5
PKY	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1	1/7
5S	5	5	5	3	5	7	5	7	1
	16.01	13.34	18.81	6.01	21.48	34.14	10.68	57.00	2.62

Book	Cell	Value	Formula
HOQ M...	J35	0.21	=J23/$J$24
HOQ M...	K35	0.47	=K23/$K$24
HOQ M...	L35	0.12	=L23/$L$24
HOQ M...	M35	0.38	=M23/$M$24
HOQ M...	N35	0.32	=AVERAGE(E35:M35)
HOQ M...	O35	10.96	=MMULT(E23:M23,$N$27:$N$35)/N35

F30 =F18/$F$24

	KAI	KAN	VIS	JIT	STA	HOS	BAL	PKY	5S	Importance Weighting	Consistency Measure
KAI	0.06	0.02	0.16	0.06	0.14	0.15	0.03	0.12	0.08	0.09	10.45
KAN	0.19	0.07	0.16	0.06	0.14	0.15	0.03	0.12	0.08	0.11	10.93
VIS	0.02	0.02	0.05	0.06	0.14	0.09	0.03	0.12	0.08	0.07	10.04
JIT	0.19	0.22	0.16	0.17	0.14	0.15	0.28	0.12	0.13	0.17	11.24
STA	0.02	0.02	0.02	0.06	0.05	0.09	0.03	0.12	0.08	0.05	9.87
HOS	0.01	0.01	0.02	0.03	0.02	0.03	0.02	0.12	0.05	0.04	9.52
BAL	0.19	0.22	0.16	0.06	0.14	0.15	0.09	0.12	0.08	0.13	11.32
PKY	0.01	0.01	0.01	0.02	0.01	0.00	0.01	0.02	0.05	0.02	9.59
5S	0.31	0.37	0.27	0.50	0.23	0.21	0.47	0.12	0.38	0.32	10.96
	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00		

CI=	0.18
RI=	1.45
CR=	0.12