A Framework for Implementing Lean Practices and Tools to Support ISO 55000 Compliance for Physical Asset Management

Jeanne-Marie de Villiers

Thesis presented in fulfilment of the requirements for the degree of Master of Engineering (Engineering Management) in the Faculty of Engineering at Stellenbosch University

Pectora roborant cultus recti
UNIVERSITEIT
iYUNIVESITHI
STELLENBOSCH
UNIVERSITY
100
1918 · 2018

Supervisor: Dr JL Jooste
Co-Supervisor: Prof CJ Fourie

March 2018

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: March 2018

Abstract

Effective physical asset management (PAM) is essential to the success and safety of any organisation. This is apparent when considering cases such as the explosion of the Piper Alpha, Britain's biggest oil and gas producing platform. This explosion killed 167 people and occurred due to a lack of safety and maintenance precautions. The ISO 55000 series, launched in 2014, is dedicated to the management of physical assets, where compliance assures an effective, standardised and safe PAM system. Currently, there is no standard framework organisations can follow to change the state of their PAM to prepare for ISO 55000 accreditation. This creates uncertainty regarding *how* to become ISO 55000 compliant.

Lean and PAM have similar fundamentals, of which one of the most important includes the maximisation of value for the end-user. This study derives from an opportunity identified for the development of a framework to aid ISO 55000 compliance, specifically through the utilisation of Lean principles and tools. A framework is proposed that (i) provides orientation and direction on the use of Lean principles and tools to support requirements set out in the ISO 55001 document and (ii) provides cross-referencing between ISO 55001 and 55002 clauses.

The literature study addresses the definition of physical assets and PAM and investigates the building blocks of PAM. It further provides literature on Lean and a detailed overview of the ISO 55000 series, which are two focal points to the study. PAM focus areas are chosen through qualitatively analysing the importance of each PAM subject area addressed in the literature study. Asset Information and Knowledge, Asset Lifecycle Management, Risk and Opportunity Management, Reliability Engineering and Maintenance is identified as the most important areas of concern in PAM and further literature is provided on each area.

The process of conceptualising the framework commences based on the findings of the literature study. The ISO 55001 and ISO 55002 documents are investigated and applicable clauses are categorised under the chosen PAM focus areas. Each Lean principle and tools is compared to the chosen ISO 55001 clauses, where a qualitative analysis is performed on their potential in supporting relevant clauses. The framework is validated through face validation via semi-structured interviews with experts within the fields of PAM, ISO 55000 and Lean. According to the expert panel, the framework successfully achieves the desired framework attributes, namely (i) useful, (ii) ease of use, (iii), understandable, (iv) flexible and (v) objective-orientated. This thesis comes to a closure by concluding that Lean principles and tools can be structured in a framework to guide organisations in supporting the clauses set out in the ISO 55000 series.

Opsomming

Effektiewe fisiese batebestuur is noodsaaklik tot die sukses van enige organisasie. Dit is oënskynlik in gevalle soos die ontploffing van die Piper Alpha, Brittanje se grootste olie en gas vervaardigingsoord. Hierdie ontploffing het die lewens van 167 mense geëis en het plaasgevind as gevolg van 'n tekort aan veiligheids- en instandhoudings voorsorgmaatreëls. Die ISO 55000 reeks riglyne, vrygestel in 2014, is toegewy tot die bestuur van fisiese bates. Nakoming tot die riglyne van hierdie standaard verseker effektiewe, gestandaardiseerde en veilige fisiese batebestuur vir enige maatskapy. Tans is daar geen standaard raamwerk wat organisasies kan volg om die toestand van hul fisiese batebestuur te verander om voor te berei vir ISO 55000 akkreditasie nie, wat onsekerheid veroorsaak rakende *hoe* om te voldoen aan die vereistes.

Lean en fisiese batebestuur het soortgelyke grondbeginsels, waarvan die belangrikste die maksimalisering van waarde vir die eindverbruiker is. Hierdie studie is afkomstig as gevolg van 'n geleentheid wat geïdentifiseer is vir die ontwikkeling van 'n raamwerk om ISO 55000-nakoming te ondersteun, spesifiek deur die gebruik van Lean gereedskap en beginsels. 'n Raamwerk work voorgestel wat (i) oriëntering en leiding bied tot die gebruik van Lean beginsels en gereedskap om die vereistes soos uiteengesit in die ISO 55001-dokument te ondersteun en (ii) kruisverwysings te bied tussen ISO 55001 en ISO 55002 klousules.

Die literatuurstudie brei uit op die definisie van fisiese bates en fisiese batebestuur en ondersoek die boustene van fisiese batebestuur. Dit verskaf ook literatuur oor Lean en 'n breedvoerige opsomming van die ISO 55000 dokumente. Fisiese batebestuur fokusareas word gekies deur die belangrikheid van elke PAM vakgebied wat in die literatuurstudie aangespreek word, kwalitatief te analiseer. Bate Inligting en Kennis, Bate Lewensiklusbestuur, Risiko en Geleentheidsbestuur, Betroubaarheids Ingenieurswese en Instandhoudings Ingenieurswese word geïdentifiseer as die belangrikste areas van fokus vir hierdie studie en elke veld word uitgebrei deur verdere literatuur.

Ontwikkeling van die raamwerk is gebaseer op die navorsing uitgevoer op die literatuurstudie. Die ISO 55001 en ISO 55002 dokumente word ondersoek en toepaslike klousules word gekategoriseer volgens die fisiese batebestuursfokusareas. Die potensiaal van elke Lean gereedskap en beginsel tot ondersteuning van gekose klousules word kwantitatief ontleed. Die voorgestelde raamwerk word bekragtig deur sigwaarde bekragtiging waar semi-gestruktureerde onderhoude gevoer word met kundiges in die velde van fisiese batebestuur, ISO 55000 en Lean. Volgens die deskundige paneel behaal die raamwerk die verlangde kenmerke, naamlik (i) bruikbaar, (ii) gemak van gebruik, (iii), verstaanbaar, (iv) buigsaam en (v) doelgerig.

Die slotsom van hierde tesis bevestig dat Lean beginsels en gereedskap gestruktureer kan word in 'n raamwerk om organisasies te lei ter ondersteuning van die klousules in die ISO 55000 reeks.

Acknowledgements

I would like to express my sincere appreciation and gratitude to the following people and organiations for their roles in completion of this study:

- My husband, Roberto, for always being there for me and always giving me something to laugh about, and for his unwavering strength, positivity, encouragement, love and support.
- My mother, Desiree, for the care, support and love she always welcomes me with.
- My brother, Jacques, for teaching me the importance of preserverence and always making me laugh with his dry sense of humour.
- Dr J.L. Jooste, my supervisor, and Prof C.J. Fourie, my co-supervisor, for their guidance and advice throughout the duration of this study.
- Bashier Rawoot, for assisting me with proofreading in the last stretch.
- The individuals and organisations that supported the research and agreed to partake in the validation of this study.

The Author

November 2017

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

ABRAMAN Brazilian Society for Maintenance and Asset Management

ALCM Asset Lifecycle Magement

AMBoK Asset Management Body of Knowledge

AMCouncil Asset Management Council

AMIP Asset Management Improvement Planning

AML Asset Management Landscape

AMP Asset Management Plan

AMS Asset Management System

BSI British Standard Institution

CBM Condition Based Maintenance

CBM Condition-based Maintenance

CMMS Computerised Maintenance Management System

CPFR Collaborative Planning Forecasting and Replenishment

DIKW Data-Information-Knowledge-Wisdom Hierarchy

ECR Efficient Consumer Response

EFNMS European Federation of National Maintenance Societies

FIFO First-in first-out

FIM Iberoamerican Federation on Maintenance

FPS Ford Production Systems

GFMAM	The Global Forum on Maintenance and Asset Management
GSMP	Gulf Society of Maintenance Professionals
HRM	Human Resource Management
IAM	Institute of Asset Management
ISO	International Organisation for Standardisation
IT	Information Technology
JIT	Just-in-Time
JTA	Job Task Analysis
KPI	Key Performance Indicators
MTBF	Mean Time Between Failure
PAM	Physical Asset Management
PDCA	Plan-Do-Check-Act
PDSA	Plan-Do-Study-Act
PEMAC	Plant Engineering and Maintenance Association of Canada
PM	Preventive Maintenance
PM	Project Manager
PRASA	Passenger Railway Agency of South Africa
QCO	Quick Changeover
RCM	Reliability Centered Maintenance
SAAMA	The Southern African Asset Management Association
SAMP	Strategic AM Plan
SMED	Single-Minute Exhange of Die
SMRP	The Society for Maintenance and Reliability Professionals
SPC	Statistical Process Control
TCO	Total Cost of Ownership

TOC	Theory of Contstraints
TPM	Total Productive Maintenance
TPS	Toyota Production Systems
TQM	Total Quality Management
UK	United Kingdom
VSM	Value Stream Mapping
WIP	Work In Process

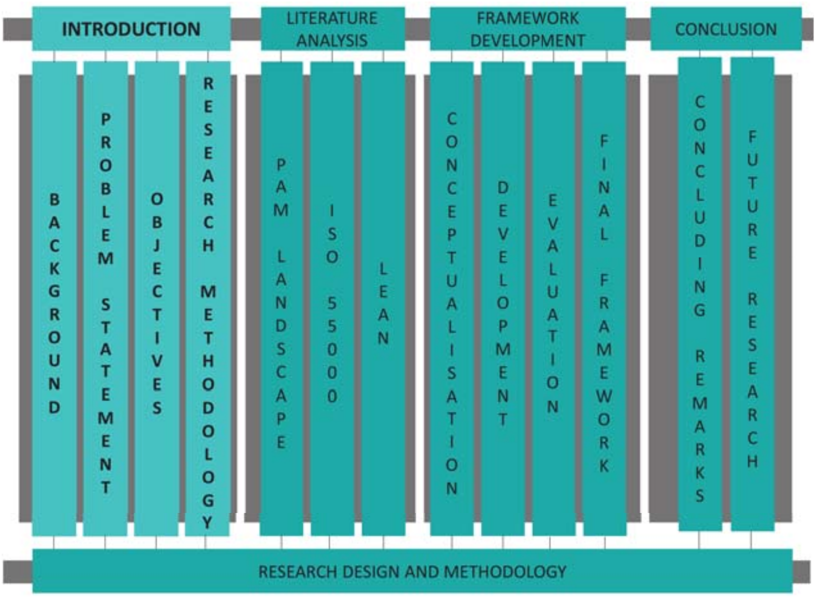
Chapter 1

Introduction

Chapter Outcome

1. Introduction to the research domain i.e. PAM, ISO 55000 and Lean.
2. Delineation of the research problem.
3. Scope of the study.
4. Research design, methodology and thesis layout.

Chapter Route Map



1.1 Background

This section gives a brief background of the key concepts and themes that lead to this study. It also aims to provide an understanding on the importance and impact Physical Asset Management (PAM) and Lean Thinking can have in an organisation.

1.1.1 Physical Asset Management and ISO 55000

PAM is defined as the methodical and synchronised events and practices through which an organisation manages its assets and systems over their life span to assure maximum value and return (ISO 55000, 2014). Assets refers to any tools or equipment used to convert an input into an outcome of value to the organisation, which may include equipment, inventory or any necessary buildings or structures supporting this process (Hodges, 1996; ISO 55000, 2014).

In 1988, The Piper Alpha explosion, documented as one of the largest man-made catastrophes, killed 167 workers and led to a significant decrease in oil prices, as Piper Alpha was previously Britain's biggest oil and gas producing platform (The Guardian, 2013). According to The Guardian (2013), the explosion occurred due to gas leakage and investigations determined the main cause to be a lack of safety and maintenance precautions. This motivated the North Sea Oil and Gas Industry to take serious steps of treating each oil platform as an asset and managing it through its whole life cycle. Incidents such as the Hatfield train disaster in the United Kingdom in 2000, the Columbia space shuttle disaster in 2003, and the New York, London and Italy blackout in 2003 were also ultimately due to the failure of physical assets (Hodkiewicz, 2014).

Incidents of this nature significantly increased pressure to consider health, safety and the environment. Properly maintaining assets, keeping facilities in optimal condition and preventing critical failures are key factors in reducing the risk of service disruptions, pollution and industrial accidents (Mitchell, 2002).

The importance of effective PAM is endless and is increasingly becoming standard practice in the engineering maintenance and asset management industry (Basson, 2016). In 2004, the British Standard Institution (BSI) published the first publicly available specification, PAS 55, for the optimised management of physical assets as a result of industry demand (Ma, 2014). This specification was only acknowledged two years after, when the United Kingdom (UK) utilities sections started implementing the concepts lined out in the specification (Basson, 2016). PAS 55 galvanised the PAM community, which led to the standard being reviewed and re-issued in 2008 by the BSI. It was known to be a great success, though criticised for lacking detail (Ma, 2014). Due to continuous increased global interest in the contents of this specification and its international success, BSI collaborated with the International Organisation for Standardisation (ISO) and initiated the translation of PAS 55 into an ISO standards, leading to the publication of ISO 55000 (Hodkiewicz, 2014).

ISO 55000 is the first attempt to capture what must be done to effectively manage any asset type.

It consists of three documents (ISO 55000, 2014):

1. ISO 55000 Asset Management –Outline, principles and terminology
2. ISO 55001 Asset Management –Requirements
3. ISO 55002 Asset Management –Management Systems: Guidance for the application of ISO 55001

According to Minnaar *et al.* (2013, p.99), the standard provides:

> "*a minimum set of requirements for an effective asset management system, but allows the organization itself to determine how best it should be implemented to suit their needs.*"

Thus, organisations should adapt the requirements set out in ISO 55001 document to best suit the nature of their operations. This can be seen as a downside to the ISO 55000 Series, as it only tells organisations *what* to do and does not provide guidence or a process on *how* to do it (Basson, 2016).

1.1.2 Lean

Lean (also referred to as lean manufacturing or lean production) is a continuous improvement strategy that focusses on creating value with the least possible resources and, when implemented, has the potential of creating great competitive advantage to any organisation (Warnecke and Huser, 1995; Flynn and Vlok, 2016; Womack and Jones, 1996; Tapping *et al.*, 2002). Flynn and Vlok (2016) states that value is created when the output (product or service) meets the customers' needs at a specific price and a specific time and can only be defined by the ultimate end user. It is based on the principle of continuously minimising waste to maximise flow, where constant awareness of what constitutes waste and how to eliminate it is key (Tapping *et al.*, 2002).

The start of the revolutionary lean thinking dates back to 1913, when Taichi Ohno, a mechanical engineer and businessman who worked at Toyota in Japan, started implementing assembly lines as opposed to the usual large batch and queue production. He was inspired by Hendry Ford's breakthrough in 1914 where he placed assembly in continuous and lined up machines in process sequence. Ohio had to change the production processes of Toyota out of necessity as the market demanded a greater variety of vehicles (Holweg, 2007; Liker and Womack, 1998). Ohno's great success led Toyota to start an organisation inside Toyota called Toyota Production Systems (TPS), specifically to train suppliers to become lean. In the 1980s, TPS was brought to the United States in a joint venture with General Motors called New United Motor Manufacturing, Inc. In the following decade, numerous companies within the United States started implementing lean and, in a short period of time, showed astounding performance improvements. Toyota was soon known to be the best manufacturing company and competitive benchmark in the world because of its production system (Liker and Womack, 1998).

In the early 1980s, Ford went through a severe crisis and realised that immediate change is necessary in order to prevent the company from closing down. It soon started implementing continuous improvement initiatives and integrated quality systems into their production processes by hiring some of the best TPS experts and benchmarking Toyota. Ford realised that for this initiative to be successful, all employees had to be trained. It started numerous employee involvement programme which enabled Ford employees to gain critical skills, supported great changes in Ford's management philosophy and greatly increased personal growth in the workforce.

Ford's focus on quality was felt throughout the workforce of all plants and lead to quality improvements of up to 65 percent over a timeframe of 8 years. Its hourly workforce simultaneously reduced by 45 percent and productivity increased by 6 percent per year. By 1995, Ford achieved a total of 83 percent customer satisfaction, with Toyota being at 87 percent. Ford called this system the Ford Production System (FPS), where the biggest variation from the TPS is production system standardisation and its intense involvement of the workforce (Liker and Womack, 1998).

The term *lean* was first used by a John Krafcik, a student at Massachusetts Institute of Technology (MIT) International Motor Vehicle programme at the time. He observed that the TPS requires less of everything to create a given amount of value and labeled it *lean* (Paterson, 2015).

Recent studies conducted at Volvos Group worldwide programme suggested that when implementing lean at an organisation, improvement takes place in an S–curve shape. First, the company's operational performance improves slowly as they experiment with lean principles. Then, it starts growing rapidly as it realises its benefits (Netland and Ferdows, 2016). This can is illustrated in Figure 1.1.

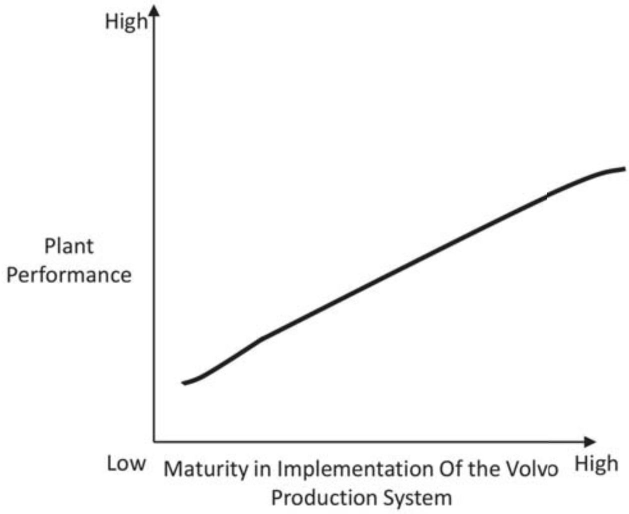


Figure 1.1: The Relationship between Maturity in Lean Implementation and Operational Performance in a Plant.
Adapted from Netland and Ferdows (2016, p.1111)

This section provided a brief background on lean thinking and the competitive advantage the implementation of lean tools can provide an organisation. The following section describes the link between PAM and lean.

1.1.3 The Integration of Lean Thinking and PAM

ISO 55000 (2014, p.3) states that

> *"Asset Management does not focus on the asset itself, but on the value that the asset can provide to the organization.The value (which can be tangible or intangible, financial or non-financial) will be determined by the organization and its stakeholders, in accordance with the organizational objectives."*

Lean's first principle includes clearly understanding customers' perception of value and making its creation the organisation's primary focus (Paterson, 2015). From the statements above, it is clear that both of these concepts have the same point of focus, which is to create value for an organisation. PAM creates value by managing assets optimally to assure maximum return, while lean creates value by streamlining processes and increasing quality by continuously reducing waste.

These principles complement one another. For example, Total Productive Maintenance (TPM) focuses on operators maintaining their own equipement effectively to leave it in a state as good as, or better than, what it previously was (by eliminating breakdowns, stops and defects - lean waste) (Flynn and Vlok, 2016)).This forms part of PAM, as assets are managed to create value in the organisation. Another common point of focus is the critical role the workplace culture plays in the successful execution of both these concepts. According to ISO 55000 (2014, p.3):

> *"Leadership and commitment from all managerial levels is essential for succesfully establishing, operating and improving asset management within the organisation."*

Liker and Womack (1998) states that

> *"The creators and supporters of FPS believe that winning not only the minds but the hearts of everyone involved in manufacturing at Ford was an essential condition for long-term success."*

In both these concepts, the hierarchy of a company needs to be in support in order to receive the benefits assosiated with succesful implementation. Lean thinking is incorporated within the AM framework, as defined by ISO 55000. This is illustrated in Figure 1.2.

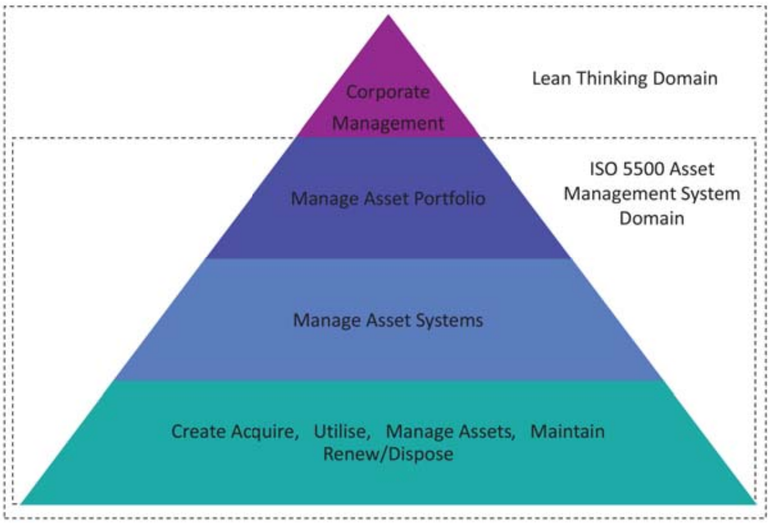


Figure 1.2: Link between Lean Thinking and ISO 55000 Asset Management
Adapted from Flynn and Vlok (2016)

Lean tools such as TPM and Value Stream Management (VSM) are two tools amongst possibly many that will enhance PAM and may bring an organisation closer to ISO 55000 accreditation.

1.2 Problem Statement

From the literature provided in Section 1.1, it is clear that effective PAM is imperative to the success of any company. This realisation led to the development of the ISO 55000 series. Becoming ISO 55000 compliant is important to ensure a company's PAM is standardised and effective.

The problem is that there is no general process which organisations can follow to prepare for ISO 55000 accreditation and for gaining the associated benefits of effective PAM. There is also a lack of skills and expertise on how to change the current state of PAM within an organisation to adhere to ISO 55000 requirement and receive accreditation.

Section 1.1 states that Lean and PAM have similar fundamentals, which includes creating value for an organisation and its stakeholders. Lean practices and tools therefore have the potential to advance AM within an organisation and aid ISO 55000 accreditation.

This points to the following research questions:

1. **What can be done to create a standard framework addressing *how* organisations can prepare for ISO 55000 accreditation?**
2. **How can Lean principles and tools be used to support the process of becoming ISO 55000 compliant?**
3. **How can a framework be structured to provide guidance on the use of Lean principles and tools to support the requirements set out in the ISO 55000 Suite of Standards?**

By addressing the research problem and answering the research questions posed an opportunity exists to add value to the PAM domain and the body of knowledge surrounding ISO 55000 implementation.

1.3 Research Objectives

The main objective of this thesis is to provide a framework to guide any industry in supporting the requirements of ISO 55000 through the use of lean practices and tool. This objective is divided into sub-objectives in order to systematically address more manageable sub-tasks. These objectives are illustrated in Table 1.1.

Table 1.1: Sequence of Research Objectives

Chapter 2
1. Establish the fundamentals of PAM.
2. Construct a summary of the ISO 55000 series.
3. Provide exhaustive literature on Lean.
Chapter 3
4. Establish this thesis' research design and methodology.
Chapter 4
5. Select PAM focus areas for this study.
6. Provide literature on selected PAM focus areas.
Chapter 5
7. Categorise ISO 55001 requirements according to PAM focus areas.
8. Identify Lean tools applicable to the identified ISO 55000 requirements.
9. Formulate objective eight intp a framework.
Chapter 6
10. Perform face validation of the developed framework through semi-structured interviews with experts in the fields under study.
11. Modify the framework by incorporating expert opinion, where applicable.
Chapter 7
12. Draw conclusions from the validation and answer the research question.

Objective four determines the research design and methodology of this study. This is done by exploring secondary sources of different designs and methodologies used in research and selecting those applicable to this study.

The fifth and sixth objectives focus on narrowing the scope of this study by selecting PAM focus areas and providing detailed literature on each.

Objectives seven and eight focus on selecting the ISO 55000 requirements applicable to this study and the Lean practices and tools with the potential of supporting the chosen requirements. This is done by investigating each requirement in the ISO 55000 Suite of Standards and looking for key words associated with the chosen PAM areas of focus. Thereafter, the objectives of each Lean practice and tool is compared with the objectives of each chosen requirement and their alignment determined.

In the ninth objective, this thesis' ultimate research objective is presented by providing a generic framework to aid the process towards ISO 55000 accreditation through the use of Lean tools.

Objectives ten to twelve validates the derived model and draws conclusions in order to answer the research question and provide a solution to the problem statement.

1.4 Delimitation

When conducting new research, it is imperative that limits be set in order to fully understand the context in which the research is conducted. The following list sets the boundaries of this study.

- This thesis is bound by the use of Lean tools to satisfy ISO 55000 requirements.
- The framework developed in this thesis will not enable a company to become fully accredited, but merely *aid the process* towards accreditation.
- Due to time limitations, this thesis will only focus on satisfying requirements applicable to a limited number of PAM and Lean focus areas to be determined in this study.

1.5 Research Design and Methodology Overview

Research design refers to the way in which the different elements of the study is integrated in order to form a logical sequence and effectively answer the research question. According to Creswell (2009),there are three elements of research design:

1. Philosophical worldview
2. Research methods
3. Strategy of inquiry

The philosophical worldviews refers to the way in which the researcher views the world and how the researcher's background influences the manner in which research is conducted. This research mainly stems from pragmatism, as it is objective and its primary focus is on solving the problem statement and answering the research question.

Research methods and strategy of inquiry is focussed on the manner in which research is conducted, quantitative or qualitative, and how it translates to practice (Creswell, 2009). This research takes a qualitative approach and uses primary and secondary data to provide a solution to the problem statement, which is expressed in words rather than numbers. It consists of three phases: 1) literature analysis, 2) conceptual framework development and 3) final framework development. In the first two phases, existing textual data is analysed and used to build a conceptual framework for solving the problem statement. In the final phase, the conceptual framework is modified based on expert input obtained through semi-structured interviews in order to establish its validity. Table 1.2 illustrates each phase of this study.

Table 1.2: Research Method of this Thesis

Step	Research Method	Strategy	Chapter
1	Structured Literature Study	Qualitative	2
2	Conceptual Framework Development	Qualitative	4, 5
3	Framework Validation	Qualitative	6

This section briefly describes the design and methodology used in this study. This is discussed in more detail in Chapter 3. The following section provides a description of the thesis layout.

1.6 Thesis Layout

In correspondence with the research design, the document layout follows a logical approach to allow continuous flow of the basic foundations of the research in focus and sequentially satisfy its objectives. This section gives a brief summary of each chapter of this thesis.

Chapter 1: Introduction

Chapter 1 is the introductory section of the thesis. It introduces the research domain and states the importance of the research and the research problem to be solved. A research question is derived from the problem statement to form a basis for the study and to be answered throughout this thesis. It also states the objectives to be reached, the scope of the thesis as well as the document methodology.

Chapter 2: Literature Review

Chapter 2 provides literature on the PAM and Lean landscapes. It builds on understanding the fundamentals of these two fields in order to identify their synergy. It explores key Lean practices and tools in order to determine which practices and tools fall within the PAM landscape. It furthermore provides a summary of the ISO 55000 series.

Chapter 3: Research Design and Methodology

Chapter 3 provides the research design and methodolgy used in this study to obtain an answer to the research questions. It provides information on the philosophical world view, research method and strategy of inquiry used throughout this project.

Chapter 4: PAM Focus Areas

Chapter 4 investigates key PAM areas, selected through qualitatively analysing the literature provided in Chapter 2.

Chapter 5: Framework Development

Chapter 5 analyses the literature of Chapter 2 and Chapter 4 and develops a framework for aiding ISO 55000 compliance through the implementation of Lean practices and tools.

Chapter 6: Framework Validation

Chapter 6 is focused on validating the proposed framework through face validation. Semi-structured interviews are conducted with experts within fields related to PAM, Lean and ISO 55000. Thereafter, appropriate modifications are made, which results in the final framework.

Chapter 7: Closure

Chapter 7 briefly reflects on the conducted research and results and identifies limitations. Thereafter, a conclusion is drawn by answering the research question. The thesis finally concludes with an outlook and recommendations for future research.

1.7 Chapter Summary

This chapter serves as the introduction to this research. It presents a background on the key concepts within the study, provides a problem statement and poses a research question. Research objectives are derived and demarcations are stated from the problem statement. The main objective of this thesis is to provide a framework to guide any industry in satisfying the requirements of ISO 55000 by using Lean practices and tools and consequently lead an organisation closer to becoming compliant. Finally, the research design and methodology is presented, together with a thesis layout. In accordance with the thesis layout, the next chapter will present a literature analysis on Lean, PAM and ISO 55000.

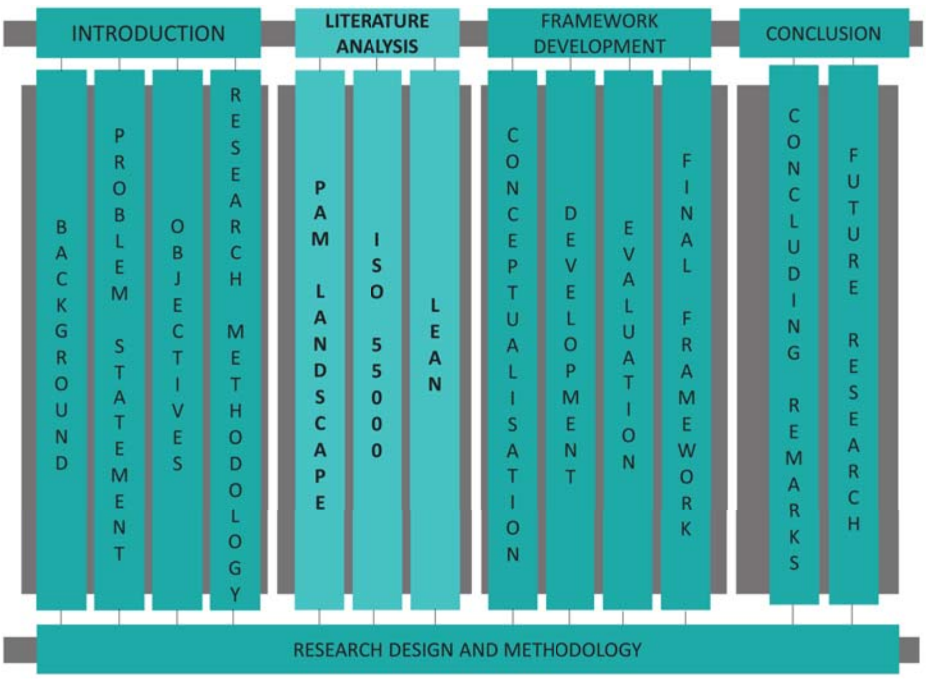
Chapter 2

Literature Review

Chapter Outcome

1. Provide literature on the PAM and Lean Landscapes
2. Provide a summary of the ISO 5500X Family of Standards

Chapter Route Map



2.1 Physical Asset Management

The aim of this section is to establish an understanding of the PAM landscape by providing definitions on physical assets and PAM and what PAM encompass.

2.1.1 The Definition of Physical Assets and Physical Asset Management

The purpose of this section is to give extensive literature on the meaning of *physical* assets in order to fully grasp what PAM aims to manage. According to Hafeez *et al.* (2007), physical assets are easy to identify due to their visible or perceptible existence and are considered of great value on the balance sheet of a firm. Hastings (2010) states that due to the close link between asset management and financial management, it is important to consider the accounting definition of assets and how fixed and current assets are distinguished. According to Hastings (2010, p.3), when considering financial management:

> *"A fixed asset (also called a non-current asset), is a physical item which has value over a period exceeding one year, for example land, buildings, plant and machinery."*

Hastings (2010) further explains that for tax purposes, when a fixed asset is purchased, only its depreciation is considered an expense within the same year of being acquired and not its cost. The reason for this is that when fixed assets are bought or sold, it is seen as the exchange of assets, for example the exchange of money and equipment.

Current assets, on the other hand, are fast moving assets such as inventory (work in progress, consumables, and materials), cash and accounts receivable.

When considering asset management, Amadi-Echendu (2004, p.i) defines a physical asset as *"an entity that is capable of creating, sustaining or destroying value at any stage in its life cycle."*

Hodges (1996, p.1) describes assets as *items* needed to *"carry out the project and convert the input, 'feed material' into the desired product"*.

In manufacturing organisations, the physical assets used to produce the final product is fairly self-evident as the output normally involves physical products, which will in some cases act as raw materials or "feed materials" to be combined and produce further products (Hodges, 1996). Mitchell (2002) states that PAM is applicable to all equipment and fixed assets, which may include buildings, piping, electrical distributions or control systems. Amadi-Echendu (2004) classifies physical assets in four groups:

- Plant
- Equipment
- Buildings
- Infrastructure
- Information technology

For commercial organisations, this may include feed materials, the plant and site supporting the manufacturing process, asset completion contracts and spares for assets.

In other industries, for example the service industry, identifying physical assets are not as apparent, but the same principles apply. In this type of organisation, the physical assets may include the buildings and any equipment or data used to support the services provided. The product of the company, which is in this case the service provided, can act as feed material in the form of data, which can be used in combination with other physical assets to further produce tangible or intangible products.

The British Standard Institute (2008) defines assets in five categories:

- Human assets
- Financial assets
- Information assets
- Intangible assets
- Physical assets

These five asset types need to be managed holistically in order to achieve the optimised management of physical assets and the strategic plan of the organisation. The links between physical asset management and the five asset categories are explained in further detail in Figure 2.1 (British Standard Institute, 2008, p. vi).

According to ISO 55000 (2014), assets include anything that can potentially create value to an organisation. They further define physical assets as equipment, inventory and property which a company owns. They state that physical assets specifically exclude intangible assets such as leases, brands, reputation, intellectual property rights, licences, agreements or use rights.

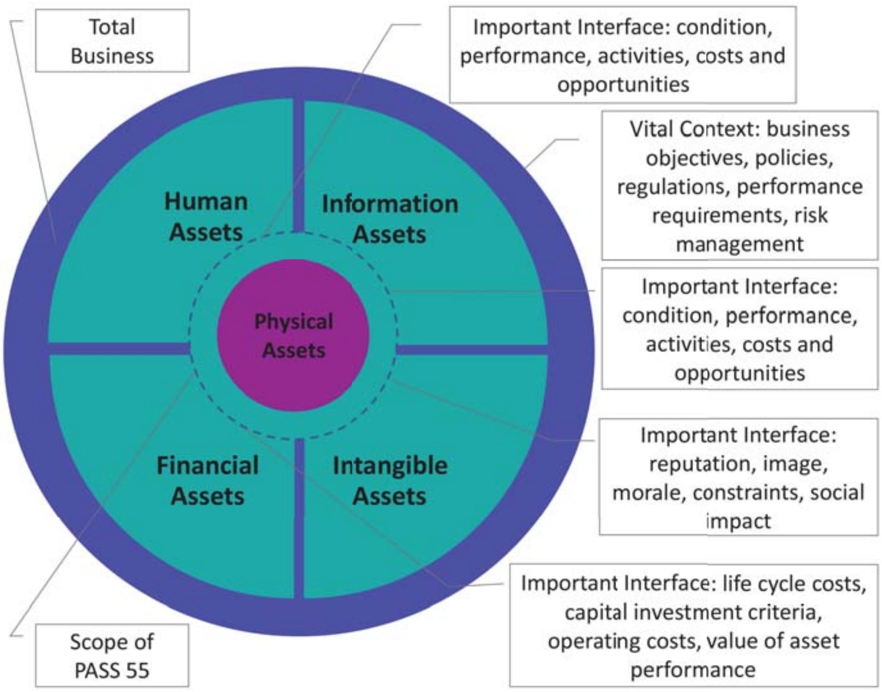


Figure 2.1: PAS 55 Asset Categories.
Adapted from British Standard Institute(2008, p.vi)

To summarise the literature above, a physical asset is a physical item which is used to convert an input into a desired output and has the potential to create, sustain or destroy the value of an organisation. It includes plant, buildings, infrastructure, inventory and information technology and is distinguished from other asset types by its perceptible existence.

Having properly defined the scope of physical assets, it is easier to understand what the asset management process aims to manage.

The British Standard Institute (2008, p.v) defines AM as:

> *"systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset*

> *systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan"*

According to Hastings (2010) AM is the set of activities related to

- recognising what assets are required;
- identifying capital requirements;
- procuring assets;
- providing logistic and maintenance upkeep for assets and
- disposing or refurbishing assets

to effectively and efficiently achieve the desired objective. In other words, its function is to manage asset procurement processes, support and manage assets throughout their life cycle in alignment with company objectives. This entails much more than maintenance, which is normally believed to be at its core. According to Fogel *et al.* (2017), asset data configuration and information management serves as the basis of this process. Finally, ISO 55000 (2014, p.3) defines AM as *"the balancing of cost, opportunities and risks against the desired performance of assets, to achieve organisational objectives"*, where the balancing act needs to be performed over different timeframes.

2.1.2 The Building Blocks of PAM

The Global Forum on Maintenance and Asset Management (2011), who developed the AM Landscape, build a conceptual model of Asset Management, which provides an overview and perspective of AM and its various features. The Global Forum on Maintenance and Asset Management (GFMAM) has been established with the goal of sharing advancements, knowledge and standards in Maintenance and AM (The Global Forum on Maintenance and Asset Management, 2011).

The members of the GFMAM includes (The Global Forum on Maintenance and Asset Management, 2011):

- Asset Management Council (AMCouncil), Australia;
- Associacao das Empresas Brasileiras de Manutencao (ABRAMAN), Brazil;
- European Federation of National Maintenance Societies (EFNMS), Europe;

- Gulf Society of Maintenance Professionals (GSMP), Arabian Gulf Region;
- Iberoamerican Federation on Maintenance (FIM), South America;
- Institute of Asset Management (IAM), UK
- Plant Engineering and Maintenance Association of Canada (PEMAC), Canada
- The Society for Maintenance and Reliability Professionals (SMRP), USA.
- The Southern African Asset Management Association (SAAMA), South Africa

According to The Global Forum on Maintenance and Asset Management (2011, p.5), the AM Landscape is focussed on achieving a third of the GFMAM's objectives, which is *" to facilitate the exchange and alignment of maintenance and asset management knowledge and practices."*

It is made up of three critical areas:

1. **The core**, which is common across all GFMAM members and includes AM principles and subjects;
2. **The knowledge and practice area**, which contains knowledge and practices of each member society within their own AM framework and
3. **The supporting area**, which includes reference to standards and other knowledge and landscapes considered out of the scope of AM, but may influence AM practices of different organisations.

In order for the GFMAM's members to compare, contrast and align their AM knowledge and to provide a common understanding of the AM Scope, they developed six subject groups. These subject groups were derived from an international review of an exhaustive list of AM assesment methodologies and models. They are illustrated in Figure 2.2, known as the IAM's AM conceptual model.

Asset Management Strategy and Planning includes planning for AM on a strategic level.

Asset Management Decision-Making includes defining maintenance requirements and deciding on different renewal and maintenance interventions for sustainable and effective maintenance services. The outcome of this subject is the knowledge of performing maintenance tasks cost-effectively, while managing risk and optimising the use and performance of all assets throughout their lifecycle. It also includes determining appropriate interventions for ageing assets, which may include life extension, disposal, or assessing the cost and risk of alternative interventions.

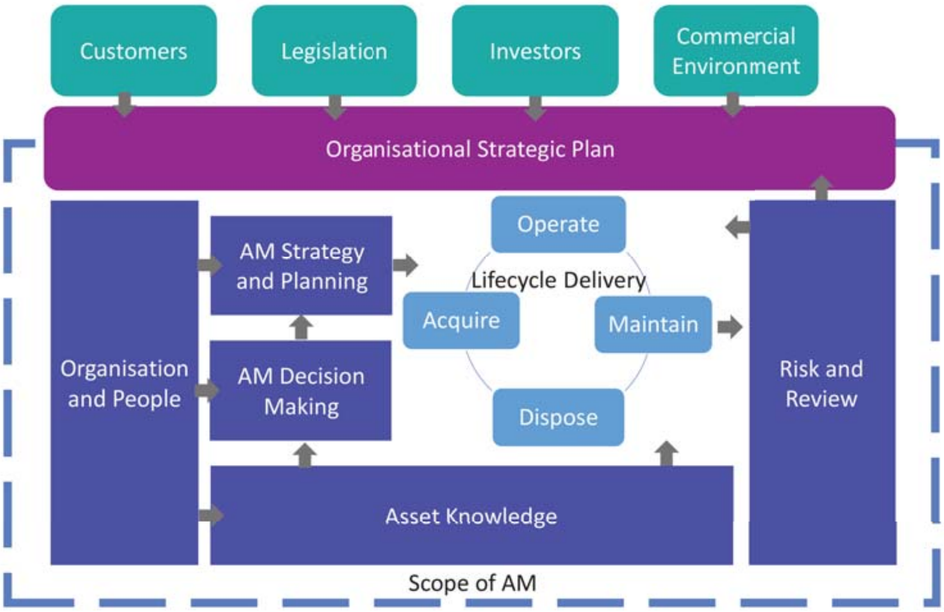


Figure 2.2: The IAM Conceptual Model for Asset Management.
Addapted from The Global Forum on Maintenance and Asset Management (2011, p.20)

Lifecycle Delivery Activities focusses on the effective management of assets and all possible influences throughout their life cycle.

This includes:

- Technical Standards and Legislation – ensuring all AM activities are aligned with relevant technical standards and legislations.
- Asset Acquisition and Commissioning – processes used by the organisation to acquire, install and commission assets.
- Systems Engineering – the effective design, creation and operation of all interrelated AM systems.
- Configuration Management – ensuring consistency in the physical and functional attributes of a product throughout its lifecycle.
- Maintenance Delivery – managing maintenance activities

- Reliability Engineering – ensuring assets will perform to defined standards for a pre-determined period of time in a specific environment.
- Asset Operations – ensuring the performance of assets are aligned with business goals.
- Resource Management – the effective management of organisational resources in support of its AM plans.
- Fault and Incident Response – organisational processes to respond to accidents.
- Asset Rationalisation and Disposal – Increasing asset efficiency to meet capacity requirements, or disposing asset if unable to meet desired outcome.

Asset knowledge enablers includes collecting, reporting, managing and storing asset information and knowledge consistently and systematically in support of the organisation's AM strategy and AM decision-making.

Organization and People Enablers includes effectively establishing and managing contractors and suppliers, AM leadership, organisational structure and culture and competence and behaviour.

Risk and Review includes the policies and processes put in place for managing risk and enhancing opportunity. This may include social and environmental responsibility to ensure sustainable AM activities. Assets and maintenance activities should be audited and reviewed periodically to ensure continuous effectiveness (The Global Forum on Maintenance and Asset Management, 2011).

The six subject areas are further divided in 39 subjects, illustrated in Table 2.1. Visser and Botha (2015) conducted studies about the importance of the 39 subjects of AM defined by GFMAM, where they sent surveys to two sample groups. The first sample included individuals with different backgrounds enrolled for a Masters of Engineering Management and were mostly Managers and Supervisors. The second sample included individuals enrolled for a Honours degree in the Management of Technology taking a Maintenance Management course at the University of Pretoria and were mostly Engineers and Managers.

Subjects regarded as important includes AM strategy, reliability engineering, asset operations, AM plan, maintenance delivery, capital investment decision-making, AM policy, maintenance tactics, AM leadership, systems engineering and risk assessment and management. Subjects regarded as unimportant include weather and climate change, accounting practices, contract and supplier management, asset change management, asset knowledge standards, stakeholder relations, asset rationalisation and disposal, configuration management, system engineering, recoursing strategy and optimisation, shutdowns and outage strategy, procurement and supply chain management, organisational culture, contingency planning and resilience and demand analysis (Visser and Botha, 2015).

Table 2.1: 39 AM Subjects.
Adapted from The Global Forum on Maintenance and Asset Management (2011, p.7,8)

AM Subject Group	AM Subject
AM Strategy and Planning	AM Policy AM Strategy Demand Analysis Strategic Planning AM Plan
AM Decision-Making	Whole-life Cost and Value Optimisation Operations and Maintenance Decision-Making Capital Investment Decision-Making Resourcing Strategy and Optimisation Shutdowns, Outage Strategy and Optimisation Ageing Assets Strategy
Lifecycle Delivery Activities	Technical Standards and Legislation Asset Acquisition and Commissioning Systems Engineering Configuration Management Maintenance Delivery Asset Operations Resource Management Shutdown and Outage Management Reliability Engineering Fault and Incident Response Asset Rationalisation and Disposal
Asset Knowledge Enablers	Asset Information Strategy Asset Knowledge Standards Asset Information Systems Asset Data and Knowledge
Organization and People Enablers	Contract and Supplier Management Asset Management Leadership Organizational Structure and Culture Competence and Behaviour
Risk and Review	Criticality, Risk Assessment and Management Contingency Planning and Resilience Analysis Sustainable Development Weather and Climate Change Asset and Systems Change Management Assets Systems, Performance and Health Monitoring Management Review, Audit and Assurance Accounting Practices Stakeholder Relations

In the previous section, extensive literature was provided on the definition of PAM and certain concepts were continuously repeated as the essence of PAM.

These concepts include the following:

- Organisational Alignment
- Risk and Opportunity Management
- Financial Management
- Performance Management
- Asset Lifecycle Magement (ALCM)
- Optimal Decision Making
- Sustainability
- Maintenance

ISO 55000 (2014) identified six critical elements of AM:

- Context of the Organisation;
- Planning;
- Support;
- Operation;
- Performance Evaluation and
- Improvement

Context of the Organisation refers to all internal and external contexts an organisation should take into consideration. Internal context include organisational cutlure, environment, mission, vision and values. External context includes social, cultural, economic and physical environment as well as stakeholder inputs, concerns and expectations.

Leadership requires top management to develop AM policies, objectives, visions, values and responsibilities and aligning it with those of the organisation. It also requires top management to ensure that all resources are available to support the AMS. Management from all levels are furthermore responsible for the planning, implementation and operation of its AMS and communicating the AM objectives and importance of its AMS to the rest of the organisation.

Planning refers to planning the translation of organisational objectives to AM activities. This section addresses the importance of Stakeholder involvement, risk management, continuous improvement and ALCM for the establishment and to operate an AMS.

Support addresses the importance of resource management and asset information management in support of the AMS.

Operation states that the organisation's AMS should direct its AM activities and stretches the importance of risk management when change occurs in its AM plans and procedures

Performance evaluation addresses the importance of asset data and its translation to information in order to effectively evaluate AM performance. It furthermore addresses the importance of continually comparing asset performance obtained through audits with desired objectives and evaluating reasons for not reaching it or opportunities when it is exceeded.

Improvement requires an organisation to continually determine opportunity for improvements through monitoring the performance of the AM system or the performance of the assets through audits and management reviews. Risk Management is critical before implementing improvements or when mitigating possible asset-related incidents or emergency situations.

When considering these six critical elements of AM and investigating the ISO 55002 and ISO 55002 documents, there are a few critical AM functions mentioned:

- AM Strategy and Planning;
- AM Leadership;
- Risk and Opportunity Management;
- Resource Management;
- Continuous Improvement;
- Asset Information Management and
- ALCM
- Work Management
- Stakeholder Management
- Management Review, Audits and Assurance

– Competence and Behaviour

– Change Management

– Operations and Performance Management

– Fault and Incident Responce

This section investigated what is regarded as the bulding blocks of PAM through the perspective of the AML, the ISO 55000 series, PAM definitions and research students. Due to time limitations of this study, not all PAM areas can be included in its scope. Chapter 4 quantitavely analyses the literature of this section in order to determine PAM focus areas for this study, which is followed by literature on each selected area. The following section will provide literature on the ISO 5500X Family of Standards, which provides guildelines for the effective management of physical assets.

2.2 The ISO 55000 Series

The aim of this section is to provide a summary of each document of the ISO 5500X Family of Standards. It is recommended to read this section with the ISO 55000 document at hand should more information on specific aspects be desired, as this is merely a summary.

2.2.1 The ISO 55000 Document Overview

ISO comprises of a worldwide federation of international standards bodies (ISO member bodies), which establishes ISO technical committees for specific subjects. These committees carries out the work for preparing international standards, where any of the ISO member bodies have the right to be part of it and normally do so in collaboration with international organisations - government and non-government (ISO 55000, 2014).

It took the ISO three years to publish a standard for asset management systems, which consists of three different documents (Jenkins, 2014; van den Honert *et al.*, 2013):

1. **ISO 55000** – Gives an overview of the field of asset management as well as standard terms and definitions to be used.

2. **ISO 55001** – States the requirements for an integrated management system for assets.

3. **ISO 55002** – Provides guidance for ISO 5500X implementation.

These documents are together referred to as the ISO 5500X suite of standards (van den Honert *et al.*, 2013). The ISO 5500X family of standards is categorised under the ISO's "*management system standards*", together with other well-known standards such as ISO 9000 Quality Management, which are intended to provide a framework for setting up and operating management systems (Jenkins, 2014; ISO 55000, 2014).

The standard's goal is to undertake wholesale business transformation, rather than just fixing what is broken. This causes great alignment across all business functions in order to meet current and future needs of an organisation as a whole, where decisions are more likely to be sub-optimal, as focus is given on all departments (ISO 55000, 2014).

An organisation is most likely to realise great value in the implementation of this standard if they (ISO 55000, 2014):

- consider to increase the realisation of value from their asset base;
- are involved in the establishment, implementation, maintenance and improvement of an AMS and
- are involved in the planning, design, implementation and review of AM activities, together with service providers

According to ISO 55000 (2014), the greatest benefit achieved through the adoption of the ISO 5500X family of standards is reaching organisational objectives through effective and efficient AM consistently and sustainably.

2.2.2 ISO 55000

The ISO 55000 document provides a summary of the asset management landscape and asset management systems as well as conditions for the ISO 55001 and ISO 55002 documents (ISO 55000, 2014). This includes the basic AM principles, benefits an effective AM system (AMS) has to offer and a brief outline of the role the different management levels of an organisation has to play in the AMS (van den Honert *et al.*, 2013). It is divided into three different sections: Scope, Asset Management and Terms and definitions.

2.2.2.1 ISO 55000 Scope

The scope of this international documents outlines three main points:

Note 1 : *The intended application of ISO 55000 is specific to physical assets, but can also be used for other asset types.*

Note 2: *ISO 55000 does not provide guidance on managing physical assets on a financial, accounting or technical basis.*

Note 3 : *The term "asset management system" in the ISO 55000, 55001 and 55002 documents is used to describe a management system for asset management.*

2.2.2.2 Asset Management

The primary goal of this section is to provide an overview of AM and an AMS. This consists of information on the different types of assets as well as the fundamentals and benefits of AM in general. It also includes information on the relationship between AM and an AMS and a detailed explanation on the different elements of an AMS.

Assets

According to ISO 55000 (2014), in order to identify the critical assets of an organisation, the following key factors first need be identified:

- The nature and motivation of the organisation
- The organisation's operating context
- The organisation's financial limitations and regulatory requirements
- The needs and expectations of the organisation and its stakeholders

These factors need continually be considered when establishing, implementing, maintaining and continually improving asset management. ISO 55000 (2014, p.2) defines an asset as:

> *"an item, thing or entity that has potential or actual value to an organisation. The value will vary between different organisations and their stakeholders, and can be tangible or intangible, financial or non-financial."*

An important concept to understand when considering asset management is the life of an asset. This is defined by ISO 55000 (2014) as the period from asset creation to asset depletion, where it can provide value to more than one organisation and its value can change over its life time. Assets can also be managed in groups in order to achieve specific or additional benefits. Groups of assets are usually referred to as *asset types, asset systems or asset portfolios*.

Asset Management

As mentioned in Section 2.1.1, ISO 55000 defines AM as the act of balancing costs, opportunities and risks against an asset's desired performance, to achieve the objectives of an organisation. This may be considered over different timeframes during an asset's lifecycle.

The ISO 55000 document states that the benefits of AM may comprise of, but is not restricted to:

- increased financial performance;
- informed asset investment decisions;
- managed risk;
- improved services and output;
- demonstrated social responsibility;
- demonstrated compliance;
- enhanced reputation;
- improved organisational sustainability and
- improved efficiency and effectiveness.

ISO 55000 identifies four fundamentals of AM:

1. Value
2. Alignment
3. Leadership
4. Assurance

Value refers to the value the asset brings to an organisation, as asset management does not focus on the asset itself, but rather the value it creates.

Alignment refers to the translation of organisational objectives into technical and financial decisions, plans and activities.

Leadership and workplace culture will determine whether value will be realised from assets. It is essential for all levels of an organisation to be committed to implement, operate and improve an AMS. Employees and stakeholders should at all times be informed and roles and responsibilities should clearly be defined and assigned to employees showing competence.

Assurance that assets will perform as desired. This can be achieved by implementing processes that connects asset performance with organisational objectives. Capable and competent resources should also be assigned to managing the AMS.

The Asset Management System

> *"An asset management system is used by the organisation to direct, coordinate and control asset management activities. It can provide improved risk control and gives assurance that the asset management objectives will be achieved on a consistent basis."* –ISO 55000 (2014, p.4)

Some aspects such as leadership, culture, motivation and behaviour, which can influence the effectiveness of the AM objectives, may be managed by functions outside the AMS.

The relationship between managing the organisation, AM, the AMS and asset portfolio is illustrated in Figure 2.3. As discussed previously, AM refers to coordinated *activities* of an organisation to *realise value* from assets. According to ISO 55000 (2014, p.4), the AMS is:

> *"A set of interrelated and interacting elements of an organisation, whose function is to establish the asset management policy and asset management objectives, and the processes needed to achieve those objectives."* –ISO 55000 (2014, p.4)

An asset portfolio contains the collection of assets within the scope of the AMS.

The elements of an AMS can be viewed as a set of tools to assure that AM activities will be executed. An asset can contribute to more than one business function, where the AMS focusses on coordinating these contributions as well as the interaction between business functions. ISO 55001 identifies specifications for an AMS, but not the design of the system. ISO 55002 provides guidance to implement and operate an AMS.

The process of creating an AMS has the potential to bring numerous benefits to an organisation.

Figure 2.3: Relationship Between Key AM Terms.
Adapted from ISO 55000 (2014, p.4)

Firstly, it can increase organisational knowledge and decision-making by implementing tools and processes to collect and analyse data. Secondly, it provides employees with new perspectives on creating value within the company, which can be used in business functions outside of asset management. Thirdly, it is focussed on identifying possible issues regarding the functional integration of the organisation and life cycle planning, as the implementation of an AMS is cross-functional.

Almost the whole organisation benefit from an AMS. Top management benefits from new insights instilled and cross functional integration. The AMS improves cross-functional communication and assures that the organisation's assets are sustainable and benchmarked against best practices. Financial functions benefit through increased data accuracy and linkages. Human resources benefit through newly developed competency models, training programs and processes for coaching and mentoring.

From the above literature, it is clear that an AMS has an impact on the whole organisation, including stakeholders and external service providers. It is therefore important to have a thorough understanding of all the elements that it is made up of. This includes:

1. context of the organisation;
2. leadership;
3. planning;
4. support;
5. operation;
6. performance evaluation and
7. improvement.

The structure of the ISO 55001 document is categorised in a manner consistent with these elements. More detail will be given on each element in section 2.2.3, which provides literature on the ISO 55001 and ISO 55002 documents.

2.2.2.3 Integrated Management System Approach

An *integrated management system approach* is the process of building a management system on elements of management systems already established within the organisation. Examples of already established management systems may include health, safety, environment, quality and risk management. This will aid cross-functional support and reduce the efforts, expenses and time of building a newly created management system.

2.2.2.4 Terms and Definitions

The terms and definitions section of this international standard provides definitions on different terms used in the ISO 5500X series. It gives descriptions of general terms used, terms specific to assets and terms specific to asset management.

This section provided a brief summary on the ISO 55000 document. The next section will provide literature on the ISO 55001 and ISO 55002 documents.

2.2.3 ISO 55001 and ISO 55002

The main purpose of the ISO 55001 document is to specify the requirements for the establishment, implementation, maintenance and improvement of an asset management system. It can be used by any organisation and the organisation should by itself determine which assets are applicable. It is important to note that all sections in the ISO 55001 document is equally important. The ISO 55002 document gives guidance for the implementation of an AMS, as stated by the requirements within the ISO 55001 document.

The scope of these documents is bound by the same limitations as mentioned in section 2.2.2.1 (ISO 55002, 2014; ISO 55001, 2014).

The ISO 55001 and ISO 550002 documents are categorised according to the main AM fundamentals, as defined by the ISO 55000 document. The structure of the body of these documents is as follows:

1. Context of the Organisation
2. Leadership
3. Planning
4. Support
5. Operation
6. Performance evaluation
7. Improvements

The rest of this section will provide information on the primary focus of each category within the ISO 55001 and ISO 55002 documents, which will follow the general layout of these documents.

2.2.3.1 Context of the Organisation

In the ISO 55001 document, the main focus of this section is to define the boundaries of the AMS, asset portfolio and criteria for decision making. In order to determine the boundaries of the AMS, the stakeholders relevant to the AMS and their requirements for recording AM data need be identified. Their needs and expectations should also be identified and documented and benchmarked against the performance of the assets contained in the organisation's asset portfolio.

A Strategic AM Plan (SAMP) should be developed and documented and should include information on how the AMS will support successfully achieving AM objectives. It should also record information on the relationship between organisational objectives and AM objectives. The scope of the AMS should also be aligned with the SAMP and asset management policy and its interaction with other management systems identified (ISO 55001, 2014; ISO 55002, 2014)

According to ISO 55002 (2014), the AMS should consist of:

1. the AM Plan;
2. the AM Objective;
3. the AM Policy and
4. the SAMP.

Figure 2.4 shows the relationship between these key elements as well as relevant clauses in the ISO 55001 document. This figure can also be found in the ISO 55002 document in Appendices B.

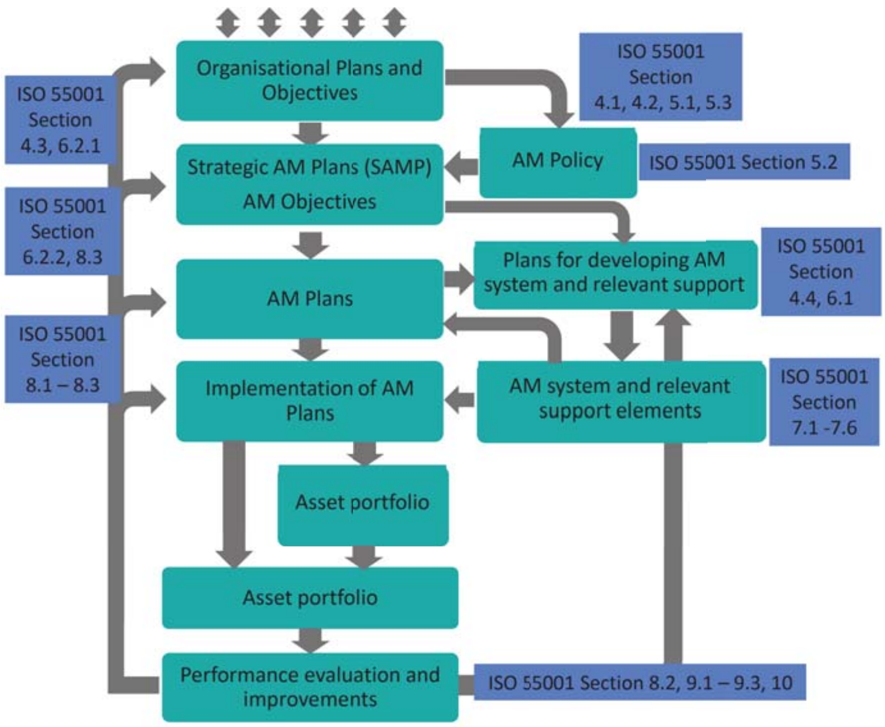


Figure 2.4: Relationship Between Elements of an AMS.
Adapted from ISO 55002 (2014, p.30)

From Figure 2.4, it can be seen that the organisational plans and objectives are formed depending on the scope set out by the organisation and stakeholders. An AM policy, SAMP and AM objectives are derived from these organisational plans and objectives. The AM policy, SAMP and AM objectives should be used to form formal AM plans and plans for developing and AMS and relevant support, which should guide the organisation towards the successful implementation of a management system for the assets contained in the asset portfolio. The performance of the assets should continually be evaluated and improved, where applicable (ISO 55001, 2014).

2.2.3.2 Leadership

The main focus of this section is on the commitment of senior-level leaders of an organisation. They should drive effective collaboration between the AMS and different organisational functions, make necessary resources available, ensure alignment between risk management of the organisation and asset management, and ensure that employees are informed at all times.

They should also ensure that the AM policy, SAMP and AM objectives are aligned with organisational objectives. The AM policy demonstrates the organisation's commitments and expectations for decisions, activities and behaviour concerning AM. Commitment should be demonstrated by upper management by authorising the AM Policy.

Furthermore, competent employees should be assigned to roles involved with the maintenance and usage of the AMS and their roles should clearly be communicated to stakeholders (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

2.2.3.3 Planning

The main aim of this section is to ensure that the AMS achieves the desired outcome, while eliminating undesirable effects.

An SAMP should be developed, documented and updated to indicate the activities to be executed and resourced used to reach AM objectives. The SAMP should also periodically be assessed in order to determine if it is supporting current AM objectives. The SAMP should address risk and opportunity and contain a detailed plan to reach asset management objectives. Furthermore, the AM risk management approach should be consistent with the risk management approach of the organisation, where applicable.

The importance of considering economic aspects of AM is also considered in this section. Different effects on capital expenditure, operational expenses and pricing impacts should be taken into consideration when making any decisions regarding AM.

A structured approach for prioritising the resources used and steps taken to achieve the organisation's SAMP and AM objectives should be put in place. It is important to always consider the perceptions of the stakeholders, as their actions can have a great impact on the organisation. The asset management objectives should also be measurable, in order to be monitored effectively and drive improvement actions (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

2.2.3.4 Support

The main goal of this section is to ensure that the organisation provides the necessary resources to meet AM objectives and implement the activities contained in the SAMP. These resources should at all times be competent and aware of the AM policy, their activities, risk and opportunities, the benefits of conforming to AM requirements, and consequences of not conforming. It is also important to decide on criteria and actions to take to priorotise AM activities, should recources be limited.

This section also states the importance of aligning the organisational design and business processes with asset management competencies. For example, if an asset manager atruggle to do financial transactions, it will influence business functions outside of AM.

Communication with internal and external stakeholders should be planned in detail. Information needed to support its assets, AM, the AMS and achieving organisational objectives should be identified and managed. Only the information needed to assure the effectiveness of the organisations' AM and AMS should be retrieved, documented, updated and kept under appropriate control (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

2.2.3.5 Operation

This section addresses the fact that processes needed to meet requirements should thoroughly be planned, implemented, controlled and associated risks managed. During implementation cost, risk and performance should at all times be balanced in order to identify and resolve conflicts between planned and actual. Activities outlined in the SAMP and corrective and preventive action should at all times be implemented.

This section also addresses change management and the need to manage risks related to change management.

Furthermore, the process of outsourcing activities should at all times be controlled and related risks managed, as this can have a significant impact on the achievement of AM objectives. It is also important to ensure that the service provider(s) fully understand the AMS of the organisation and that their AMS is aligned with organisational objectives (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

2.2.3.6 Performance Evaluation

This section requires an organisation to monitor, measure, analyse and evaluate asset performance, the organisation's AMS and AM activities on a regular basis. The organisation should also at all times ensure that the organisational objectives and policies are being achieved. This, and the effectiveness of managing risks and opportunities should periodically be reported on.

Performance indicators should be established and asset data retrieved in order to measure AM activities and its outcome and to identify areas for improvement.

Internal audits should be conducted in order to determine if the AMS satisfies the requirements outlined in the ISO 55001 document and to aid learning and improvement of the AMS.

Top management should at planned intervals review the organisations asset portfolio, AMS and AM activity in order to ensure their applicability, adequacy and effectiveness.

In the context of continual improvement, the organisation should update its knowledge on new asset technologies and practices (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

2.2.3.7 Improvement

This section provides requirements for corrective action should nonconformities and incidents occur. Preventive action should be taken, based on potential failure in asset performance.

Furthermore, the suitability, adequacy and effectiveness of the organisations' AM and AMS should continuously be improved. Continuous improvement should be regarded as an iterative process, with the ultimate goal of achieving organisational objectives (Jenkins, 2014; ISO 55001, 2014; ISO 55002, 2014).

This section provided a summary of the ISO 5500X Family of Standards. The next section will provide in-depth literature on the Lean Landscape.

2.3 Lean

The aim of this section is to provide literature on Lean in order to identify how it can be used to support PAM functions. The fundamentals of Lean is provided, followed by a description of its various tools and techniques to aid continuous improvement. This is followed by literature on Lean maintenance and Lean manufacturing and their interdepandant relationship, where each section describes the Lean transformation process in detail.

2.3.1 Lean Introduction

Lean is a continuous improvement strategy that focusses on increasing value by reducing waste. It is not about productivity, but about removing waste an building quality. This means that not only the manufacturing plant is involved in the Lean transformation, but all of the organisation's business processes. This includes timely billing and efficient sales and advertising, just as much as it means accurate machining and reliable production equipment (Hawkins and Smith, 2004).

According to Hawkins and Smith (2004, p.12):

> *"Lean is a comprehensive package that includes reducing inventory, standardizing work routines, improving processes, empowering workers to make decisions about quality, soliciting worker ideas, proofing for mistakes, applying just-in-time delivery and using Lean supply chain. One might work without the others, but not for long. Lean thinking is elemental to a Lean transformation...Making gains in one department at the cost of efficiency in another department is definitely not Lean thinking."*

Lean consists of five principles, which are of fundamental importance to Lean Implementation (Hawkins and Smith, 2004). According to Hawkins and Smith (2004); Bicheno (2004); Womack and Jones (2003) the five Lean principles are as follows:

Step 1: Identify the customers and what they value

The first step involves specifying value from the perspective of the customers, both internal and external. Internal customers may include production and production equipment operators, while external customers include the product consumer. Value should be defined in terms of a specific product, which meets the customers' needs at a specific predefined cost and time. Customer requirements should bound the definition of value, and not what is preferred by the organisation or existing manufacturing facilities.

Step 2: Map the value stream

The second step consists of identifying the value stream. This includes the sequence of specific actions to transform a concept into the final product and distribute it to the end consumer. These actions form three critical management tasks of an organisation: (1) the problem-solving task, (2) the information management task and (3) the physical transformation task. A map should be created of the current and future state of the value stream, where non value-adding activities should be identified and eliminated.

Step 3: Create flow to the customer

The third step is Flow, which involves making the remaining value steps flow and continuously moving. Batch and queue should be avoided as far as possible and a non value-adding step should never delay a value-adding step. According to Bicheno (2004, p.11) *"the important thing is vision: have in mind a guiding strategy that will move you inexorably towards flow"*.

Furthermore, maintenance must be ready to restore equipment to production at scheduled on-line time.

Step 4: Establish pull based on customer demand

Step four involves enabling customers to pull as needed, eliminating the need for a sales forecast. This means responding to the short-term needs of the customers and not overproducing. Pull should be considered on two levels: micro and macro. On the micro level, pull signals are responded to from the internal customer, which may be the next step in the process. On a macro level, the organisation has to push up to a certain point, where after pull signals of the final customer should be responded to. This should commence along the whole supply chain.

Step 5: Seek continuous improvement

The final step involves perfecting the process and using benchmarking practices. Note that the process should not be benchmarked against competitors, but rather the principle of zero waste. Perfection involves quality as well as producing exactly what the customer wants, exactly when and at a relatively reasonable price with no waste. When maintenance is involved, maintenance tasks should be performed *"correctly the first time and every time"* (Hawkins and Smith, 2004, p.108). If this is not the case, the next Lean transformation should begin, which offers a product which is *"ever more nearly what the customer wants"* (Hawkins and Smith, 2004, p.108).

A key Lean concept is the *cost reduction principle*. This principle is based on the mindset that profit can only be increased by reducing waste. The price of the customer should first be determined, from which the cost of waste should be deducted in order to determine the organisation's profit margin. It is imperative to understand what Lean defines as *waste* (otherwise known as *muda*), as waste elimination is at the very core of becoming Lean. Myerson (2012) states the main goal of Lean waste elimination to be an outcome which conforms to the wants and needs of the end user. Bicheno (2004) furthermore states that waste is not an end itself, but a means to achieving the Lean ideal.

The following seven forms of waste is strived to be eliminated (Bicheno, 2004; Myerson, 2012; Hawkins and Smith, 2004; Askin and Goldberg, 2002; Womack and Jones, 2003):

1. The Waste of Overproduction

   The waste of overproduction includes making too much, too early or "just-in-case". Production costs money and there is no reason to produce what cannot be sold. The goal should be to produce exactly what is required, when it is required, with perfect quality.

2. The Waste of Waiting

   The waste of waiting is directly relevant to flow, where Lean is more focussed on the flow of product than keeping operators busy. As soon as products are not moving, it is an indication of waste. When the workforce is waiting for work or wasting time figuring out how to perform equipment repair, the wasted time could have been spent on a better activity such as training, cleaning or maintaining, of which are all value-adding.

3. The Waste of Unnecessary Motion

   The waste of unnecessary motion refers to both human and machine. This includes the consideration of human ergonomics and workplace layout. As soon as an operator has to exert themselves in any way, the quality and productivity of the process is influenced. Today, this is also a health and safety issue. Furthermore, poor workplace layout involves micro waste of movement, and is normally repeated numerous times a day. In maintenance, time is often wasted searching for key information such as repair histories, parts lists, manuals etc. Normally, Lean's 5S, which will be discussed futher in this chapter, is used to address this form of waste.

4. The Waste of Transportation

   Bicheno (2004, p.17) states that *"customers do not pay to have goods moved around, so ANY movement of materials is a waste."* The amount of transportation and material handling is directly proportional to the likelihood of damage and deterioration. Inefficient means of transportation can also lead to poor communication, as feedback on poor quality is inversely linked to transportation length. The aim should be to physically locate individuals from interacting groups as close together as possible.

5. The Waste of Over processing

   This form of waste refers to using complex machinery or processes to do simple tasks, or using machinery or processes that are unable to produce an outcome of high quality. According to Bicheno (2004, p.17) *"the ideal is to have machines with available capacity exactly matched to demand"*. He further advises to think in terms of *small is beautiful*, and that small equipment

   > *"avoid bottlenecks, improve flow lengths, perhaps are simpler, can be maintained at different times (instead of affecting the whole plant), and may improve cash flow and keep up with technology (buying one small machine per year, instead of one big machine every five years)"*. - Bicheno (2004, p.18)

6. The Waste of Unnecessary Inventory

   Inventory is viewed as the enemy of quality and productivity. In maintenance, a great contributor to waste in time and overhead costs is repair parts and storage. The cost associated with extra inventory is related to the money tied up in it. Unnecessary inventory leads to increased space utilisation, increased lead time and prevents quick identification of problems. There are three forms of inventory: raw material, work-in-process (WIP) and finished goods. Just-in-time (JIT) manufacturing has taught that inventory covers up problems faced by an organisation, such as keeping inventory to replace a product of low quality should it suffice.

7. The Waste of Defects

Defects cost money, in the short- and long-term. Defects can be categorised as internal or external failures. Internal failure includes scrap, rework or delay, while external failure includes warranties, repairs, field services and also lost custom. If defects are undetected, their costs normally tend to escalate as it moves through the process. When considering maintenance, defects are regarded as instances of reworking, redoing and repeating due to the inability to detect the root cause of a failure. It also refers to performing preventive maintenance that does not add value to the final product.

The most highly developed Lean system is the Toyota Production System. The two main pillars of the Toyota Production system includes JIT production and Jidoka (autonomation) (Tapping *et al.*, 2002; Ohno, 1988).

The purpose of *JIT* is to provide customers what they ordered, when they are needed, in the exact amount needed and to the highest possible quality (Tapping *et al.*, 2002; Ohno, 1988). According to Askin and Goldberg (2002, p.352) JIT is *"a philosophy for optimising the performance of a manufacturing system"*. This encompasses not only producing to the demand of the external customer, but also the internal customer through the value stream. Tools such as *value stream mapping, takt time, standardised work, kanban and supermarket pull* is implemented in order to create a production system that is true to JIT (Tapping *et al.*, 2002).

Jidoka refers to using automated production processes with a human touch to mistake-proof the detection of defects and apply operators effectively elsewhere, such as performing multiple tasks in work cells. The main goals of jidoka is to have zero defects and to eliminate any probability that a defective problem will move downstream and reach the end user. Jidoka also uses autonomation to promote flow and reduce waste (Tapping *et al.*, 2002; Ohno, 1988).

Lean also focusses greatly on the organisation and standardisation of the workplace. This should be strived for even before any Lean tools can be considered. This can be achieved by the 5S system (Tapping *et al.*, 2002). The 5 Ss stresses the concept of keeping things in the workplace under control. It also changes the mind-set of the workforce from *I work in a filthy factory* to *I work in a manufacturing laboratory*. It is the basic housekeeping principle for Lean, quality and safety (Bicheno, 2004; Willmott and McCarthy, 2001*b*).

The following steps should be carried out by the team and their supervisor (Bicheno, 2004; Willmott and McCarthy, 2001*b*):

1. **Seiri\Sort** – The main goal of Sort is to confiscate all items from the workplace which are undesired, unnecessary and not currently used. It works on

the principle of *only what is needed, only the amount needed and only when needed*. The main focus of the first pillar is to leave only the bare essentials and keep in mind that *when in doubt, throw it out* (Rubin *et al.*, 1996).

The greatest struggle experienced in the first phase of the 5 S's is the differentiation between the necessary and the unnecessary. To accompany this problem, a process named *Red Tagging* is commonly used. Red tagging is based on the principle that a component whose importance is uncertain gets tagged with a red tag and is put in a separate area called the *red-tag holding area*. This area is used solely for the storage of components with red tags which requires further evaluation. When an item is set aside and watched for an agreed-upon time, it tends to be easier to accept that it is unnecessary. The outcome of Sort is a work environment with optimised management and utilisation of space, time, money and energy (Rubin *et al.*, 1996).

2. **Seiton\Set in Order** – The second pillar, Set in Order, constitutes organising and labelling items for ease of accessibility. This is of high importance, because it eliminates many kinds of waste. This may include wasting time searching for components, waste due to difficulty in using and returning items, the waste of human energy, the waste of excess inventory and the waste to be found through unsafe conditions (Rubin *et al.*, 1996).

3. **Seiso\Shine** – The third pillar, Shine, consists of the removal of dirt, dust and grime from the workplace– keeping everything swept and clean. This is imperative, because regular cleaning keeps the workplace and components in top condition and ensures that components, equipment and work conditions are inspected frequently (Rubin *et al.*, 1996).

4. **Seiketsu\Standardisation** – Standardization is the result that follows when the first three pillars are properly maintained. In other words, standardization is a set of methods used to maintain the first three pillars. It works against the possibility of conditions deteriorating to their initial state. It prevents setbacks in the first three pillars, ensures that the establishment of the first three pillars becomes a daily habit and that they are maintained at all times. Standardisation consists of tasks such as assigning responsibilities to the first three S's, integrating the duties of the first three S's into daily work duties, and daily evaluation of the maintenance of the first three S's, normally in the form of check lists (Rubin *et al.*, 1996).

5. **Shitsuke\Sustain** – Sustain refers to the participation and improvement of the 5 S system. It accounts for actions performed in order to increase motivation and awareness amongst the workforce around the 5 S's. It mainly

consists of carrying out audits, mapping improvement and training (Bicheno, 2004; Rubin *et al.*, 1996).

Some organisations add a sixth S - **Safety**. Although good to highlight, it may take away from the importance of incorporating safety in each of the 5 S steps (Bicheno, 2004).

A fundamental element of Lean thinking is continuous improvement, particularly applied to people, products, processes and services. A quality tools that aids this process is the Shewart Cycle, otherwise known as Plan-Do-Study (or Check)-Act (PDSA/PDCA) or the Deming Cycle. The PDCA cycle is a problem-solving cycle that is virtually a never ending process, which is key for achieving transformation (Hawkins and Smith, 2004). Lean also has numerous strategic tools, of which Hoshin Kanri (otherwise known as policy deployment) is the most widely used. Hoshin Kanri is a tool used to align the organisation's vision with organisational objectives and ensure that everyone in the organisation is aligned and works towards the same goals (Jolayemi, 2008). It comprises of the following eight steps (Jolayemi, 2008):

1. Establish organisation vision
2. Develop 3-5 year plan
3. Develop annual objective
4. Deploy or roll down to departments to develop plans including targets and means
5. Implementation
6. Regular progress review – monthly and quaterly
7. Annual review
8. Repeat step 1, 2 or 3 again, depending on the outcome of the annual review

Lean can be divided into two main concepts (Hawkins and Smith, 2004):

1. Lean Maintenance
2. Lean Manufacturing

The largest problem in Lean Manufacturing is failing to implement a reliable maintenance system. As waste is reduced and machine operating time increased, machine reliability is decreased (Hawkins and Smith, 2004). Hawkins and Smith (2004) mentions three laws of manufacturing maintenance:

Law 1: If manufacturing equipment is properly maintained, many quality products are produced.

Law 2: If manufacturing equipment is improperly maintained, fewer products are produced with questionable quality.

Law 3: Inoperable equipment produces no products.

It will be of no use to streamline a process with inoperable equipment. Therefore, it is imperative for Lean Maintenance to first be established before Lean Manufacturing is implemented. Even prior to applying Lean tools at all, the foundation of Lean Maintenance, *Total Productive Maintenance (TPM)*, need first effectively be put in place, otherwise the structure is designed to fail (Hawkins and Smith, 2004). In the early 1970's, Toyota was expanding rapidly due to its Lean implementation, but still continued to use the classic "run-to-failure" maintenance approach (Kelly, 2006; Bakri *et al.*, 2012). The evolution of TPM into company-wide TPM occurred because of the realisation that as equipment became more reliable, less time need be spent by management to *put out fires* (McCarthy and Rich, 2004). In order to provide effective and efficient maintenance, improve plant availability, product quality and resource utilisation, the organisation decided to use TPM (Kelly, 2006). According to Kelly(2006, p.248) , TPM is *"a sub-set of 'genba kanri' (workshop management), using a people-oriented approach to resolve maintenance and reliability problems at source."*

The relationship between Lean Manufacturing, Lean Maintenance and TPM is illustrated in Figure 2.5 and 2.6. First, equipment needs to be maintained through TPM. Secondly, the reliability and accuracy of the equipment components need be maximised through Lean Maintenance. Thirdly, Lean Production tools can be implemented to make the production process as efficient as possible. Finally, quality measures need be put in place in order to ensure an output of high quality. The final step falls out of the scope of this project. It's important to note that Lean Maintenance is not a separate entity from Lean Manufacturing, but rather an integral part of its implementation.

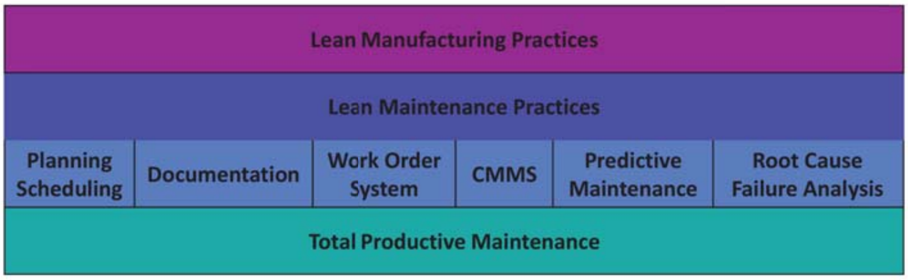


Figure 2.5: Relationship between TPM, Lean Maintenance and Lean Manufacturing. *Adapted from Hawkins and Smith (2004, p.14)*

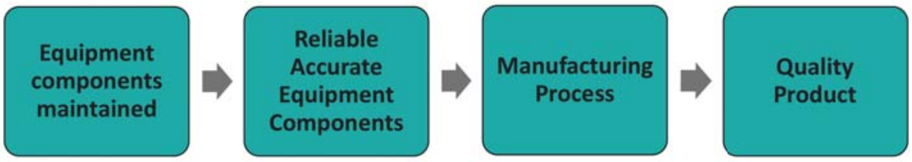


Figure 2.6: Lean Manufacturing. *Adapted from Hawkins and Smith (2004, p.13)*

The following section will provide literature on Lean production and Lean maintenance practices and tools.

2.3.1.1 Lean Production Practices and Tools

Shah and Ward (2003) studied sixteen different reputable secondary sources and made a summary on the different practices used to become Lean in a manufacturing environment, based on the frequency of which they are mentioned. They then divided these practices in four different bundles and validated it empirically through reliability analysis and pricipal components analysis with varimax rotation. These four bundles are JIT, TPM, Total Quality Management (TQM) and Human Resource Management (HRM). The division of the chosen Lean practices into the four Lean bundles is illustrated in Figure 2.7.

The main aim of Shah and Ward's study was to determine the effect of each Lean bundle on operational performance, which proved to be positive for all. HRM, TQM and safety will not be considered in this study, due to their broad scope and limited available time and resources. In order to improve the quality of this study, only Lean tools which fall within the scope of JIT and TPM will therefore be investigated. Predictive or preventive maintenance and maintenance optimisation tools and techniques is investigated in Chapter 4. To recap, JIT focusses on continuously reducing waste by implementing tools related to production flow. JIT is also known as continuous flow improvement or kaizen Alukal (2007). TPM aims at maximising equipment effectiveness through maintenance optimisaton techniques (Shah and Ward, 2003). It is one of Lean's foundation blocks that assures the elimination of waste by striving for zero breakdowns and continuous improvement in equipment optimisation (McCarthy and Rich, 2004; Hawkins and Smith, 2004; Kelly, 2006).

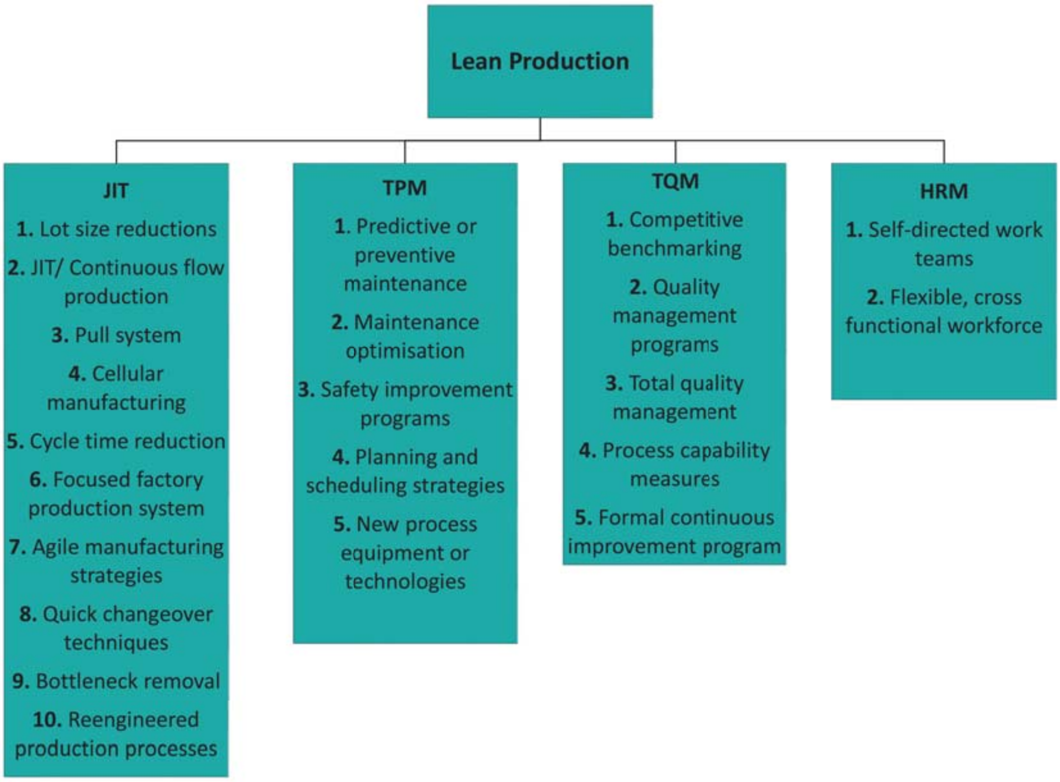


Figure 2.7: Lean manufacturing practices.

According to Kelly (2006), TPM:

- Strives to maximise equipment effectiveness through increasing equipment availability, efficiency, performance and product quality.
- Implements a maintenance strategy (level and type of preventive maintenance) throughout the equipment life.

– Stretches over all departments.

– Includes all staff, from top management to operators on the shop floor.

– Drives improved maintenance through small-group autonomous activities.

According to Bicheno (2004), TPM can be viewed in relation to the *Bathtub Curve* shown in Figure 2.8

At the beginning of the curve, in the early stages of the equipment life cycle, equipment maintenance is performed and the equipment is thoroughly understood in order to reduce break-downs. In the useful life of the equipment, the three TPM cycles and autonomous maintenance is applied, in order to extend the equipment life. Finally, during wear-out, predictive and planned maintenance is applied to address failures.

Figure 2.8: The Bathtub Curve.
Derived from Bicheno (2004, p.56)

The remainder of this section will provide literature on the Lean tools and principles illustrated in Figure 2.7 as tools which support JIT and TPM for Lean production.

Tapping *et al.* (2002) states that Lean manufacturing can be divided in three stages: demand, flow and levelling. *Demand* focusses on understanding the demand of the customer, including quality characteristics, lead time and price. *Flow* focusses on implementing continuous flow throughout the whole plant, so that the internal and external customers receives the product as required and when required. *Levelling* focusses on distributing work evenly in order to reduce inventory and WIP. The remainder of this section provides literature about the Lean principles and tools applicable to each stage.

Demand Stage

The various tools and techniques needed for meeting demand include (Tapping *et al.*, 2002; Shah and Ward, 2003):

1. Takt time (cycle time reduction).
2. Pitch (lot size reduction).
3. Takt image.
4. Buffer and Safety inventory.
5. Finished-goods.
6. Lights-out manufacturing.
7. Agile Manufacturing.

1. Takt time

Takt is a German word meaning musical beat or rhythm. Takt time is the rate at which a product must be produced to satisfy the demand of the customers. If produced to takt, the pace of production is synchronised with the pace of sales. A Standard Work Combination Sheet can be used to record the exact time for each sequence in a process, including walk time. If the cycle time is longer than the takt time, the process should be improved, which may include adding employees. Takt time should not be adjusted and should at all times be adhered to, as it is a critical measurement for standardised work (Tapping *et al.*, 2002).

In Production,

$$TAKT = \frac{Available\,Work\,Minutes}{Production\,Quantity}$$

The output of this will be the minutes per piece, or cycle time.

In Maintenance,

$$TAKT = \frac{Available\,Work\,Minutes\,for\,Scheduled\,Maintenance}{Scheduled\,Time}\;or\;\frac{Time}{Volume}$$

2. Pitch

The ideal state for Lean is creating *one-piece flow* through the production system, and eliminating all forms of waste in that process. Customers do, however, not usually order one piece at a time, but rather a standard quantity. When this is the case, takt time should be converted to a unit called *pitch* (Tapping *et al.*, 2002). According to Tapping *et al.* (2002, p.50), pitch can be defined as:

> *"the amount of time-based on takt– required for an upstream operation to release a predetermined pack-out quantity of work in process (WIP) to a downstream operation."*

Based on the above definition,

$$Pitch = takt\,time \times pack - out\,quantity$$

where takt is customer-driven and pack-out not necessarily.

Common advantages of working in smaller batches include safety improvements, inventory control improvements, ease of problem identification and reaction and ease of batch transportation (Tapping *et al.*, 2002).

3. Takt image

According to Tapping *et al.*(2002, p.51) Takt image is:

> *"the vision of an ideal state in which you have eliminated waste and improved the performance of the value stream to the point that you have achieved one-piece flow based on takt time."*

The organisation must ensure that it is doing everything possible to reach this ideal state (Tapping *et al.*, 2002).

4. Buffer and Safety Inventories

Buffer inventory is used when customer demand increases and the process in unable to produce more product without increasing its takt time. Safety inventory is used when internal issues occur, such as labour power issues, equipment reliability problems etc. By establishing these inventories, customer demand can be met without greatly changing cycle time. These inventories should periodically be reviewed when waste is increasingly eliminated, as excess inventory is seen as waste (Tapping *et al.*, 2002). Excess inventory should be sufficient to cover frequent upstream disruptions, but not unusual events (Bicheno, 2004).

5. Finished-Goods Supermarket

According to Tapping *et al.* (2002, p.53), a finished-goods supermarket refers to:

> *"a system used in the shipping part of the value stream to store a set level of finished goods and replenish them as they are "pulled" to fulfil customer order. Such a system is used when it is not possible to establish pure, continuous flow."*

The preferable state would be to instill continuous flow by withdrawing product directly from the assembly line. Only when this is not possible, a finished-goods supermarket should be established. It is important to note that the finished-goods store should not include any buffer or safety inventories (Tapping *et al.*, 2002).

6. Lights-Out Manufacturing

Lights-out manufacturing involves meeting customer demand automatically without human interaction. This may increase the amount of produced products, but will also increase the likelihood of producing numerous defective products, as there are no operators present to detect defects. This will lead to increased time needed to inspect the output of the process. The following factors should be considered before implementation (Tapping *et al.*, 2002):

1. The process must have adequate and proven process capability.
2. The materials used should be reviewed, as some materials must be monitored to ensure product or equipment reliability.
3. If parts are complex, lights-out machining is not recommended.
4. The lot-size should be consistent with one-pitch increments.

Although this type of manufacturing may produce numerous production benefits, the costs and concerns should be weighed up against the advantages decide if this strategy makes good business sense (Tapping *et al.*, 2002).

7. Agile Manufacturing

According to Samman (2014, p.1093), agile manufacturing is:

> *"the capability of surviving and prospering in a competitive environment of continuous and random change by reacting quickly and effectively to changing markets, driven by customer-designed products and services."*

This means making your production system as flexible, responsive, competent and efficient as possible in order to effectively and efficiently adapt to change. This is not aligned with Lean's continuous strive for "zero inventories, zero downtimes, zero defects, and zero delays". However, according to Samman (2014), when demand is unpredictable and customer requirements for variety is high, customer satisfaction is prioritised over eliminating waste, as Lean ultimately strives for customer satisfaction. The implementation of agile tools will therefore enable a production system to be as Lean as possible in a continuously changing environment.

Tools commonly used to create an agile system is:

1. Standardisation;
2. Buffer or de-coupling;
3. Multi skilled workforce;
4. Pull system;
5. IT systems

Components should be standardised and kept in buffers until customer pulls customised product, whereafter standardised components are assembled. The point in the supply chain where the semi-finished goods are kept is called the de-coupling point and should be closest to the customer in order to respond to customer demand as rapid as possible. The use of IT systems, such as efficient consumer response (ECR), customer relationship management (CRM) and collaborative planning forecasting and replenishment (CPFR) are very useful, as data is captured in real-time directly from the point of sales and consumer buying habits can be predicted Basu and Wright (2011).

Flow Stage

Once demand is established and a system is put in place to ensure that you can meet demand, the flow of the system should be perfected to ensure that the customers receives products as per requirements. This stage includes tools and techniques such as

1. Continuous flow – one-for-one manufacturing.
2. Work cells (cellular manufacturing, Focused factory);
3. Line balancing;
4. Standardised work;
5. Quick changeover;
6. Autonomous maintenance;
7. In-process supermarkets;
8. Kanban systems.;
9. First-in, first-out (FIFO) lanes;
10. Production scheduling (Establish Pull) and
11. Bottleneck Removal.

1. Continuous Flow

Understanding continuous flow is imperative to the JIT philosophy in order to ensure that an upstream operation does not produce more than downstream demand. It is based on three principles, to produce (Tapping *et al.*, 2002) 1) Only what is needed,2) Only when it is needed and 3) Only the amount that is needed.

One piece or small batch is produced only after a piece or small batch is *pulled* downstream. This is also known as a *pull production system* and is characterised by the fact that it is faster than *push production*, it controls the flow between operations and eliminates the need for production scheduling. This is illustrated in Figure 2.9 and 2.10. Poor plant layout and varying speed of processes are common obstacles preventing the implementation of continuous flow (Tapping *et al.*, 2002).

2. Work Cells

According to Tapping *et al.* (2002, p.56) a work cell is *"a self-containing unit that includes several value-adding operations."* It contains equipment and personnel in process sequence and all of the operations needed to produce a product. It can be considered a *mini business* (Bicheno, 2004). This allows operators to produce products one-piece at a time with minimised waste of transportation and safety hazards (Tapping *et al.*, 2002).

One key consideration when designing a cell layout is the fluctuation of product demand – the cell must be arranged in such a manner that it is able to adapt to changes in production requirements (Tapping *et al.*, 2002).

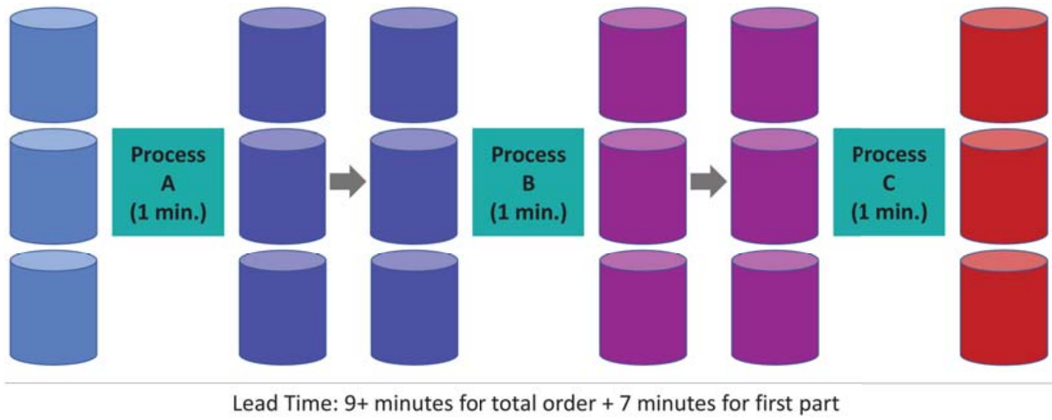


Figure 2.9: Batch Processing.
Adapted from Tapping et al. *(2002, p.55)*

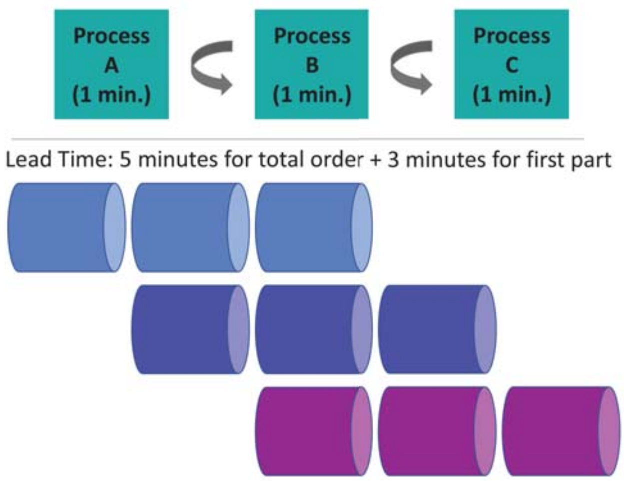


Figure 2.10: Continuous Flow Processing.
Adapted from Tapping et al. *(2002, p.55)*

Principles of work cells include (Tapping *et al.*, 2002):

- Sequential arrangement of the process.
- Counter clockwise flow direction to encourage operators to use their right hands for activities.
- Closely positioned equipment, where safety should be kept into consideration for hand and material movements within a small area.
- Close placement of the last and first operations.
- U-, C-, L-, S- or V- cell shapes, depending on equipment, constraints and resource availability.

3. Line Balancing

Line balancing involves evenly distributing work elements in a value stream in order to meet the takt time. This includes optimising the use of personnel in order to ensure that no one does too much or too little. The best tool used to perform this task is an *operator balance chart*, which is a visual display indicating the work elements, time requirements and operators at each station (Tapping *et al.*, 2002; Askin and Goldberg, 2002).

Line balancing involves the following steps (Tapping *et al.*, 2002):

1. Determine the current cycle time, number of operations and number of assigned operators for each operation.
2. Create a bar chart displaying the different cycle times (y-axis) for each operation and number of assigned operators (x-axis), to give a better visual representation of the condition. The takt time should also clearly be indicated on this chart.
3. Calculate the number of operators by using the following formula:

$$Number\,of\,operators\,needed = \frac{Cycle\,time}{takt\,time}$$

If a the required number of operators is a fraction, waste should be eliminated as much as possible in order to round this figure down to the nearest whole number. A decimal less than or equal to 0.5 suggests this to be a realistic goal (Tapping *et al.*, 2002). By standardising the work performed by the operators, reaching their assigned takt times would be easier.

4. Standardised Work Flow and Operating Procedures

> *"To standardise a method is to choose out of many methods the best one, and use it. What is the best way to do a thing? It is the sum of all the good ways we have discovered up to the present. It therefore becomes the standard. Today's standardisation is the necessary foundation on which tomorrow's improvement will be based. If you think of 'standardisation as the best we know today, but which is to be improved tomorrow' – you get somewhere. But if you think of standards as confining, then progress stops"* – (Ford, 2002)

Hawkins and Smith (2004) states that a standard is the easiest, safest and best process to complete a job.

According to Hawkins and Smith (2004), Standard and Davies identified three crucial concepts of standardisation:

1. Standard work is dynamic and should be updated when a better way is found.
2. Standard work supports stability and reduces variation, because work is performed the same every time.
3. Standard work is critical to continuous improvement.

The components of standards include: work time \takt (cycle) time, work sequence and standard WIP (Bicheno, 2004; Hawkins and Smith, 2004).

Bicheno (2004) states to be aware of thinking that non-repetitive work such as maintenance, service or design do not need standards. In fact, good, flexible maintenance and service work is built on combining several small standard work elements.

Work sequence refers to individual steps performed by employees. All steps that does not add value to the organisation should be eliminated. The goal of standard WIP is to possess the smallest amount of WIP required to do the job (Hawkins and Smith, 2004). A Standard Work Sheet, displaying the sequence of operations within a process and operation cycle times should be posted in the work area in order to create a visual display of what needs be done (Tapping *et al.*, 2002).

When setting standards, it is important to include operators in the process. No one knows how to perform the job best than workforce working on the equipment daily. A Standard Work Combination Sheet, which displays the material and human workflow for a process, including the exact time for each operation, can be used to compare process cycle times and takt times. It is important to adhere to takt time and to rather streamline processes by adjusting the workforce should demand fluctuations occur.

5. Quick Changeover (QCO)

There are three widely used definitions of changeover. The first view defines changeover as the time of which a machine is idle between batches (the *internal* time). The second view states changeover to be the time from the last piece of the first batch to the first good piece of the second. The third view defines it as the time from the standard rate of running the first batch to the standard rate of running the second (Bicheno, 2004).

Quick changeover originated from a concept designed by Shigeo Shingo at Toyota called single-minute exchange of die (SMED). It focusses on increasing the variety of products produced, which normally requires tooling changes, without disrupting production flow. It is based on the theory that changeover should be performed in less than 10 minutes (Tapping *et al.*, 2002).

The classic Shingo methodology from SMED includes the following steps (Bergsjo, 1999; Tapping *et al.*, 2002):

1. Identify and classify internal and external activities. This can be done by studying a video of the process. Internal activities include setup tasks that can only be performed while the machine is shut down, while external activities include setup tasks that can only be performed while the machine is running.

2. Separate internal and external activities and convert internal to external activities, where possible. Also streamline external activities by reducing wasteful activities such as movement, fetching tools or filling out forms.

3. Minimise and streamline all setup activities by implementing parallel operations (assign more than one operator), using functional clamping methods instead of bolts, eliminating adjustments and mechanize where possible.

According to Bicheno (2004), McIntosh identified two general approaches to quick changeover: Organisation led (i.e. SMED) and design led.

In both cases, four areas need be addressed:

1. On-line activities – internal and external task reallocation or altering the sequence by design.
2. Adjustments – reducing trial and error or changing the design to allow 'snap-on' adjustments.
3. Variety – by standardising or changing the design to reduce possible variations (pokayokes)
4. Effort – by simplifying or preparing work or by incorporating simplification into design i.e. fixing multiple hoses by one fixture.

Design led normally leads to more sustainable improvements than organisation led, but is more costly. Objectives should thoroughly be assessed in order to determined which one is best to implement (Bicheno, 2004).

6. Autonomous Maintenance

Autonomous maintenance is focussed on establishing operator asset care and should be integrated in each step of the TPM cycle. According to Willmott and McCarthy (2001*b*), it follows a seven step process:

Step 1: Initial cleaning – The first step of autonomous maintenance involves the five S's mentioned earlier in this chapter.

Step 2: Countermeasure at the source of the problem – The second step of autonomous cleaning is focussed on cleaning, checking, oiling, tightening and alignment of equipment daily in order to enable operators to detect abnormalities as soon as they suffice. An important rule in this step is to use visual marking to encourage ease of inspection, order and tidiness. Examples of this may include highlighting critical areas or displaying charts and graphs.

Step 3: Cleaning and lubrication standards – This step involves setting standards for continuous care of the plant and equipment.

Step 4: General inspection – Step four compromises of guiding the operators towards carrying out general inspections independently. By following the previous steps, they understand the function and structure of the equipment and have gained self confidence in operating it effectively.

Step 5: Autonomous inspection – Step five consists of operators carrying out self-directed inspection routines and repairs/services as necessary.

Step 6: Organisation and tidiness – The 5 S's should have by now shown great improvements and operators will have reached a stage where they take responsibility for autonomous inspection. They should have also developed a thorough understanding of the relationship between equipment accuracy and product quality.

Step 7: Full autonomous maintenance – In the final step of autonomous maintenance operators are able to maintain equipment independently. This includes cleaning, checking, lubricating, repairing and checking for precision daily.

7. In-Process Supermarkets

In-process supermarkets are normally used when one machine has multiple demands and WIP is necessary in between production steps to ensure continuous flow. It is a compromise to the ideal state, together with pitch, buffer inventory and safety inventory (Tapping *et al.*, 2002).

Advantages of using supermarkets include (Tapping *et al.*, 2002):

– continuous flow when using shared equipment;

– better use of capital equipment when new technology is not Lean-orientated and

– the possibility of enhanced labour balance.

Disadvantages of using supermarkets include (Tapping *et al.*, 2002):

– difficulty to control quality;

– the possibility of losing sight of takt image and

– increased space utilisation.

8. Kanban

Kanban is a form of a pull mechanism, where production is triggered by customer demand with no advance notice or signalling system and orders is regulated from the factory to the supplier (Bicheno, 2004; Askin and Goldberg, 2002; Tapping *et al.*, 2002). It builds on the JIT philosophy and Lean's fourth principle of implementing a pull system, and is therefore imperative to continuously improve flow (Askin and Goldberg, 2002; Bicheno, 2004). There is a lot to do first before introducing Kanban – reducing demand amplification and defect rate, standardise work and reducing changeover (Bicheno, 2004).

The word *e* is the Japanese word for *card*, *billboard* or *sign* and refers to the inventory control card of a pull system (Askin and Goldberg, 2002; Bicheno, 2004).

There are three types of kanban (Bicheno, 2004):

1. production kanban;
2. withdrawal kanban and
3. signal kanban.

A *production kanban* is a single printed card operating between two workstations and illustrating the number of parts to be produced to replace what the customer pulled. A *withdrawal kanban* is a card indicating the number of parts that need to be pulled from the supermarket and supplied downstream. A *signal kanban* is used when there is a changeover. A target batch size is normally calculated for each product to be produced and, when the amount of kanban cards reaches the calculated amount, a batch is made. This type of card indicates the number of parts to be produced at a batch operation in order to replace what has been pulled from the supermarket (Bicheno, 2004; Tapping *et al.*, 2002).

The following rules is imperative for Kanban to work properly:

– Downstream operations withdraw items from upstream operations.

– Upstream operations produce only when in possession of a kanban card, and only the number of parts as per the card.

– Only 100-percent defect-free products must be sent downstream.

– Kanban cards should move with material in order to provide visual control.

– The aim should be to reduce the number of kanban cards in circulation to reduce inventory and strive for improvement.

The reorder point can be determined by the following calculation (Bicheno, 2004):

$$ROP = D \times LT + SS$$

where D = demand rate during the lead-time LT between placing an order and receiving a delivery, and SS = Safety Stock. If the container quantity is Q, the number of kanbans is

$$N = \frac{D \times LT + SS}{Q}$$

where N should be rounded up. If safety lead time is used, rather than safety stock,

$$N = \frac{D \times (LT + ST)}{N}$$

Finally, when there is a changeover,

$$N = \frac{D \times (EPE + delivery\,time + safety\,time)}{Q}$$

where EPE = the interval in days between running a product

9. FIFO Lanes

A first-in-first-out (FIFO) lane is used when the variety of products is too big to use an in-process supermarket system. It ensures that the oldest inventory is used first. It is a useful tool when dissimilar parts go through the same operations, such as welding or painting, before being customised. FIFO must be designed in such a way that it is nearly impossible to draw any other part than the oldest, where the designated number of parts between two processes should be loaded sequentially. Furthermore, a signal should be used to notify the upstream when the lane is full and production should stop immediately, to avoid the waste of overproduction (The Guardian, 2013). This is illustrated by Figure 2.11.

Figure 2.11: FIFO Lanes.
Adapted from Tapping et al. *(2002, p.65)*

Product should at all times be pulled in FIFO order, where pull processes should be standardised in order to maintain the sequence of pulling (Tapping *et al.*, 2002).

Advantages of using FIFO lanes include (Tapping *et al.*, 2002):

– continuous flow when there is a great possibility of chronic failure in an upstream process;

– continuous flow during changeover and

– enabled complex labour demands within an assembly line.

Disadvantages of using FIFO lanes include (Tapping *et al.*, 2002):

– difficulty in controling quality;

– the possiblity of losing sight of takt image and

– increased space utilisation

10. Production Scheduling

As a pull production system is based on actual customer need, it is imperative to have a production schedule to schedule production and inventory. This should be based on the demand of the downstream operation closest to the client. It should also include supermarkets or FIFO, if deemed necessary. The schedule should strive to have zero downtime, little to none changeover and optimised worker flexibility (Tapping *et al.*, 2002).

Levelling Stage

After customer demand have been established and flow streamlined, production should be levelled. Levelling involves distributing work evenly in order to fulfil customer demand (Tapping *et al.*, 2002).

Tools and techniques to level production include (Tapping *et al.*, 2002):

1. Paced withdrawal
2. Heijunka
3. Heijunka box
4. The runner

The first two methods are used to balance the pace of production with the pace of sales or takt time (Tapping *et al.*, 2002).

1. Paced Withdrawal

Paced withdrawal is a method for moving batches from one operation or process to the other in constant time increments equal to the pitch. It is used when there is no product variety, and therefore, have identical pitch increments. Even though the ideal Lean state is one-piece flow, customers normally order in containers that hold a standard pack-out quantity. This method ensures that the production requirements per shift equals the pack-out quantity and, therefore, levels production. The frequency of which containers are shipped is determined by the pitch (Tapping *et al.*, 2002).

2. Heijunka (Load Levelling)

Heijunka is a sophisticated method used for planning and levelling customer demand when a wide range of products need be produced. As the ideal Lean state for one-piece flow and smaller lots is instilled, large orders may immediately deplete inventory. Heijunka uses paced withdrawal based on pitch, but categorises it according to product variety and volume as demanded by the end-user. For example, a common Heijunka demand may be the following (Tapping *et al.*, 2002) (2002, p.69):

> *"Over the course of the day, the value stream must turn out 12 of container A, 8 of container B and C, and 2 containers each of D and E....or, for every three containers of product A produced, two containers each of products B and C and 0.5 containers each of product D and E must be produced"*

Implementing Heijunka clearly requires a sound understanding of customer demand and its effects on the upstream. These ratios are managed through distributing kanbans using heijunka boxes, explained in the next section. For this to be effective, strict principles of stabilisation and standardisation is imperative (Tapping *et al.*, 2002).

3. Heijunka Box

As mentioned in the previous section, a Heijunka Box is used to manage levelled production volume and variety. Kanban cards are slot according to the pitch increments of their respective products, where products are produced sequentially. Note that in the example of the previous section, 0.5 of product D and E should equal 3 containers of product A and 2 containers of product B and C. Thus,

$$A : B : C : D : E = 3 : 2 : 2 : 0.5 : 0.5$$

Due to the fact that products are produced according to pitch, and producing a product in half a pitch is impractical and would increase changeover, the ratios shown above should be doubled in order to equal one pitch for products D and E. Thus, the sequence of production would be A, A, A, B, B, C, C, A, A, A, D, B, B, C, C, and E.

4. Runner

There is a possibility that during line balancing, a worker can be eliminated from a target value stream and assigned elsewhere. A displaced operator can sometimes be redeployed as a runner, provided he has the following attributes (Tapping *et al.*, 2002):

- Understands the production requirements of the value stream.
- Effective communication.
- Able to recognise and report abnormalities.
- Sound understanding of Lean concepts.
- Sound understanding of takt time and pitch.
- Work efficiently and effectively.

The main goal of the runner is to ensure that the pitch is maintained. In their role, they cover a route within the pitch period and pick up kanban cards or components and deliver them to their appropriate places. The runner can be viewed as a mail man, where the heijunka box is the mailbox and the kanban card is the mail. If a haijunka box is not used, the runner will distribute tools and components from the store in order to sustain continuous flow. They can help solve problems before they occur and become large problems that disrupts production flow (Tapping *et al.*, 2002).

Bottleneck Removal

The identification and elimination of bottlenecks is imperative to an efficient production system. This can be done with a tool called Theory of Contstraints (TOC). TOC can be seen as a management philosophy that enables a system to achieve more than it is designed to. It it comprised of five key steps:

1. Identify;
2. Exploit;
3. Subordinate;
4. Elevate and
5. Repeat the process.

The constraint must first be identified, whereafter the throughput per unit of the constraining factor should be determined and improved with existing resources during exploitation. During the subordinate step, the whole process should be evaluated in order to determine if the constraint has enough support to operate at an optimum. If not, it should be elevated and other means of dealing with the constraint should be considered, which normally involves assigning additional recources. The final step involves finding the next constraint and repeating the cycle in order to make the process as efficient as possible Basu and Wright (2011).

Even though Tapping *et al.* (2002) and Shah and Ward (2003) provides quite a comprehensive list of Lean tools and principles applicable to Lean production, there are two critical JIT tools which they failed to mention: value stream mapping (VSM) and PDCA.

Value Stream Mapping (VSM)

VSM is a tool used to map, understand and redesign information, people and product flow and create improvements to represent only the processes that add value within an organisation (Srinivasan *et al.*, 2014; Eator, 2013). According to Belekoukias *et al.* (2014), it comprises of three tools:

1. Current state map;
2. Future state map;
3. Flow diagrams;

The first step in VSM is understanding and mapping the current state of a process. This should be done preferrably in a group of no more than four to six people and can take up to two days to complete. After the current state is thoroughly understood, it should be mapped between 50 to 100 states, to ensure that the map does not consist of too many or too little detail.

The second step involves identifying value-adding and non-value-adding steps.

The third step is the ideal state, which is a creative process that generates ideas for improvement that can be used in the future state. In this state, it is important for team members to understand that anything is possible, solutions must answer questions, and that the current state should not be recreated.

The fourth step consists of mapping a realistic future state with actions to be implemented, which will represent how the process will work in the future. An important part of this step is to think of possible ways the future state may fail and make changes to the future state to avoid this.

The final step is creating a project plan to achieve the future state and prioritise actions Eator (2013).

Plan-Do-Check-Act (PDCA)

PDCA is a method for implementing change. It is used for (American Society for Quality, 2014):

- continuous improvement;
- starting a new improvement project;
- developing a new or improved process, product or service design;
- developing a new or improved process, product or service design;
- when defining a repetitive work process;
- When planning data collection and analysis to verify and prioritise problems and root causes and
- When implementing change.

PDCA follows the following four step process (American Society for Quality, 2014):

1. Plan – identify an improvement opportunity and plan a change;
2. Do – Test the change by carrying out a small–scale study;
3. Check – Review the test, analyse the results and determine what can be learned;
4. Act – Take action grounded on what was learned in the study; If the change does not work, the cycle should be repeated with a different plan. If the change was successful, it should be tested in possible other areas, beginning the cycle again.

According to Alukal (2007), the implementation of Lean kaizen (incremental improvements) has helped Toyota become the great success it is today. Lean Kaizen typically requires four to five uninterrupted days of work improvement, focused on empowering frontline staff and using their knowledge to create processes which are more effective and efficient (Smith *et al.*, 2012). Lean Kaizen uses two methodologies: the PDCA cycle and the standardise-do-check-act (SDCA). These methodologies are focused on continuous improvement efforts and problem solving efforts, respectively.

2.3.1.2 Lean Maintenance Practices and Tools

Recently, an increasing amount of organisations are trying to incorporate *Lean Maintenance*, an effort to incorporate Lean Manufacturing and its efficiency improvements, into the field of PAM. Though this have shown great increases of efficiency in some instances, asset maintenance and production has great fundamental differences and thus, the same Lean manufacturing fundamentals cannot be brought directly from the production environment to the AM environment (Mather, 2007).

Mather (2007) identifies three main differences as follows:

1. Difference in driving force.

   Production is driven by sales forecasts, while asset maintenance is driven by a schedule of routine work as well as failure statistics. Due to this, common Lean Manufacturing tools such as JIT inventory management have only limited ability to aid efficiency improvements in maintenance (Mather, 2007).

2. Difference in time perspectives.

   Production efficiency is gained by eliminating waste and managing the production processes daily. Asset maintenance has a different time element to take into consideration. For maintenance to be efficient, issues related to asset use, type, expected life etc. need be addresses and involves business functions outside of maintenance. An example of this may include increased capital investment at an early lifecycle phase for equipment subject to regular overload situations.

3. Difference in data management and collection.

   Production process improvements can normally be achieved through recording and acting upon dynamic operational data. This is also useful for asset maintenance, but effective maintenance also requires data forecasting operations in order to predict failure or future spending. This requires statistic data on equipment type, data on equipment failure, asset condition and other areas.

For the reasons listed above, Lean Maintenance and Lean Productions need to have two different points of focus. Mather (2007) identified eight different wastes applicable to Lean Maintenance:

1. Unproductive work – Efficiently producing work that is unnecessary.

2. Delays in motion – Wasted time waiting for parts, machinery, people etc.
3. Unnecessary motion – Unneeded travel, looking for items, trips to tool stores etc.
4. Poor inventory management – Not having the right parts at the right time.
5. Rework – Needing to repeat tasks due to poor workmanship
6. Underutilisation of people – Not utilising people to their full ability
7. Ineffective data management – Collecting data of no use, or not collecting imperative data.
8. Misapplication of machinery – Operations that leads to maintenance when it is not needed.

Even though some of these wastes are similar to Lean Production, there are some notable differences.

According to Hawkins and Smith (2004), Equipment reliability, for which literature is provided in Chapter 4, is a full prerequisite to full Lean implementation, and should be at the heart of Lean Maintenance together with TPM.

Studies have been conducted regarding the tools to be used to make a maintenance process *Lean*. Mostafa *et al.* (2015*b*) conducted a similar study than Shah and Ward (2003), by studying eighteen credible secondary sources and determining the Lean practices applicable to Lean maintenance. They also divided the Lean practices in the Lean bundles identified by Shah and Ward (2003). This can be seen in figure 2.12.

Literature on Kanban, single-minute-exchange-of-die (SMED), work standardisation, Takt time and autonomous maintenance was already provided earlier in this chapter. Literature on planned maintenance is provided in Chapter 4.

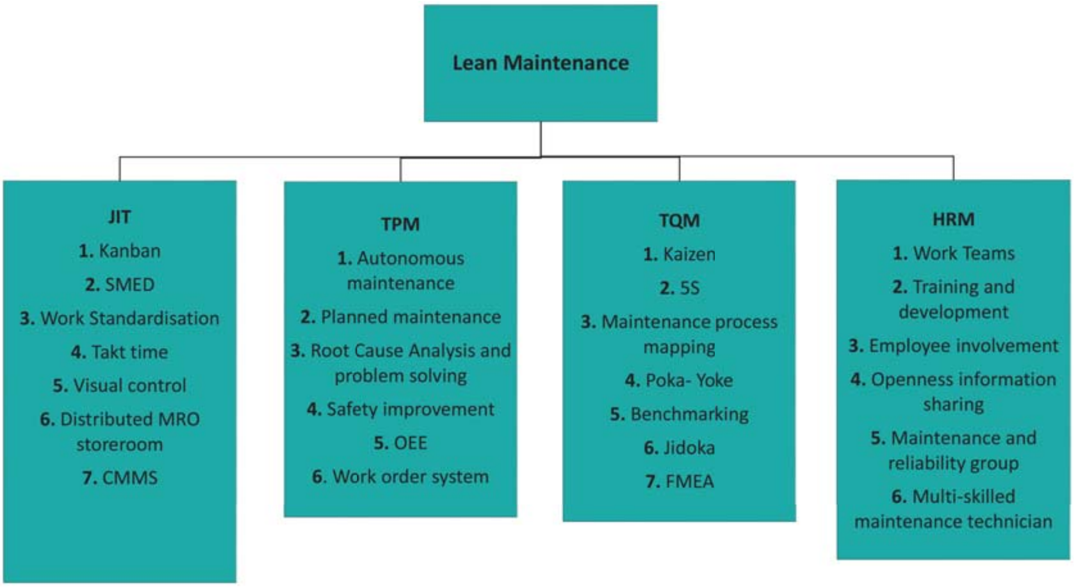


Figure 2.12: Lean maintenance practices.

Visual Control

According to Liker (2013), the main aim of visual control is to avoid the inability to see problems immediately as they occur. The core idea is to make everything visual and support smooth flow and takt time by cleaning it up. It includes any communication device that can tell anyone at a glance how work should be done and if it is variating from the standard. The 5S's, covered earlier in this chapter, is a popular tool used in this regard. Without the implementation of the 5S's, waste accumulates and covers up numerous problems, which is often realised when it is too late.

A shadow tool board, which consists of painting a "shadow" of where each tool should be hanged, is also effective, as it is obvious if the hammer is missing. Another effective tool is visually indicating maximum and minimum levels of inventory, as managers can immediately see if inventory is being managed optimally. A Kamishabi, which indicates the phased and daily maintenance activities and safety, quality and operator check, is also often used. A Kamishabi board is simply a T-card display board, where each column represents each day of the week and each card has different colours front and back. The daily activities are written on each card, where the cards are placed in slots under the appropriate day and turned around when the activity is completed. It is visible, kept at the work place and updated by the operators. Anyone walking past can see what activities have been done and what is still outstanding. Common activities indicated on the Kamishabi board includes TPM activities, training, meetings, 5S activities, and planned daily activities (Bicheno, 2004)

Toyota also believes in putting key information, in the form of numbers and graphs, visually on one piece of A3 paper right where the work is being performed.

The 7th principle of Toyota is to use visual control to improve flow. Tools such as kanban, andon(visual display boards or lights), the one-piece-flow cell and standardised work are commonly used specific for this purpose. This section described the key Lean concepts, tools and techniques used in each stage of a production process. As mentioned earlier, it is imperative for an effective maintenance system to first be in place in order to fully implement Lean Production. The following section will provide in-depth literature on Lean Maintenance (Liker, 2013).

Distributed Maintenance, Repair and Overhaul (MRO) Storeroom

The key principal of a Lean MRO storeroom is its central location and to standardise material and to operate based on planning and forecasting techniques (Mostafa *et al.*, 2015*a*). An effective tool used for the Lean management of inventory is ABC analysis. ABC analysis is an inventory categorisation method that enables storeroom managers to focus on the important few and not the trivial many. Inventory is divided into three codes:

A: Most important
B: Marginally important
C: Least important

These categories should be audited quaterly to ensure the right codes are issued to the right parts. The decision criteria for these codes should be based on the percentage usage of the parts, calculated from their net value, where

$$Net\,Value \;=\; Unit\,Cost \times Anual\,Ussage$$

$$\%\,Ussage \;=\; \frac{Net\,Value\,Part}{Total\,Net\,Value}$$

It is important to also consider part criticality, where some parts may not be used often, but is imperative for the functioning of the operations in the plant. The "A" classified parts should represent approximately 20 percent of all inventory and should be easily accessible and be the focus point for JIT practices. The "B" parts should typically be reordered every six months and the "C" parts every year Hawkins and Smith (2004). This will free up a great deal of floor space as well as operating costs and reorganise the storeroom to make it "Lean".

Computerised Maintenance Management System (CMMS)

A challenge faced by organisations when transitioning to TPM, is changing the current work flow and organisational structure to aid the implementation of a CMMS. Although this tool is optional, it is highly recommended as it can achieve great management efficiencies that would be impossible without it.

CMMS provides system modelling, which assists in organised, proactive work flow arrangements and aids shifting from reactive to proactive maintenance. The CMMS will help define or completely restructure any current work order systems, which will act as the basis for proactive maintenance, information input and feedback. It is important that all information is captured on the work order, as it will be the primary tool for managing labour resources and measuring the effectiveness of the department. In order for a CMMS to be successful, the data entered need be accurate and understandable to the user as well as the software. Inventory can be eliminated by using the CMMS to schedule when repair parts and consumables are required, of which the supplier should deliver on demand through JIT (Hawkins and Smith, 2004; Hodkiewicz and Ho, 2016).

Root Cause Analysis (RCA) and Problem Solving

The process of systematically evaluating root causes to problems is called RCA. Root cause analysis focuses on improvement. By analysing the OEE mentioned earlier, a specific loss is highlighted, which leads to the root causes, which leads to solutions. Popular tools used for RCA includes brainstorming, cause and effect diagrams (CED), the five whys, a tree diagram, fault tree analysis and SDCA. A popular tools for problem solving includes PDCA and set-based concurrent engineering (SBCE). Literature using PDCA for continuous improvement was provided earlier in this chapter. When using PDCA, the "planning" phase focuses on identifying the problem and planning for a solution.

The basic principle of CED is to explore all potential causes through brainstorming and grouping these according their natural association. The five Why's requires the user to ask *"why"* numerous times, until the root cause is established. Note that it does not necessarily have to be asked five times as the name imply, but simply until the root cause is identified. This tool is normally used when the root cause is assumed to be linear to the problem. When this assumption does not hold, a tree diagram can be used. When using a tree diagram, the root cause of the primary problem (A) is assumed to be due to a few sub-events (B,C,D...), which is assumed to be due to further sub-events. This continues until the one final cause is found. If probability analysis is incorporated into the tree diagram, the diagram is termed Fault Tree Analysis. This is often used when performing risk assessments to determine the probability of the occurance of an undesired event (Sarkar and Mukhopadhyay, 2013). SBCE uses the principle of developing varous sets of solutions to a problem in parallel, rather than working with one idea at a time, which is known as the point-based approach. A point-based design considers one best solution and iteratively modifies it until it meets necessary criteria. When using SBCE, participants reason, develop and communicate about a set of solutions in parallel, where they narrow their set of solutions based on knowledge gained during the process, and finally commit to one set of solutions. This design has many benefits, such as avoiding fixation on first suggested solution, time delays before feedback or defining viability before commitment (Maulana *et al.*, 2017).

Overall Equipment Effectiveness (OEE)

Kelly (2006) states that the main goal if is to maximise OEE, where

$$OEE = Availability \times Performance\,rate \times Quality\,rate$$

$$Availability = \frac{Run\,time}{Planned\,production\,time}$$

$$Performance = \frac{Ideal\,cycle\,time \times Total\,Count}{Run\,time}$$

$$Performance = \frac{Good\,count}{Total\,count}$$

This is accomplished by eliminating the following six main losses (Kelly, 2006; McCarthy and Rich, 2004) :

1. Breakdown due to failure of equipment;
2. Downtime due to set-up and unnecessary adjustments;
3. Speed losses due to idling and minor stops;
4. Running at reduces speed due to discrepancies between designed and actual speed of the equipment.
5. Reduced yield due to start-up losses;
6. Production and reworking of defects.

When calculating OEE, the first two mentioned losses affects the availability of the equipment, the second two affects the performance rate and the last two affects the quality rate (Willmott and McCarthy, 2001*a*). McCarthy and Rich (2004) identifies the main reasons for these losses to be poor equipment condition or human error either to lack of motivation or lack of understanding.

OEE is not only limited to the effectiveness of machinery, but can also be applied to the business as a whole. It can be applied at three key levels (Willmott and McCarthy, 2001*a*):

– Shop floor: floor-to-floor OEE
– First-line management: door–to–door OEE
– Senior-management: supplier to customer, value chain

If the door-to-door or supplier-to-customer OEE stays low, it will not increase customer satisfaction by only increasing the machine OEE. This stretches the fact that TPM is enterprise-wide, which, if integrated through all business processes, is commonly known as *Total Productive Manufacturing*. In fact, TPM is about asset care, where its scope stretches far more than only "maintenance" (Willmott and McCarthy, 2001*a*).

It should be assured that all members of the team fully understand the meaning of OEE and that it is shown on the display board in the factory. Possible causes should be brainstormed and displayed on a chart, where the six big losses should be identified for different situations (Bicheno, 2004).

Work Order System

In TPM, a work order system is the backbone for the work execution of proactive maintenance and the input and feedback from the CMMS. It is imperative for all work orders to be documented and to be well defined and categorised. Common categories used include planned/scheduled, corrective and emergency maintenance. A work order is a primary tool used to determine the efficiency and effectiveness of the department and managing labour (Hawkins and Smith, 2004). Common metrics used to determine the efficiency of the work order system includes

1. Number of pieces of paper generated per work order.
2. Annual paper cost.
3. Travel distance of work order.
4. Average time to assign work order.

In order to make a work order system as Lean as possible, the focus should be on reducing these metrics, which will reduce a great amount of waste in the maintenance system (Balzer, 2010).

2.4 Chapter Summary

This chapter provids literature about the PAM and Lean landscapes, together with a summary on the ISO 5500X Family of standards.

First, the field of PAM is studied in detail. Literature is provided on the definition of physical assets, PAM and areas considered as *important* to the field of PAM.

Secondly, an overview is given on each standard within the ISO 5500X family of standards. This is categorised in the six critical areas of AM identified by ISO 55000 as: context of the organisation, planning, support, operation, performance evaluation and improvement

Finally, the Lean landscape is studied. An introduction on Lean is provided, where its core concepts and principles are discussed. This is followed by research on Lean maintenance and production practices, tools and techniques, where the implementation of Lean production cannot be successful without the effective implementation of Lean maintenance.

The next chapter provides detail on the research methodology and design of this thesis in order to systematically solve the research problem and answer the research questions.

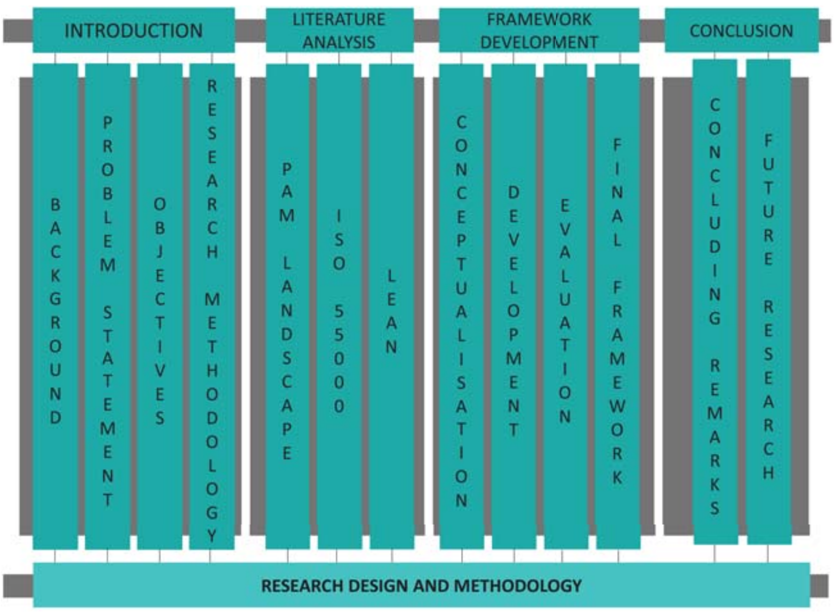
Chapter 3

Research Design and Methodology

Chapter Outcome

1. Determine the elements of inquiry of this thesis.
2. Provide a detailed description of the research approach of this thesis.
2. Provide a detailed description of the research design of this thesis.

Chapter Route Map



3.1 Introduction

Research Methodology refers to a systematic and holistic process of which research problem is solved. It is the science of studying how research is carried out scientifically (Sahu, 2013). It aims to understand how the research question is answered, the different methods and tools to be used and alternative ways of solving the research problem. A research method is a technique used to perform a research operation within the research methodology.

Research design, on the other hand, is a detailed plan or outline of work to be undertaken during the process of conducting research (Sahu, 2013). It refers to the way in which the different elements of the study is integrated in order to form a logical sequence and effectively answer the research question. Creswell (2003) identifies the following three questions at the core of designing research:

1. What knowledge claims are being made by the researcher?
2. What strategies of inquiry will inform the procedure?
3. What methods of data collection and analysis will be use?

He furthermore developed Figure 3.1 illustrating how these three questions combine to form different methods to research, which are translated into different practical research design processes (Creswell, 2003).

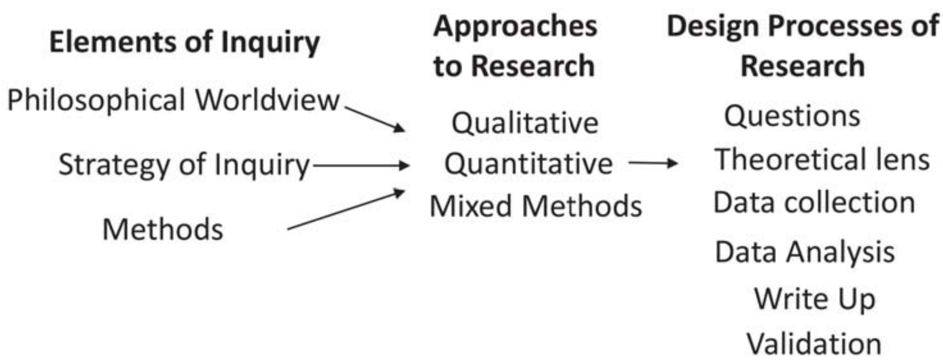


Figure 3.1: Knowledge Claims, Strategies of Inquiry, and Methods Leading to Approaches and the Design Process.
Adapted from Creswell (2003, p.5)

3.2 Elements of Inquiry

This section investigates the philosophical world view, strategy of inquiry and research methods of this dissertation.

3.2.1 Philosophical World View

The philosophical worldviews sets out a basis for research. It is the way in which the world is viewed out of the eye of the researcher, and has a direct influence on the way research is conducted. It consists of a basic set of assumptions and beliefs, deeply rooted in one's experience, culture and history and may change the way in which one's life is shaped by new experiences and thoughts (Creswell, 2009).

Creswell (2009) stretches the importance of identifying one's own worldview before conducting research, in order to realise that behind each study lays one's own assumptions based on life experience and how knowledge is gained.

There are four different worldviews applied in research. Table 3.1 illustrates these four world views and their main concepts.

Table 3.1: Philosophical Worldview

Postpositivism	**Constructivism**
Determination	Understanding
Reductionism	Multiple participant meanings
Empirical Observation	Social and Historical Construction
Empirical Measurement	Theory Generation
Theory Verification	
Advocacy/ Participatory	**Pragmatism**
Political	Consequences of Action
Empowerment issue–orientated	Problem-centred
Collaborative	Pluralistic
Change–oriented	Real–world practice oriented

The philosophical worldview followed in this study stems from a pragmatic worldview. It focusses on the importance of the research question rather than the methods used to solve it and gives the researcher freedom of choice regarding techniques or methods to meet their needs. It adapts any method that works and may include singular or multiple realities, for example test hypotheses and give multiple perspectives (Creswell, 2009). Even though a pragmatic worldview is predominantly found in research using mixed methods, the conducted research is objective when qualitative methods is used to solve the problem statement. This concludes the research to be that of pragmatism.

3.2.2 Strategy of Inquiry

Strategy of Inquiry operates at a more applied level and refers to the manner in which the researcher is implements each step of the study – with a quantitative or qualitative nature.

Quantitative research deals with measurable characteristics and normally focusses on how data fits an existing theory. Qualitative research is more focused on making conclusions based on observations and expressing results in words as opposed to numbers. It interprets its findings as the project evolves and considers phenomena in the natural setting, rather than testing a hypothesis based on facts. Mixed methods research includes combining qualitative and quantitative research methods in a single study (Cresswell, 2014).

If literature is included in the theory, it can serve as evidence for the purpose of the study, and therefore not lead the development of research questions. It can also be used to test theories or research questions and establish the importance of the purpose of the study. The first point of focus refers to qualitative research while the latter refers to quantitative research (Creswell, 2009).

It is important to note that these two methods are not mutually exclusive nor are they on opposite sides of the same coin. They should rather be considered as differences on a continuum, where any given study tends to be more of the one than the other. In order to distinguish between these two extremes, predominate use of words or open–ended questions (qualitative) versus numbers or closed–ended questions (quantitative) should be investigated. Mixed methods incorporates an equal amount of quantitative and qualitative aspects, and resides in the middle of the continuum (Cresswell, 2014).

Table 3.2 illustrates the different strategies of inquiry used for each research approach, according to Cresswell (2014).

This study stems from a qualitative nature, as the literature in the study serves as the basis for the scope of the study and the development of the proposed framework. The proposed framework is validated through the use of predominantly open-ended questions and the results of the study is expressed in words, which also proves the study to be qualitative.

Table 3.2: Strategy of Inquiry in Research

Quantitative	Mixed-Methods	Qualitative
Experiments	Sequential procedures	Ethnographies
Surveys	Concurrent procedures	Grounded theory
	Transformative procedures	face validation interviews
		Case studies
		Phenomenological research
		Narrative research

3.2.3 Research Methods

Research methods refers to the procedures and methods used to translate the approach to practice. It comprises of specific methods of data collection and analysis (Creswell, 2009).

Table 3.3 illustrates different data collection methods in quantitative, qualitative and mixed methods research.

Table 3.3: Quantitative, Qualitative and Mixed Methods Research Methods. Adapted from Creswell (2003, p.17)

Quantitative	Qualitative	Mixed methods
Predetermined instrument based questions	Emerging	Predetermined methods
Performance data	Open–ended questions	Open–ended questions
Attitude data	Interview data	Closed–ended questions
Observational data	Observation data	Multiple forms of data drawing
Census data	Document data	Statistical and text analysis
Statistical analysis	Audio-visual data	
	Text and image analysis	

In this thesis, the research question is addressed by conducting an in depth study of the critical concepts within the problem using secondary research data. This serves as a basis for framework development.

The validation of a study such as this should should ideally aim to quantify the success of the implementation of the proposed framework. Due to time and cost constraints, as well as the unavailability of applicable sites to perform such an implementation, such a form of validation is however impossible. A qualitative approach to validation is used, where the validity of the proposed framework is achieved based on the achievement of certain criteria. This is determined through the conduction of open–ended (predominently) and closed–ended semi–structured interviews with experts within the field under study, otherwise known as face validation. The outcome of the semi–structured interviews is also used to modify the framework to increase its practicality. An in–depth study of face–validation is provided in Section 6.2.

3.3 Approaches to Research

The philosophical worldview, strategy of inquiry and research methods all contribute to a research approach that is either qualitative, quantitative or mixed. When considering these three elements, this study concludes to be qualitative. Even though a pragmatic world view tends to stem from a mixed methods research approach, the research conducted in this dissertation is objective and its primary focus is on solving the problem statement and answering the research question.

The extensive research conducted on PAM, the ISO 55000 series and lean proves qualitative in nature as it serves as evidence for the purpose of the study and does not by itself answers the research question. The development of the conceptual framework also stems from qualitative analysis, as it is formed based on PAM focus areas selected through qualitative analysis and the integration of the key concepts investigated in the literature study and does not involve the collection or analysis of numerical data.

Collecting data through open-ended (predominently) semi-structured interviews to validate the thesis, also proves this study to have a qualitative nature.

Table 3.4 illustrates the research approach of this thesis through sequential steps.

Table 3.4: Reasearch Approach of this Thesis

Step	Research Method	Strategy of Inquiry	Chapter
1	Structured Literature Study	Qualitative	2
2	Framework Development	Qualitative	4, 5
3	Framework Validation	Qualitative	6

3.4 Design Process of Research

This section will consider the data collection methods and tools to be used in this thesis, as well as sample selection and data analysis.

3.4.1 Data Collection Method and Tools

Secondary data, such as the ISO 55000 series and relevant books and articles, acts as the basis for the literature study. The provided literature is analysed in order to select PAM focus areas and is used to derive a proposed framework. During face validation, interviews are conducted to collect data. A detailed description on the type of interview used in this study is provided in Chapter 6.5.

3.4.2 Sample Selection

There are two main types of sampling methods, probability sampling and nonprobability samples. Probability sampling includes two types of samples: (1) random samples - respondents are chosen at random, (2) stratified samples - respondents are chosen based on a ranking system. Probability sampling is mainly used in quantitative studies, where a sample is generalised to a population. Nonprobability samples are normally used when generalisation is not applicable to the type of study being conducted. This can be done through *quota sampling*, *purposive sampling* or *convenience sampling*. In quota sampling, the population is predetermined in order to ensure inclusion. Purposive and convenience sampling is used mainly in studies where generalisation is not applicable. Purposive sampling involves conducting in-detail investigations on important cases, normally including experts in the field under study. Convenience sampling is unguided, such as chosing volunteers randomly (Onwuegbuzie and Leech, 2007).

For the purpose of this thesis, *purposive* sampling is used as sample members are selected based on their knowledge, involvement, work experience and expertise within the field under study. This includes individuals with expertise within the fields of PAM, ISO 55000 or Lean. Detailed information on the participants chosen for this study is provided in Chapter 6.3.

3.4.3 Data Analysis

Zhang and Wildemuth (2016) identifies three types of qualitative content analysis:

1. Conventional qualitative content analysis
2. Directed content analysis
3. Summative content analysis

Conventional qualitative content analysis is used for grounded theory development, where categories and themes are derived inductively from raw data.

Directed content analysis is typically used when validating or extending a conceptual or theoretical existing framework, through the analysis of collected qualitative data. Existing theory can assist in focussing the research question, provide prediction about variables in the study and their relationship. Through the use of existing theory, key concepts are identified as initial coding categories whereafter detailed definitions are provided for each category using existing theory.

Summative content analysis focusses on counting and comparisons, usually of keywords or content, with the goal of giving meaning to the underlying context (Zhang and Wildemuth, 2016).

This thesis uses directed content analysis. First, existing theory is investigated, which serves as a basis for the selection of PAM focus areas. Secondly, during framework development, clauses within the ISO 55001 and ISO 55002 documents are categorised according to the chosen PAM focus areas and applicable Lean principles and tools. Finally, face validation is used to validate the proposed framework, where semi-structured interviews are conducted with an expert panel. The outcome of the semi-structured interviews is quantitatively analysed in order to determine if a set of pre-determined success criteria is met. All three phases of this study stems from directed content analysis, as an existing theory is extended and validated through the analysis of qualitative primary and secondary existing data.

3.4.4 Ethical Consideration

The following points are ethical implications that is addressed during the study:

- Throughout the study, beneficence, responsibility, scientific validity and justice upholds at all times. This is done by acknowledging the authors who contributed to the research, display true results, and using research funds only for the purpose of enhancing the quality of the study.
- Informed consent is asked from participants taking part in the study by providing an information sheet with details of the study and asking them to sign a consent form.
- No pressure is applied on individuals to participate in the study. If participants fail to complete questionnaires, they are not victimised.
- An individual's autonomy is respected upon request and they are given the freedom to withdraw from the study without providing a reason.

3.5 Chapter Summary

This chapter gives a detailed description of the elements of inquiry, approaches to research and design process of this thesis. When describing the elements of inquiry, this thesis' philosophical worldview, strategy of inquiry and research method is described. The philosophical worldview is concluded to be that of pragmatism, due to its point of focus and the method followed to solve the research problem. A framework will be developed and validate qualitatively. Furthermore, a description of the research design is provided, which gives an outline of the data collection tools, sample selection and data analysis method to be followed. Directed content analysis is used to qualitatively analyse secondary data in this thesis' literature study and framework development and to analyse the data obtained by individuals selected through purposive sampling. Finally, consideration is given to ethical implications to be considered throughout this study.

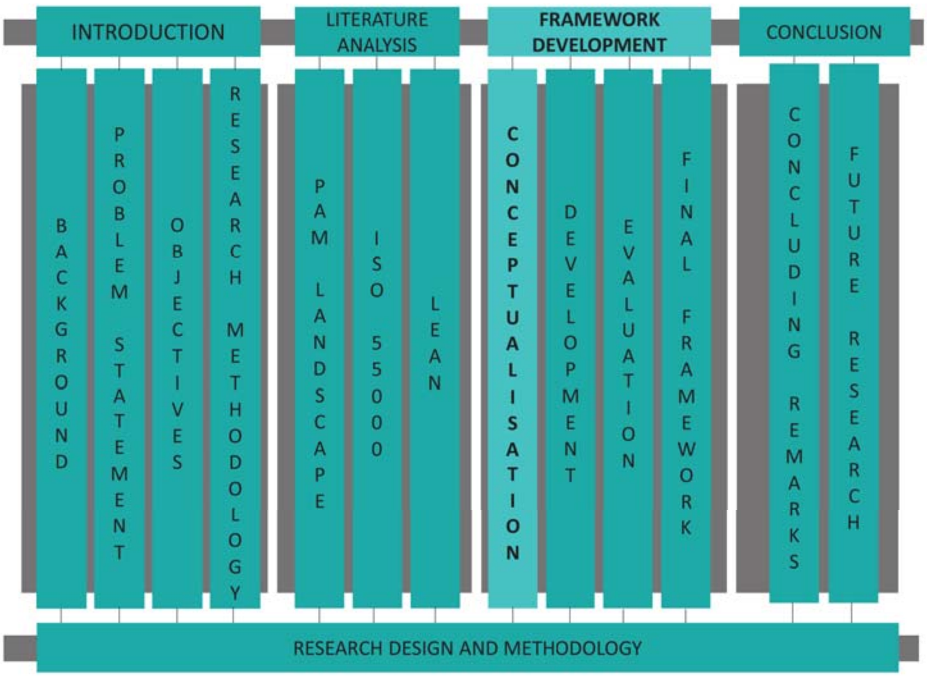
Chapter 4

PAM Focus Area

Chapter Outcome

1. Select PAM focus areas through qualitative analysis
2. Provide literature on the selected PAM areas

Chapter Route Map



4.1 Selecting PAM Focus Areas

In Chapter 2, the building blocks of PAM is investigated. This section investigates the literature provided in Chapter 2 to narrow the scope of this research by selecting PAM focus areas for this study.

The requirements within the ISO 55000 document address the all different fields within the field of Physical Asset Management. To study each of these fields in depth to ensure an accurate interpretation of these requirements, would take more time and resources than what this research can allow. Therefore, to increase the quality of the study, the first part of analysing the literature involves selecting a limited amount of physical asset management subjects and providing detailed literature on each.

From the subject areas the AML regards as the building blocks of AM, the subjects regarded as important AM subjects by research students, the key concepts found in the numerous PAM definitions, and the six areas defined by ISO 55000 as critical AM areas (Chapter 2.1.2), the following PAM areas were considered as possible focus areas for this study:

- AM Policy
- AM Strategy
- Demand Analysis
- AM Plan
- Strategic Plan
- Asset Lifecycle Management
- Maintenance
- Shutdowns, Outage Strategy and Optimisation
- Technical Standards and Legislation
- Systems Engineering
- Configuration Management
- Optimal Decision Making
- Operations and Performance Management

- Resource Management
- Reliability Engineering
- Fault and Incident Responce
- Info and Knowledge Management
- Contract and Supplier Management
- AM Leadership
- Organisational and People Enablers
- Competence and Behaviour
- Risk and Opportunity Management
- Sustainable Development
- Stakeholder Management
- Change Management
- Risk and Opportunity Management
- Systems Engineering
- Organisational Alignment

Four factors were used to decide on PAM focus areas within this study. Ultimately, this research aims to include as many of the requirements within the ISO 55001 documents as possible to increase the comprehensiveness of the developed framework. The selection criteria were therefore chosen with this as the primary goal.

In determining the PAM focus areas, the following factors were taken into consideration:

- Factor 1: The amount of times each PAM subject area is mentioned in the various PAM definitions.
- Factor 2: If the PAM subject area is regarded as a subject group or AM subject in the AML (from Table 2.1).

- Factor 3: The amount of times each PAM subject area is addressed in the ISO 55001 document.
- Factor 4: The importance of each PAM subject area, as perceived by research students and studied in Section 2.1.2.

In Factor 1, when a PAM area is directly addressed in the definitions of PAM studied in the literature (especially the definitions provided by PAS 55 and ISO 55000), it is given more importance. The reason for this is that it can be considered as part of the essence of the field of study and has the potential to be addressed in a greater amount of requirements within the ISO 55000 series. When considering factor 2, subject groups are given preference, as it will enable a greater variety of areas within the field of PAM to be incorporated in this study. Factor 3 considers the amount of times each PAM area is directly and indirectly addressed within the ISO 55001 document. PAM areas addressed more are given preference, as it will enable the inclusion of a greater amount of ISO 55001 requirements. Finally, Factor 4 considers the importance of the 39 PAM subjects as defined by the GFMAM and covered in the literature study in Section 2.1.2.

When considering Factor 1, asset lifecycle management and risk and opportunity management were most prominently in the PAM definitions investigated. Other PAM areas mentioned includes maintenance, optimal decision making, operations and performance management, reliability engineering, sustainable development, organisational alignment and asset information and knowledge.

Factor 2 includes investigating the PAM areas provided by the AML. AM Strategy and Planning, asset lifecycle management, maintenance, optimal decision making, reliability engineering, asset information and knowledge management, risk and opportunity management and organisation and people enablers were regarded as *subject groups*. The remaining PAM areas is considered by the AML as PAM subjects, which, when grouped together, comprises of the different PAM subject groups. When determining PAM focus areas, subject groups are given preference, as they cover a broader scope than individual subject areas. Subjects mentioned in more than one subject group were also given preference.

Upon investigating the ISO 55000 Suite of Standards, it was concluded that the PAM areas referred to the most throughout all sections includes maintenance, fault and incident response, information and knowledge management, risk and opportunity management, AM policy and stakeholder management. However, this does not disregard the importance of the other PAM subject areas in the ISO 55000 Suite of Standards. They are given preference due to covering a broader scope of ISO 55000 requirements, which enables the researcher to maximise the amount of solutions provided to the problem statement.

PAM areas regarded as most important through the perception of research students (Factor 4) includes AM policy, AM strategy, AM plan, strategic plan, asset lifecycle management, maintenance, operations and performance management, reliability engineering, AM leadership, risk and opportunity management and systems engineering.

When comparing the outcome of all four factors, the following PAM subject were chosen as focus points of this study:

- Asset Information and Knowledge
- Asset Lifecycle Management
- Risk and Opportunity Management
- Reliability Engineering
- Maintenance

Asset information and knowledge management was addressed approximately 12 times in the ISO 55001 document and according to the PAM definitions, is considered to be the basis of PAM. Even though it is not given high importance by research students, it is considered a PAM subject group by the AML and covers a broad scope of PAM subjects.

Asset lifecycle management and risk and opportunity management are both mentioned in all of the provided PAM definitions, are considered PAM subject groups and are regarded as important by research students. Risk and opportunity is addresses most (approximately 15 times) in the ISO 55001 document. Furthermore, both reliability engineering and maintenance are addressed in the PAM definitions, are subject groups in the AML and are rated as important by research students. The ISO 55001 document also refers to maintenance approximately 12 times, which is, together with asset information and knowledge, the PAM area addressed second most in the ISO 55001 document. For these reasons, these five PAM areas will be the focus point for the remainder of this thesis. As mentioned earlier, it is important to note that these areas are not chosen based on importance, but rather their potential of providing a thorough solution to the problem statement.

The selected five PAM focus areas will be explored in the rest of this chapter.

4.2 Asset Information and Knowledge

Data used to analyse assets and the rest of the PAM system can be compared to a structure that supports a building from underneath, where the structure represents the data and the building represents the rest of the PAM system. If the structure of a building is not adequate to hold the building and not of good quality, it will decrease the reliability of the building, which ultimately may cause the building to collapse. Just like this phenomena, if the foundation of PAM is not in place, the reliability of the whole PAM system will decrease.

The process of managing engineering assets is greatly affected by the data obtained to make applicable decisions. If the quality of data is poor, it will have an unfavourable effect on EAM, which may lead to substantial financial losses (Baskarada *et al.*, 2006). In fact, according to a study conducted by Friedman (2010), 36 percent of participants involved in the study claimed that they lose more than 1 million dollars annually due to data quality issues.

The survival of any organisation today depends heavily on data, as it links directly with an organisations' long–, short–and medium–term objectives.

Ackoff (1999, p.170) states that:

> *"Data is raw. It simply exists and has no significance beyond its existence (in and of itself). It can exist in any form, usable or not. It does not have meaning of itself".*

but is important, because:

> *"An ounce of information is worth a pound of data. An ounce of knowledge is worth a pound of information. An ounce of understanding is worth a pound of knowledge"* (Ackoff, 1999, p. 170).

Data is thus being viewed as an asset for any organisation, if and only if it is current and accurate (Lake and Crowther, 2013). Ackoff (1999) named the above finding the *Data-Information-Knowledge-Wisdom (DIKW) Hierarchy*, which is illustrated in Figure 4.1.

The IAM states that asset data should be understood, managed and assessed in order to provide necessary support to business decision-making and processes.

According to Lin *et al.* (2006, p.473):

"There is strong evidence that the most organizations have far more data than they possibly use; yet at the same time they do not have the data they really need."

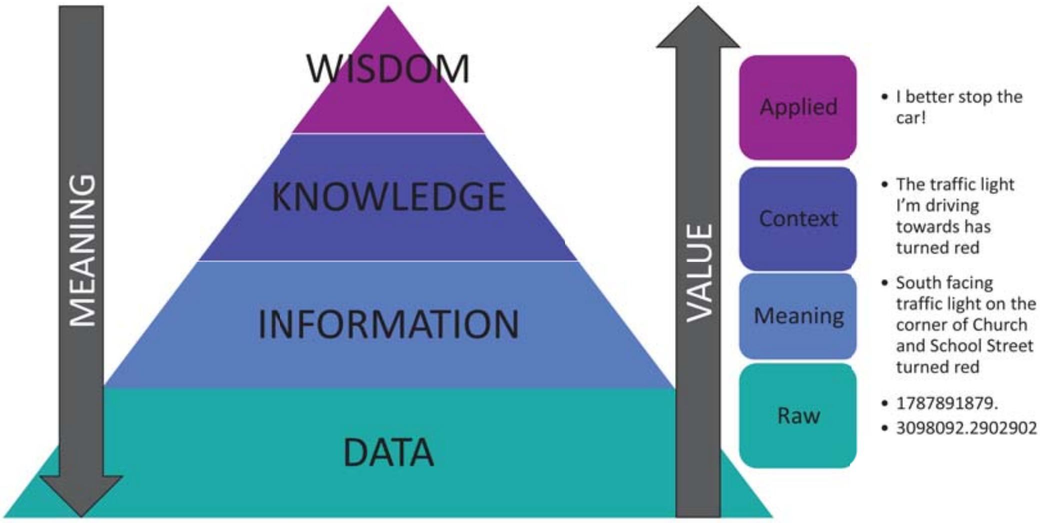


Figure 4.1: The Data-Information-Knowledge-Wisdom (DIKW) Hierarchy. *Derived from Ackoff (1999)*

.

Organisations need to asses which data is of value to the company and determine what activities need be followed in order to obtain it.

Huh *et al.* (1990) states that faulty data is difficult to fix once they are in the database. He compares a database to a lake - to ensure that a lake is clean, the water flowing into the lake should be clean; it is nearly impossible cleaning a lake which is polluted already. Only once processes are put in place to introduce, modify and transform data, and when these processes are in a state of statistical control, can sustainable data improvements exist in data quality. He further identifies four dimensions of data quality:

– Accuracy

– Completeness

– Consistency

– Currency

Firstly, for data to be accurate, it should be in agreement with an identified source, which on numerous accounts can be the real world, another database or computational algorithms. Secondly, for data to be complete, all of the relevant data aligned with a given purpose should be within a set. Thirdly, data should be consistent, meaning that it should not conflict with other sets of data and, when compared to other data sets, should confirm each other's correctness. Finally, data should be current, meaning that it should at all times be up-to-date.

Ensuring that data is of high integrity is an imperative step to an effective AM system, as it acts as a key enabler of gaining control of assets and making business decisions (Lin *et al.*, 2007). This is supported by Hastings (2010, p.16), who states that:

> *"The management of assets is dependent on knowledge about the organization asset, in terms of both current equipment, business role of the assets and future prospects. Asset managers need to have practical working knowledge of the major assets at a management level so as to be able to make sound business decisions."*

According to Hamza (2009), tacit and explicit knowledge is transferred in an organisation through employees, where Information Technology (IT) acts as a support system for knowledge transfer in terms of capturing, storing and retrieving. It is imperative for tacit knowledge to be transferred to explicit knowledge in order to easily be understood (Gumbley, 1998). An example of tacit knowledge is data manually or automatically captured without any intelligence. Reports which are compiled after the data have been analysed can be viewed as a representation of explicit knowledge. If explicit knowledge on the current states of operations within a company is gained, it can be acted upon in order to gain improvements. Knowledge is also critical for understanding risk and opportunity within any company. If the data captured is inaccurate, the reports generated from the data will be inaccurate, which negatively influences the process in which knowledge is transferred. This also results in Upper Management having inaccurate knowledge on the current state of the business and being unaware of possible risks and opportunities.

Gumbley (1998) states that if we fail to protect and fully exploit knowledge, the true potential of the organisation and employees are not being realised. Those organisations who make it will be those who fully grasp the intellectual capacity of their employees, which includes building appropriate business processes and information support systems (Gumbley, 1998).

The main reason why the concept of knowledge management is currently rising is due to the fact that technology advancement is reaching a point where knowledge management is becoming possible and economically feasible (Gumbley, 1998). Knowledge management however should not solely rely on information systems. According to Rubenstein-Montano *et al.* (2001), practitioners are beginning to realise that the key driving factors of the success or failure of knowledge management are people and organisational culture. If only focussed on information systems, the growth and sustainability of knowledge management might be inhibited (Rubenstein-Montano *et al.*, 2001).

Rubenstein-Montano *et al.* (2001) gives two recommendations for an effective knowledge management system:

1. It must be both prescriptive and descriptive.
2. It must be consistent with systems thinking.

If the latter is in place, the following important aspects will be in place:

a. The organisational strategies and goals will be linked to knowledge management

b. Planning will be executed before knowledge management activities are undertaken

c. Organisational culture will be recognised and aligned with knowledge management

c. Knowledge management will be an evolutionary, iterative process with feedback loops

Armistead and Meakins (2002) further suggests business processes to be mapped out and reviewed through a knowledge management lens.

This section provided literature on data, reporting and knowledge management. The next section will consider Lifecycle Delivery and Activities.

4.3 Asset Lifecycle Management

According to Haffejee and Brent (2008, p.286), the life cycle of an asset can be defined as the:

> *"period that an entity can foresee itself utilising an asset on an economically effective and efficient basis for the furtherance of the entity's trade or service deliverance"*

This includes the procurement phase, the use and maintenance of the asset and eventually the disposal of the asset (Haffejee and Brent, 2008). Haffejee and Brent(2008, p.286) further defines ALCM as:

> *"the application of life-cycle thinking to modern business practice, with the aim of managing the total life cycle of an organisation's products and services towards more sustainable consumption and production."*

According to Campbell *et al.* (2010), traditional view of PAM often separate key phases, such as procurement and maintenance, which may cause an organisation to lose potential profit. For example, when purchasing a new asset, if its repair costs are not factored in, an organisation may incur great costs maintaining the asset, even if its purchasing cost is low.

Figure 4.2 illustrates the total life-cycle AM process. Each of the illustrated phases has its own financial management implications and planning requirements. They are traditionally focussed on most during the design, procure and disposal phases, but are equally important in the operation and maintenance phases. Maintenance, for example, can be a great contributor to total cost of ownership (TCO), and the performance of the asset during its operation phase can be a huge contributor to financial performance. Technology is also a great support system for each phase, where technological tools can be used to improve each phase by collecting asset information to aid strategic decision-making (Campbell *et al.*, 2010).

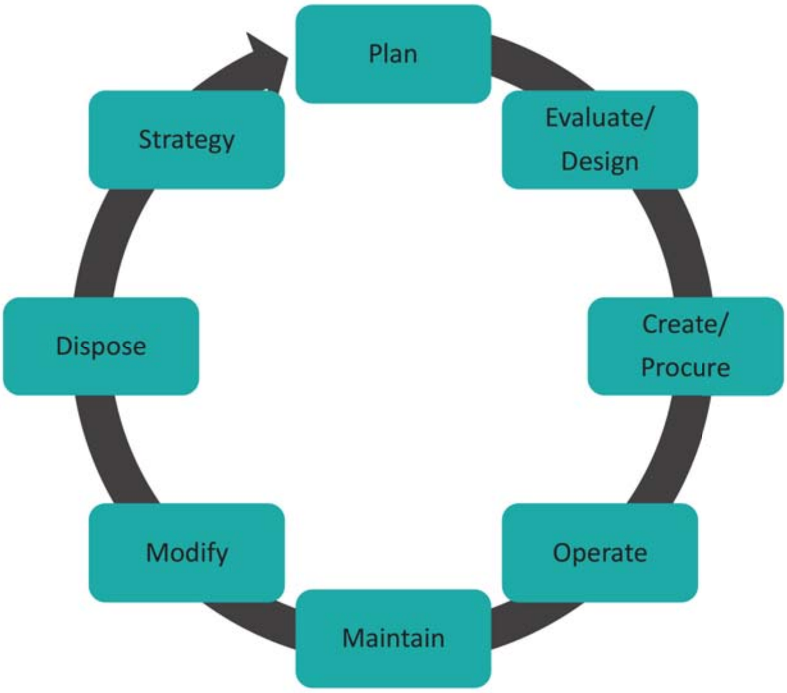


Figure 4.2: Total life-cycle asset management..
Derived from Campbell et al.*(2010, p.16)*

.

Planning includes defining asset targets, standards, policies and procedures in terms of delivering the organisation's AM strategy.

Evaluate and Design involves evaluating or designing the assets purchased or created. This includes financial consideration as well as all aspects of practicality regarding purchasing the asset, such as shipping, storage, manufacturing space etc.

Create and Procure includes creating, building, or procuring the planned asset.

Operate is the phase where the asset's value is realised through its performance. It involves operating the asset according to the AM strategy and applicable standards, policies and procedures.

Maintain involves maintaining the assets to minimise asset downtime. This phase will be discussed in more detail further in this chapter.

Modify encompasses modifying assets when required and ensuring that these modifications are aligned with the AM strategy, policies and procedures. This may include modifying the assets' IT-system, or modifying the asset itself for performance improvements. This may have a great effect on the life extension of an asset, as it can include upgrading or retooling the asset.

Dispose includes disposing, retiring or liquidating the asset in accordance with the organisation's AM strategy, policy and procedures.

According to Haffejee and Brent (2008), internal and external drivers have a great influence on the planning of procuring new assets, as well as the disposal of old ones. External drivers include external factors resulting in organisational changes for example cost of electricity, competition, social concerns, the environment etc. Internal drivers of change are factors inside of the company that results in organisational change, such as loss of skilled personnel, process efficiency etc. Haffejee and Brent (2008) further states that assets should periodically be assessed in order to gain the assets' economic, social, environmental and technical influence, which should aid in deciding how the asset should be disposed of. This information should be obtained by collecting data at each phase, which is normally done through a supporting IT system.

4.4 Risk and Opportunity

The decisions that are made daily are based on the understanding and interpretation of data accessible to the decision-maker. This data can be full of uncertainty due to equipment error, human error, biased readings etc., which is part of our everyday lives (Schoeman and Vlok, 2014). Today, an increasing amount of uncertainties such as financial crises, terrorist attacks and natural disasters have great impacts on the operational environment of businesses, which, in return, has a significant impact on its short- and long-term performances (Tang, 2006; Lai and Lau, 2012). Furthermore, businesses continuously undergo great transformations to keep up with globalisation. According to Lacy and Pickard (2008) (2008, 140):

> *"The question for businesses is therefore not about whether events and circumstances will change, rather how, where, when and to what degree...A clear understanding of the associated risks and opportunities will lead business to innovate through new products, strategies, processes and technologies. In contrast, a failure to grasp them will threaten the survival of the firm"*

According to ISO 31000 (2009), risk is *"the effect of uncertainty on objectives."* Knechel (2002) defines risk as the probability that the result of a process will not meet expectations. Khan *et al.* (2008, p.103) further describes risk as *"the product of the consequence of a failure, and the probability of the occurrence of that failure."* He also states that it is modelled as the product of two parameters:

1. The likelihood of occurrence of failure
2. The loss resulting from that failure

There are numerous types of risks. These includes, but are not limited to (Hastings, 2010):

- sovereign risks;
- solution risks;
- technical development risks;
- performance risks;
- commercial or financial risks;
- administrative risks;
- safety and environmental;
- supplier risks and
- resources.

The concept of risk is broad and has expanded in recent times to almost anything except a racing certainty. This concept is normally concerned in situations where an unfavourable occurrence may occur (Hastings, 2010).

Diligent devotion to projects, the broad commitment of senior personnel and a wide range of high level stakeholders make it difficult to admit or avoid risk (Hastings, 2010). In order to survive in today's competitive environment, the risk faced by organisations need be assessed and contingency plans need be developed in order to reduce unfavourable consequences and assure that critical processes are being sustained (Lai and Lau, 2012). This is done through risk analysis and management. The main purpose for risk management is not to remove risk, but rather to determine which risks are worth taking and which risks should be completely avoided (Schoeman and Vlok, 2014).

In risk analysis, plausible risks are identified and their potential effects reduced through mitigation policies. It is important to note that the concept of risk does not only refer to unfavourable outcomes, but can also present significant opportunities and possibilities for organisational innovation and new competitive advantage leading to short- and long-term profitability. In fact, risk and opportunity can be considered as a duality- two sides of the same coin (Bekefi *et al.*, 2008). Nevertheless, the primary aim of risk analysis is to avoid only the occurrence of hazardous effects (Hubbard, 2009), therefore focus will first be given on risk, which will be followed by literature on opportunity.

Hastings (2010) mentions three critical terms related to risk analysis that should be clearly understood. These include:

1. Hazard – a source of potential harm
2. Consequence – the result of an occurrence in the form of loss, gain, injury, advantage or disadvantage.
3. Likelihood – a qualitative description of probability of frequency

Risk management involves recognizing risk as an issue and implementing a pro-active approach to identify, assess and prioritise risk. This is followed by coordinated and economical application of resources to minimise, keep track of, and control the likelihood and impact of unfortunate occurrences (Hubbard, 2009; Hastings, 2010; Lai and Lau, 2012).

In 2009, ISO created a standard for Risk Management called the ISO 31000 standard. This standard provides a detailed approach to a Risk Management process to ensure effective Risk Management, applicable to companies in any industry.

According to ISO 31000 (2009), if an effective risk management plan is in place, an organisation will receive numerous benefits, including but not limited to:

- achieving their objectives;
- managing pro-actively;
- being aware of the criticality of identifying risks and treating them throughout the whole organisation;
- improving processes to identify opportunities;

– adhering to legal and regulatory requirements as well as international standards;

– gaining trust and confidence form stakeholders;

– improving controls;

– improving the effectiveness and efficiency of operations;

– reducing losses and

– building organisational resilience.

Schoeman and Vlok (2014) emphasises the importance of risk management, stating that nearly 75 percent of the sections of the PAS 55 document directly relates to this concept. They also state that the entire PAM process can, by itself, be seen as a risk management process as it is focused on identifying and executing AM activities.

Figure 4.3 illustrates the Risk Management process, as defined by Hastings (2010). Firstly, the context of the internal and external environment is defined as well as the risk management process context and risk criteria. Examples of the internal context include organisational policies, objectives, structures etc. and external context include culture, key drivers, social environment etc. Secondly, a hazard analysis is conducted, where potential risks are identified and recorded in a file known as a *risk register*. Thirdly, risks and the significance of their impact is analysed and possible ways to overcome or mitigate them identified. Finally, necessary controls, procedures and contingency plans are put in place to manage these identified risks (Hastings, 2010; ISO 31000, 2009).

ISO 31000 (2009) provides a more detailed approach to Risk Management, establishing a feedback loop by integrating *continuous monitoring and review* as well as *communication and consultation* in each step of the Risk Management Process. This is illustrated in Figure 4.4. Communication and consultation is critical in order to continuously keep all stakeholders up to date and benchmark and receive outside opinions to continuously better each step in the process and stay competitive. Monitoring and reviewing of the entire process is important as it also focusses on continuous improvement and ensures that the whole risk management process is effective and efficient (Basson, 2016).

Figure 4.3: Risk Management Outline.
Derived from Hastings (2010, p.159)

.

ISO 31000 (2009) provides a more detailed approach to Risk Management, establishing a feedback loop by integrating *continuous monitoring and review* as well as *communication and consultation* in each step of the Risk Management Process. This is illustrated in Figure 4.4. Communication and consultation is critical in order to continuously keep all stakeholders up to date and benchmark and receive outside opinions to continuously better each step in the process and stay competitive. Monitoring and reviewing of the entire process is important as it also focusses on continuous improvement and ensures that the whole risk management process is effective and efficient (Basson, 2016).

It is important that records are kept of the risk management process in order to enable ongoing evaluation and improvement (Basson, 2016). Bekefi *et al.* (2008)

states that while evaluating risks, opportunities often hidden in risks should at all times be considered. Companies might initially forgo opportunities without properly analysing them, because they may seem too risky. The key to innovation and market success often lies in the ability of an organisation to properly identify and manage risks.

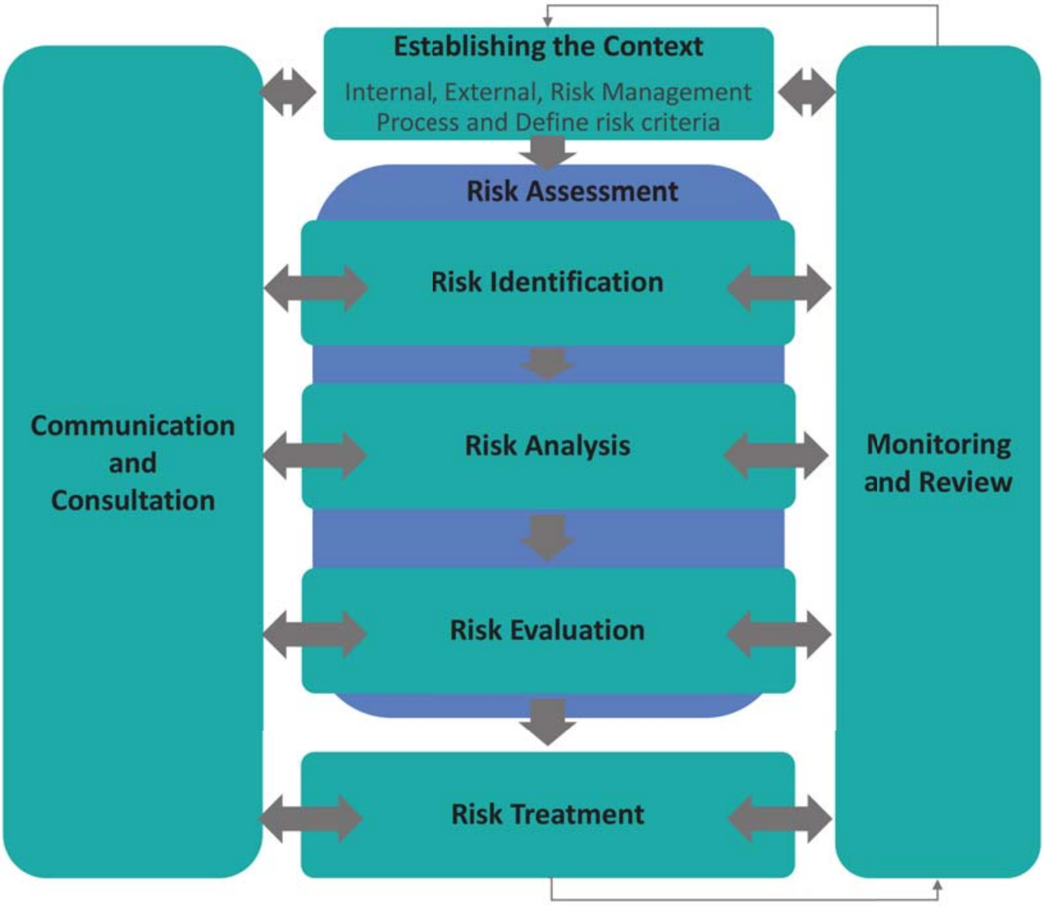


Figure 4.4: Risk Management Process as defined by ISO 31000.
Adapted from ISO 31000 (2009)

.

Internal sources of opportunities may include supply chain, product and service offering, process, technology and new markets. Common examples for external sources of opportunities includes customers, competitors, emerging technologies and scientific developments and influencers and thought shapers (Bekefi *et al.*, 2008).

Bekefi *et al.* (2008) developed a process where risk and opportunity is considered simultaneously. They state that the ability to use tools to simultaneously recognise and assess risk and opportunity can enable a company to manage risk and opportunities offensively as an opportunity, rather that defensively as a hazard, which is the more common approach. This process can be seen in Figure 4.5

Identify Risk and Opportunity includes the identification of the various sources of risk and opportunity, as mentioned earlier in this section.

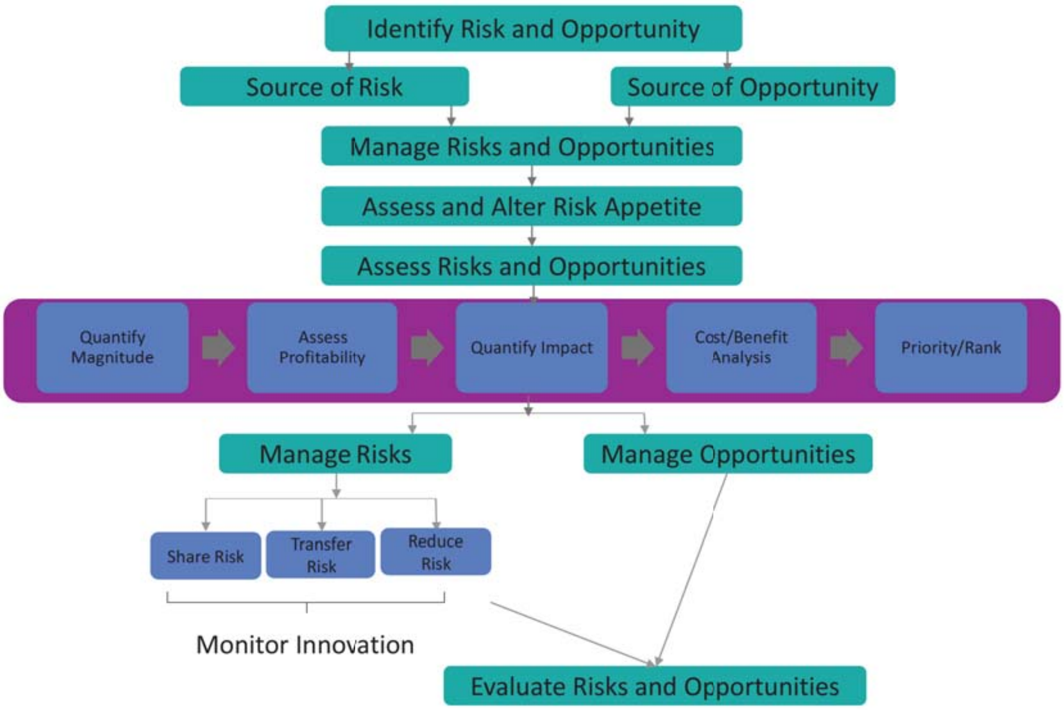


Figure 4.5: Risk and Opportunity Management Process.
Adapted from Bekefi et al.*(2008, p.8)*

.

Common ways to identify these sources include:

- Learning from the past
- Developing customer sensitivity
- Learning from others

– Scanning
– Scenario planning

Managing Risks and Opportunities includes two steps. The first step includes defining, assessing and potentially altering the risk appetite of the organization, this should be done annually. According to eAsset Management *et al.* (2015, p.19), risk appetite is *"the amount and type of risk that an organisation is willing to pursue in order to deliver value"*. They further define risk tolerance as *"the amount of risk an organisation is willing to accept (post-control) in order to achieve its objectives"* (eAsset Management *et al.*, 2015) (2015, p.19). When the risk tolerance of an organisation is reached, measures are taken to bring the exposure level back into the acceptable risk appetite range.

The second step of managing risk and opportunities include assessing risk and opportunities. Opportunities can be measured by 1) assessing increased market share, 2) Calculating the profit to be obtained, 3) Quantifying the number of new customers, 4) calculating potential sales growth and 5) measuring the residual income. In contrast, risks can be assessed by:

1. Determining the magnitude of the impact of the risk
2. Assess the probability of the risk occurring
3. Quantify the impact of the risk on the company (1) x (2)
4. Determine the cost-benefits of mitigating risk
5. Prioritise risks

Managining Risks includes moving a company within an acceptable risk range, as defined by the risk appetite of an organisation. This includes mainly sharing, transferring or reducing risk. Risk sharing includes distributing the risk amongst two or more parties and can be accomplished by joint venture. Transferring risk includes shifting the responsibility of risk to another party through for example insurance or contracts. Reducing risk includes actions to reduce the probability and/or impact of risk. Common examples include completely avoiding the risk or increasing organisational resilience.

Managing opportunities involved identifying and seizing opportunities where most people normally sees risks, which may lead to a breakthrough idea. Companies should create techniques to manage the structure, reward and evaluation methodologies that underpin innovation systems.

Evaluating Risk and Opportunity includes assessing risk and opportunities numerically through calculations such as ROI or NPV.

This section described risk and opportunity, the following section will provides literature on reliability.

4.5 Reliability

Reliability is the basis of PAM (Mitchell, 2007). Kececioglu (2002) states that no country can move forward without the knowledge and application of reliability. Especially in today's modern age, where automation is becoming the norm and equipment is becoming more complex, increasingly making it more imperative to understand the principles of reliability engineering.

Mitchell (2007, p.43) defines reliability as:

> *"The probability that a system, device, component or product will perform its required functions in a satisfactory manner for a given period of time when used under specified operating conditions in a specified environment."*

Kececioglu (2002, p.2) further provides an all-inclusive definition of reliability engineering:

> *"Reliability engineering provides the theoretical and practical tools where by the probability and capability of parts, components, equipment, products, subsystems, and systems to perform their required functions without failure for desired periods in specified environments, that is their optimized reliability, can be specified, predicted, designed in, tested, demonstrated, packaged, transported, stored, installed and started up, and their performance monitored and fed back to all concerned organizations, and any needed corrective action(s) taken, the result of these actions being followed through to see if the units' reliability has improved; and similarly for their desired and optimized maintainability, availability, safety and quality levels at desired confidence levels at competitive prices."*

According to Kececioglu (2002), reliability decrease as the number of components of a product increase. Kececioglu (2002) also states that according to customers reliability, safety, maintainability and quality are the four top requirements when purchasing products. In fact, when a customer is satisfied with these four parameters of a product, they are likely to tell 8 other people about it. In contrast, when they are not satisfied, 22 people are likely to hear about it. An increasing amount of products are being advertised by their reliability statistics, such as their mean time between failure (MTBF), failure rate and reliability. This exerts competition to have knowledge of the reliability of their products. In the future, the only companies that will succeed are the companies which has the knowledge and who will be able to control the reliability of their products (Kececioglu, 2002). Morad *et al.* (2014) states that reliability and availability can be used to quantitatively evaluate system survival analysis. Mitchell (2007) identifies three main objectives of reliability:

1. Satisfactory performance
2. Predictable
3. Minimum variation

Reliability is analysed through statistical techniques and observed failure data. It is then used to determine applicable maintenance tactics in order to improve system performance (Morad *et al.*, 2014). If these maintenance tactics are not implemented, the equipment will not remain safe and reliable (Arunraj and Maiti, 2007). According to Vagenas *et al.* (1997), there are two ways to approach maintenance: a basic maintenance approach and a reliability centred maintenance approach. The first is a simple method to determine equipment down time and the latter is focused on forecasting future operating characteristics. Basson (2016) states that it is safe to say reliability forms the basis of maintenance. Reliability figures are determined first and then, based on these values, applicable maintenance tactics are chosen. The next section will provide literature on maintenance, what is traditionally thought of as the basis of PAM.

4.6 Maintenance

In this current day, the progress of maintenance is being stimulated by the continuous growth of complexities in manufacturing processes and products, due consideration to safety and the environment, the quality of products and the profitability of an organisation (Arunraj and Maiti, 2007). According to Jardine and Tsang (2006, p.1), over the years the definition of maintenance shifted from:

> *"all activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfilment of its production function"*

to a more broader perspective such as *"the engineering decisions and associated actions necessary and sufficient for the optimization of specified capability."*

The latter definition specifically focusses on the whole life cycle of the physical asset. The word *capability* in this definition is defined as the capacity to perform a specified action within a scope of performance levels Jardine and Tsang (2006*b*).

According to Arunraj and Maiti (2007), in some industries, maintenance is regarded as the second highest to highest element of operating costs. Managers has up until recently allocated a limited budget to maintenance in order to do the necessary at minimum cost. Today, it is becoming a top cost control priority, where effort is put into investing more to optimise return (Spires, 1996; Marques *et al.*, 2009; Tsang and Albert, 2002).Furthermore, maintenance has increasingly been characterized by risk-based inspection and maintenance, together with Condition based maintenance and reliability centred maintenace. Safety and maintenance are being viewed as mutually inclusive, where the sole purpose of the maintenance process is to optimise profitability and total life cycle cost, without compromising safety or environmental issues. It is currently believed that when risk analysis is done, and maintenance tactics formed using the results as a basis, the probability of system failure and its consequences is minimized (Arunraj and Maiti, 2007).

Common maintenance tactics used from the year 1940 to today are (Arunraj and Maiti, 2007):

1. Corrective maintenance
2. Planned preventative maintenance
3. Time based maintenance
4. Condition based maintenance
5. Reliability centred maintenance
6. Risk-based maintenance

The rest of this section will provide literature on each.

4.6.1 Corrective Maintenance

Corrective maintenance, or otherwise known as run-to-failure maintenance (Prajapati *et al.*, 2012) is defined by Pham and Wang (1996, p.425) as:

> *"all actions performed as a result of failure, to restore an item to a specified condition."*

In other words, it includes any maintenance that occurs when a system fails and only occurs at this point. This might involve repair, restoration or replacement, after which the failure rate of the system will be somewhere in between as good as new or as bad as old (Prajapati *et al.*, 2012; Pham and Wang, 1996). This does not mean that the failure was not foreseen, in fact, there are many methods used, such as a maintenance tree, to establish quick recovery upon failure (Lyonnet, 1991). This type of maintenance is very costly due to its high repair costs once equipment breaks down and equipment downtime, leading to a loss of profit (Mobley, 2002).

4.6.2 Preventive Maintenance (PM)

Preventive maintenance *"aims to reduce the probability of failure"* (Lyonnet, 1991, p.2) and ensures that all equipment are kept in good operating condition (Patton, 1983). Everything is going to fail at some point in time. According to Patton (1983), the main goal of PM is to prevent failure from happening at a bad time, predict and fix them before they occur and cause damage, and preserve capital investments by keeping equipment in good operating condition. There are two types of PM:

1. Systematic or scheduled maintenance
2. Condition-based maintenance

In scheduled maintenance, components are replaced when they become worn (Lyonnet, 1991) or at fixed intervals, for example oil or spark plug changes on a car. This type of maintenance should only be used if deemed impossible to detect equipment failure predominantly (Patton, 1983). In condition-based maintenance (CBM), a diagnostic study is conducted and based on its outcome, a decision is made to replace or not to replace. This is normally done on equipment with great replacement costs and where its state can be assessed through non-destructive tests such as vibration analysis, temperature measurements, analysis of lubricating oil (Lyonnet, 1991) and statistics and probability theory (Patton, 1983). This maintenance tactic has shown great results in the automotive, aerospace, military, and manufacturing industries, with great increases in efficiency and cost savings (Patton, 1983).

4.6.3 Predictive Maintenance

Predictive Maintenance is a process which needs effective technologies and people skills to integrate and use all available diagnostic and performance data, maintenance histories, operations data and design data to determine maintenance tactics of key equipment. This tactic is proactive rather than reactive and uses condition monitoring in order to detect problems early on (eAsset Management *et al.*, 2015). According to Beebe (2001, p.5), condition monitoring is:

> *"a type of maintenance inspection where an operational asset is monitored and the data obtained analysed to detect signs of degradation, diagnose cause of faults, and predict for how long it can be safely or economically run."*

This is used in both predictive and condition based maintenance. The main difference between predictive maintenance and condition based maintenance is the fact that more factors are taken into consideration and integrated in order to predict the start of failure, rather than periodically investigating the state of equipment and reacting when the minimum threshold is close to being exceeded. This can easily be explained using the P-F curve, illustrated in Figure 4.6.

This is a common curve used to show the behaviour of equipment as it approached failure. This curve shows that as soon as failure starts, it can deteriorate to a point, P, at which failure can be detected. The interval between P and F, called the P-F interval, is the window of opportunity of which failure can be detected and measures be put in place in order to prevent a catastrophic failure, F. In condition based maintenance, diagnostic studies are continually deducted in order to determine where the equipment condition is on the curve and react when it has exceeded or is close to exceeding P, based on statistical theories. In predictive maintenance, numerous methods are used, such as the analysis of historical, operational and design data in order to predict P and F and act proactively. Common condition monitoring techniques include (Starr and Rao, 2001) vibration monitoring, lubrication (fluid) analysis, motor electrical analysis, infrared thermography, ultrasonic, valve and control action and response and visual inspections.

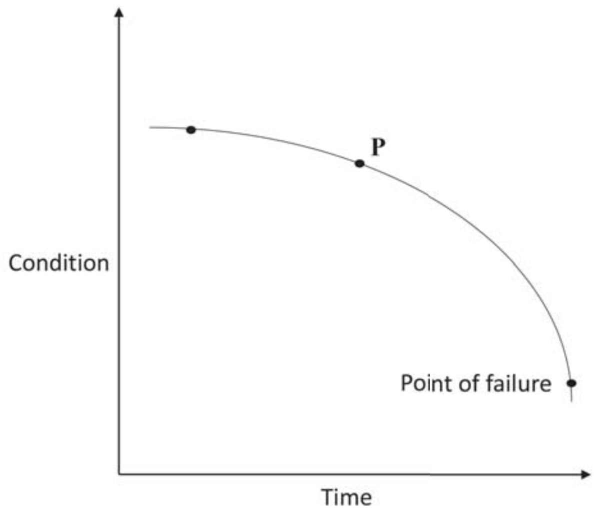


Figure 4.6: The P-F Curve.
Adapted from Arunraj and Maiti (2007, p.654)

.

The cost of failing to use condition monitoring as the basis for maintenance strategies can be seen in Figure 4.6.3.

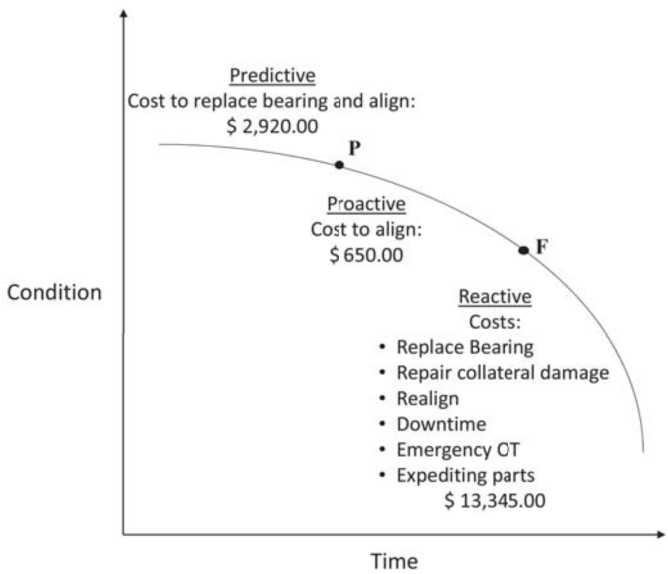


Figure 4.7: Cost Impact of Deferred Action.
Derived from Mitchell (2007, p.349).

4.6.4 Reliability Centred Maintenance (RCM)

RCM is more than just another maintenance tactic. It is a process used to determine physical asset operational requirements and investigate the consequences of its failure and mitigate these results through design, detection or effective maintenance to enable it to do what is expected in its operating context (Moubray, 1994; Wheeler, 2007).

The reason why preventive maintenance is not always adequate is due to the fact that there are numerous types of P-F curves for different equipment, where failures on many occasions happen randomly. The main objective of preventative maintenance is mostly to address basic maintenance issues and not to abolish failure completely. Furthermore, it focusses on maintaining "equipment", and not external sources which may lead to downtime, such as air-discharge temperature at the Evaporator versus Control Set Point to detect low refrigerant problems (Wheeler, 2007).According to Sutton (1995), RCM does not contain any new maintenance principles. It is simply a structured way to combine different maintenance tactics on critical components at the level of plant or equipment type, even when there is little to no historical data. It is the optimum mix of reactive, scheduled, condition-based or predictive maintenance in order to gain benefit of their respective strengths, maximise facility and equipment reliability and minimise costs. Smith and Hinchcliffe (2004) suggests four characteristics that define RCM: (1) Preserve functions, (2) Identify failure modes that can demolish the functions, (3) Prioritise function need, via the failure modes, (4) Choose only relevant and effective preventive maintenance tasks per function.Wheeler (2007) furthermore identified five steps to implement a RCM system:

1. Assess your facility's infrastructure: operating costs, performance results, regulatory requirements and capacity.

2. Identify possible gaps: places where you could cut costs or improve performance.

3. Collect operating data for systems within your infrastructure such as energy or water usage. Analyse this data and determine a strategy to address the identified gaps.

4. Develop a roadmap including the approved improvement budget, technology integration project plan, monitoring plan and a maintenance management schedule.

Wheeler (2007) states that by following these steps, operations processes would be optimised rather than simply cutting costs. Figure 4.8 illustrates the cost advantages of RCM as apposed to the previous mentioned maintenance tactics.

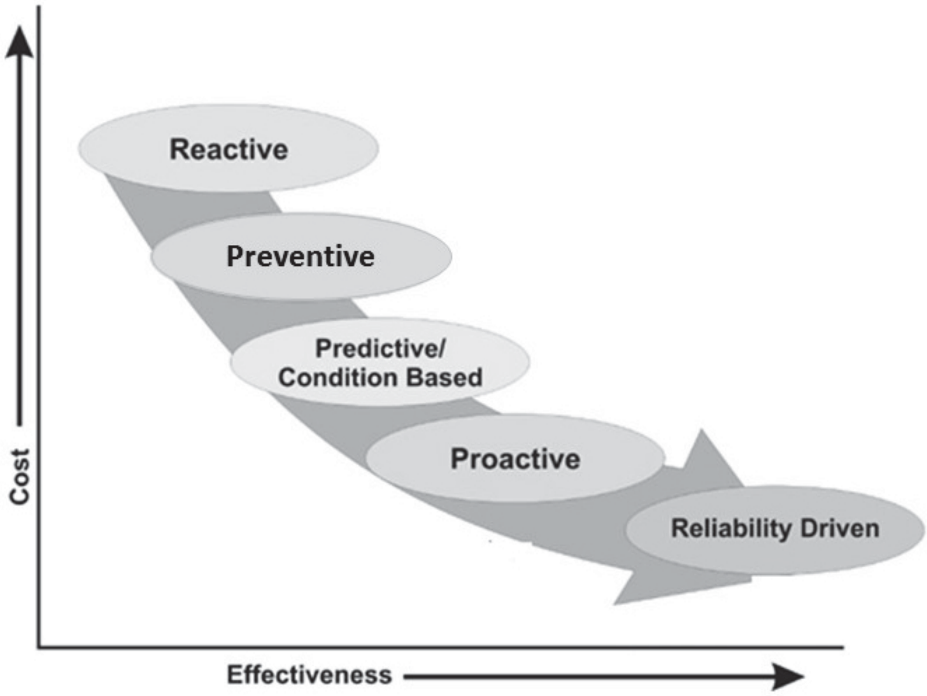


Figure 4.8: Maintenance Cost Advantages.
Adapted from Mitchell (2007, p.43)

.

As the effectiveness of the maintenance strategy increases, the cost of its implementation decreases. Proactive and reliability-based maintenance proves to be the most effective and cost-efficient maintenance tactics.

4.6.5 Risk-based maintenance

Unpredicted failures normally have inauspicious effects on the environment, which may lead to major accidents (Khan and Haddara, 2004). As the population of industries continues to grow rapidly, the risk posed by probable accidents also continues to rise (Arunraj and Maiti, 2007). Arunraj and Maiti (2007) states that high reliability systems, with a low probability of failure, is meaningless if the consequences and severity of system failure in not taken into consideration.

This is where the risk-based methodology comes into play. It is a methodology developed to investigate all of the different failure modes and their associated risks, and design a maintenance strategy to minimise the occurrence of high-risk failure mode. It is designed to satisfy the main maintenance objectives of minimising hazards to the environment and humans in a cost effective manner.

Figure 4.9 illustrates the risk based maintenance methodology.

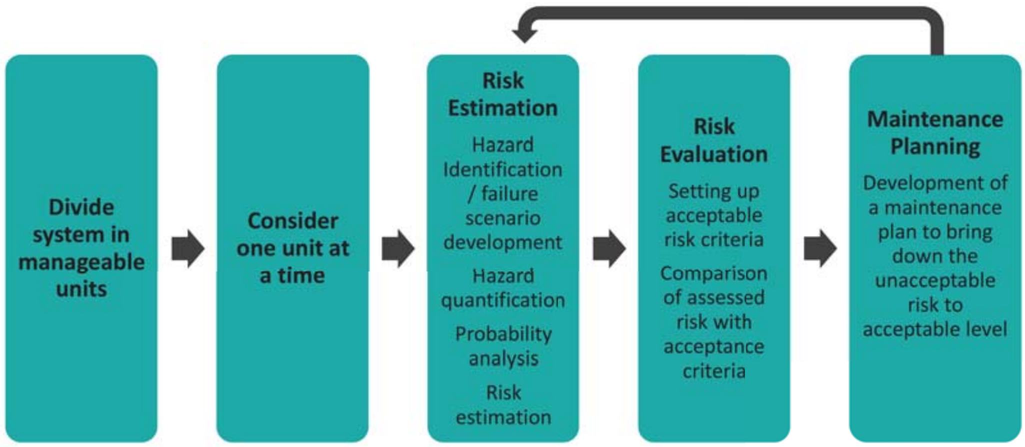


Figure 4.9: Risk-based Maintenance Methodology.
Adapted from Arunraj and Maiti (2007, p.655)

.

As can be seen from Figure 4.9 is broken into three main modules: (1) risk determination, (2) risk evaluation and (3) maintenance planning considering risk factors. *Risk determination* includes a failure analysis, where a description of events of failures possibly occuring is recorded per unit. The items on this list is then prioritised based on their contribution to a system failure and severity of consequences, normally calculated in quantitative measures. These consequences may include operational loss, financial loss, human health loss and environmental and ecological loss. These results are used to estimate the risk of each unit. *Risk evaluation* includes setting up acceptable risk criteria and comparing the risk calculated in the previous section with this criteria. Maintenance planning involves studying units whose risk exceeds the acceptable risk criteria threshold and creating a maintenance plan for each unit in order to reduce the risk. The final step is verification, in order to determine the effectiveness of the developed maintenance plan.

4.7 Chapter Summary

This chapter focuses on narrowing down the focus of the research by determining the most important areas within PAM through qualitative analysis. Literature is further provided on the selected PAM focus areas, which includes Asset Information and Knowledge, Asset Lifecycle Management, Risk and Opportunity Management, Reliability Engineering and Maintenance.

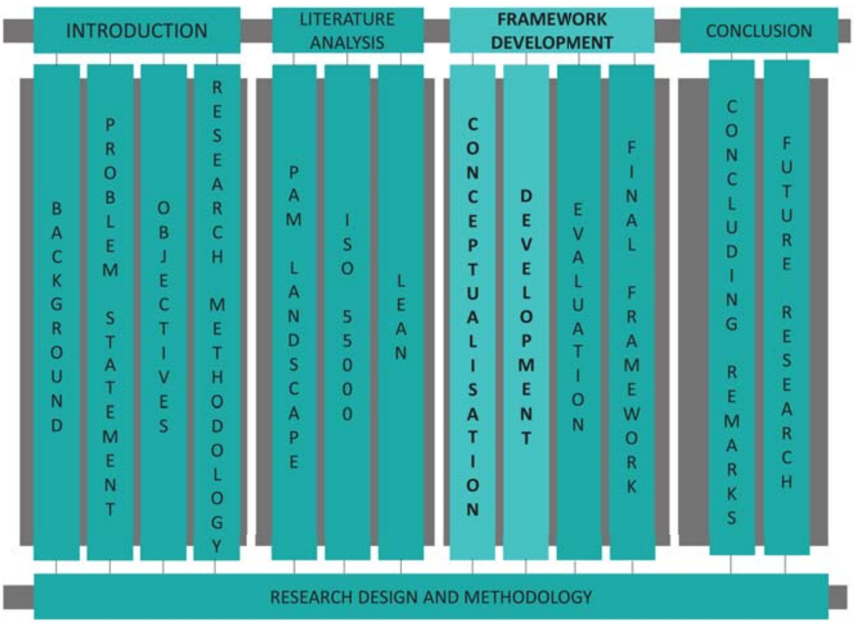
Chapter 5

Framework Development

Chapter Outcome

1. Categorise ISO 55001 requirements under PAM focus areas.
2. Cross-reference the guidelines presented in ISO 55002
3. Categorise Lean principles and tools under applicable ISO 55001 clauses.

Chapter Route Map



5.1 Introduction

In order to develop a framework, it is imperative to first have a clear understanding on what a framework encompasses.

The Cambridge Dictionary Online (2017) defines a framework as a *"system of rules, ideas, or beliefs that is used to plan or decide something"* This supports the definition provided by the The English Oxford Living Dictionaries Online (2017), which states a framework to be a *'basic structure underlying a system, concept, or text'*

The Business Dictionary Online (2017) provides a more detailed definition. It defines a framework as:

> *"Broad overview, outline, or skeleton of interlinked items which supports a particular approach to a specific objective, and serves as a guide that can be modified as required by adding or deleting items"*

According to Gale *et al.* (2013), a framework creates a new structure that is useful in summarising data in a way that can support answering the research question. It can be used with deductive, inductive or combined types of qualitative analysis and can be in the form of a process or matrix, where the summarised data are entered by columns and rows (Gale *et al.*, 2013).

The proposed framework of this study is inspired by a study conducted by Chiarini (2009), where the integration of lean thinking and ISO 9000 is mapped in a matrix format. Another study where this format is used is a study done by van den Honert *et al.* (2013), where the interconnection between ISO 55000 and PAS 55 requirements are mapped. With reference to these studies, the following steps will be used in developing the proposed framework of this study:

1. Define the purpose of the framework
2. Conduct a literature study
3. Analyse the literature by determining the key concepts within the literature and their connection.
4. Construct the proposed framework.

The purpose of this study was already defined in Chapter 1 and literature on the key concepts within the subject fields conducted in Chapter 2 and Chapter 4.

Section 5.2 and Section 5.3 aims to determine the connection between this study's key concepts, which is used as a basis for deriving the Proposed Framework in Section 5.4.

5.2 ISO 55000 Requirements related to Important PAM Areas

In Chapter 4, important PAM areas are identified as a point of focus for this research and extensive literature is provided on each. To recap, the identified functions include:

1. Asset Information and Knowledge
2. Asset Lifecycle Management
3. Risk and Opportunity Management
4. Reliability Engineering
5. Maintenance

This section seeks to cross-reference the guidelines presented with ISO 55001 requirements and to integrate parts of the standard text with these PAM areas. This assists in determining which requirements should be focused on.

5.2.1 Asset Information and Knowledge in ISO 55001

This section seeks to determine the requirements of the ISO 55001 documents that directly and indirectly address asset information and knowledge. ISO 55 000 states that the processes aligning organisational objectives with AM objectives should be information driven. It defines *documented information* as:

> *"information required to be controlled and maintained by an organisation and the medium on which it is contained. "* - ISO 55001 (2014, p.10)

This may be in any format and media and from any source.

Information and knowledge on assets and asset performance is addressed in the ISO 55001 and 55002 documents. This is summarised in Table 5.1

Table 5.1: Asset Information and Knowledge Requirements in ISO 55000

Clause	Description including ISO 55002 cross references
4.1	The organisation shall determine external and internal issues that are relevant to its purpose and that affect its ability to achieve the intended outcome(s) of its asset management system. According to ISO 55002 (4.1.2.3e), this may include information systems, information flows and decision-making processes (both formal and informal)
4.2	The organisation need to determine the stakeholder requirements for recording and reporting information relevant to asset management, and for reporting on it both internally and externally.
7.5	The organisation needs to determine its information requirements to support its assets, AM, AMS and the achievement of its organisational objectives. According to ISO 55002 (7.5.1), processes for managing its information should also be specified, implemented and maintained. Necessary asset information and asset information repositories need be identified systematically. ISO 55002 (7.5.2) and (7.5.3) lists areas and factors to consider when determining asset information requirements.
7.6.1	The organisation's AMS shall include documented information required by ISO 55000, for applicable legal and regulatory requirements and information as deemed necessary for the effectiveness of the AMS.
7.6.2	When creating and updating information, the organisation needs to ensure appropriate identification and description, format, media, review and approval.
7.6.3	Documented information need be controlled effectively to ensure adequate availability, suitability and protection.

Continued on next page

Table 5.1 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
8.3 c)	Processes and the scope for exchanging and sharing knowledge and information between the organisation and its contracted service provider need be established
9.1	An organisation should document and report on information regarding measurement, analysis and evaluation of asset performance, AM performance or the effectiveness of the AM system. According to ISO 55002 (9.1.1.3) and (9.1.2.5), quantitative or qualitative measurements should be put in place to determine success as well as areas where corrective action is necessary, where the terminology of these measurements should be consistent across all functions. ISO 55002 (9.1.2.6) further states that technical information should be linked to accounting records.
9.2	An organisation should conduct audits in order to ensure that their own and ISO 55000 AM requirements are met and to identify areas for improvement. According to ISO 55002 (9.2.1) the results of the audits, which should reflect the appropriateness and effectiveness of the AM system and areas for improvement, should be presented to top management.
9.3	Information on asset performance need be reviewed by management periodically. Reviews should be kept as proof that review was conducted. 55002 (9.3.2) considers different possible AM measurements and results to be reported on. 55002 (9.3.4) states that these results should be communicated to the internal and external stakeholders.
10.1 e)	Information on the nature of nonconformities or incidents, corrective action taken and results thereof need be documented.

Continued on next page

Table 5.1 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
10.2	The organisation shall establish processes to proactively identify potential failures in asset performance and evaluate the need for preventive action. According to ISO 55002, proactive action this requires the need for appropriate sources of information.

5.2.2 Asset Lifecycle Management

ISO 55000 (2014) describes asset lifecycle when defining *asset life* and *life cycle*.

According to ISO 55000 (2014, p.14), asset life is the *"period from asset creation to asset end-of-life"* and life cycle is *"stages involved in the management of an asset"*. The document also states that the naming and numbering of the different stages of an asset is unique to each organisation.

Table 5.2 provides a summary on clauses within the ISO 55001 and 55002 documents applicable to ALCM.

Table 5.2: Asset Lifecycle Management Requirements in ISO 55000

Clause	Description including ISO 55002 cross references
4.3	Determining the scope of the AMS. According to ISO 55002 (4.3b), this should include information on external contractors involved in meeting the organisations AMS requirements regarding the different activities related to life cycle stages.
5.2	Determining the AM policy. According to ISO 55002 (5.2d), this may include asset life cycle decision-making criteria.
6.2.1	Establishing AM objectives. According to ISO 55002 (6.2.1.3d), when establishing asset objectives, typical issues addressed include life cycle cost and life expectancy.

Continued on next page

Table 5.2 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
6.2.2 b)	When an organisation plans how to achieve its AM objectives, it should determine and document the processes and methods to be implemented when managing its assets over their life cycles.
6.2.2 i)	When an organisation plans how to achieve its AM objectives, it should determine and document the financial and non-financial implications of the AMP. According to ISO 55002 (6.2.2.4), life cycle cost should be considered when determining the financial implications of the AMP.
9.1 d)	An organisation should determine when the results from monitoring and measurement shall be analysed and evaluated. The organisation shall evaluate and report on AM performance, including financial and non-financial performance. According to ISO 55002 (9.1.2.5), because cost plays such an important role in reflecting asset related performance, it may be useful for an organisation to establish a common understanding on how asset portfolios, asset systems and individual assets are broken down in support of asset life cycle management.

5.2.3 Risk and Opportunity Management

The concepts of Risk and Opportunity is mentioned many times in the ISO 5500X Family of Standards. As mentioned in Chapter 4.4, nearly 75 percent of the sections of the PAS 55 document requires some for of risk management. To add to this, according to Basson (2016), an organisation's ability to manage risk is one of the most mentioned terms in the ISO 55000 series. This is apparent in Table 5.3, which summarises the ISO 55001 and ISO 55002 clauses applicalbe to Risk and Opportunity.

In ISO 55000 (2014, p.12), risk is defined as *"Effects of uncertainty on objectives."* An *effect* is defined by ISO 55000 (2014) as positive or negative variations from the expected. Note that when the variation is positive, it is seen as an opportunity rather than a risk. Furthermore, according to ISO 55000 (2014), *objectives* can refer to different disciplines (health and safety, the environment, financial etc.) and can also be applied to different levels in an organisation (strategic, project, process etc.). ISO 55000 (2014) characterises risk by referring to it as *events*, *consequences*, combination of these, or *likelihood of occurrences*. It furthermore defines *uncertainty* as the state of full or partial deficiency of information regarding understanding or having knowledge of an event, its consequences or likelihood.

Table 5.3: Risk and Opportunity Requirements in ISO 55000

Clause	Description including ISO 55002 cross references
4.1	The organisation shall determine external and internal issues that are relevant to its purpose and that affect its ability to achieve the intended outcome(s) of its asset management system. According to ISO 55002 (4.1.2.3), when evaluating an organisation's internal context, it may include evaluating the organisation's risk management plans.
4.3	Determining the scope of the AMS. According to ISO 55002 (4.3d), This included determining the risk an organisation is responsible for beyond the use of an asset.
5.1	Leadership and commitment. According to ISO 55002 (5.1i and k), this involves top management addressing asset related risks and incorporating them into the organisation's risk management processes as well as assuring the alignment between the organisational and AM RM approach
5.2	Determining the AM Policy. According to ISO 55002 (5.2d), this includes commitments for decision-making criteria regarding benefits and risks of assets.
6.1	Actions to address risks and opportunities for the asset management system. ISO 55002 (6.1) provides a detailed description of what this entails.

Continued on next page

Table 5.3 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
6.2	Asset management objectives and planning to achieve them, which includes determining and documenting risks and opportunities associated with managing assets and how they change with time. ISO 55002 (6.2.2) provides a detailed description of what this entails, where ISO 55002 (6.2.2.3) provides an example of a structured method to identify, analyse and evaluate risk.
7.3	Persons doing work under the organisation's control, who can have an impact on the achievement of the AM objectives need be aware of the risks and opportunities of their work and how they relate to each other.
7.5	The organisation shall determine its information requirements to support its assets, AM, AMS and the achievement of its organisational objectives. According to SO 55002 (7.5.2h) and (7.5.3b), this includes determining asset information requirements related to risk management and aligning it with the level of risk an asset poses.
8.1	The organisation need to plan, implement and control the process to meet requirements, the AMP and corrective and preventive action by treating and monitoring risks.
8.3	When the organisation outsources any activities that can have an impact on the achievement of its asset management objectives, it shall assess the associated risks. The organisation shall evaluate and report on the effectiveness of the processes for managing risks and opportunities. According to ISO 55002 (8.3.4), this also included determining which risks are not transferrable.

Continued on next page

Table 5.3 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
9.1 d)	The organisation shall evaluate and report on the effectiveness of the processes for managing risk and opportunities. According to ISO 55002 (9.1.2.1), evaluations can take the form of internal and external audits, or self-assessments. When determining the frequency of condition or performance monitoring, the risk of nonconformity or failure should be considered. ISO 55002 (9.1.2.2) and (9.1.2.5) further states that the organisation's AM should be appropriate to the level of risk faced by the organisation and the organisations risk profile should be evaluated in financial and non-financial terms. ISO 5002 (9.1.2.6) also states that monitoring should be done at a level suitable to the risk of the organisation's assets.
9.2	The organisation need to conduct internal audits at planned intervals. According to ISO 55002 (9.2.2), risks associated with assets and the AMS should be considered in order to determine the scope of the audit. This will ensure that each risk area is objectively reassessed.
9.3	Top management shall periodically review changes in the profile on risk and opportunity.
10.1	When a nonconformity or incident occurs in its assets, AM or AMS, the organisation need to evaluate the needed action to eliminate the nonconformity or incident. According to ISO 55001 (10.1.1b and c), any possible impact on risk identification and assessment results, including the need to update risk identification, assessment and control reports, need be evaluated and documented. ISO 55002 (10.1.3) states that corrective action should be consistent with risks encountered. New corrective action activities should at all times first be risk assessed prior to implementation.

Continued on next page

Table 5.3 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
10.3	The organisation shall continually improve the suitability, adequacy and effectiveness of its AM and the AMS. According to ISO 55002 (10.3.4), risk assessments should be considered at all times when processing continuous improvement activities.

5.2.4 Reliability Engineering

Reliability is mentioned in ISO 55000 once, when defining *level of service*. ISO 55000 (2014, p.15) defines level of service as:

> *"parameters, or combination of parameters, which reflect social, political, environmental and economic outcomes that the business delivers"*,

where these parameters may include reliability.

The clauses related to Reliability within the ISO 55001 and ISO 55002 documents can be seen in Table 5.4.

Table 5.4: Reliability Engineering Requirements in ISO 55000

Clause	Description including ISO 55002 cross references
4.2	Determining the requirements and expectations of the stakeholders. According to ISO 55002 (4.2.4), the organisation should measure the level of service that its assets deliver, where a level of service review process can be useful to understand the expectations of customers and users. As mentioned earlier, this may include reliability parameters.
6.2.1	The organisation shall establish AM objectives. According to ISO 55002 (6.2.1.3a), when establishing AM objectives, a common issue addressed is an organisation's level of service. Furthermore, According to ISO 55002 (6.2.1.3d), establishing asset objectives may include establishing reliability parameters such as mean time or distance between failures.

Continued on next page

Table 5.4 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
9.1	Monitoring, measurement, analysis and evaluation. According to ISO 55002 (9.1.2.4), in the context of continual improvement, the organisation can acquire knowledge on new asset management technology and practices, including new tools and techniques (e.g. development of reliability and predictive technologies during the procurement of new assets or the design of modified assets)

5.2.5 Maintenance

When considering maintenance, ISO 55001 (6.2.2) states that the organisation should document a structured AMP. There is not a fixed layout of this document, but, according to ISO 55002 (2014), it normally contains the rationale on the organisations' maintenance plans. Requirement 7.5 addresses the need to determine information requirements to act as a supporting agent and to enable the organisation to reach its objectives. ISO 55002 (2014) states that this includes the consideration of asset information related to maintenance management (historical asset failures, future maintenance requirements etc.). This addresses the importance of data, as mentioned in Chapter 4.2, and the fact that data acts as the foundation of AM and, if accurate, can play a crucial part in reaching organisational objectives.

Even though *maintenance* is not formally defined in the ISO 55000 document, it defines terminology such as *predictive action*, *corrective action*, *preventive action* and *monitoring*, which forms an integral part of the different maintenance techniques. The following definitions are given:

> Predictive action is *"to monitor the condition of an asset and predict the need for preventive action or corrective action"* - ISO 55000 (2014, p.15)
>
> Preventive action is *"to eliminate the cause of a potential nonconformity or other undesirable potential situation"* - ISO 55000 (2014, p.14)
>
> Corrective action involves *"the action to eliminate the cause of a nonconformity and to prevent recurrence"* - ISO 55000 (2014, p.15)

ISO 55000 mentions *condition monitoring* when defining *monitoring*. It defines monitoring as ISO 55000 (2014, p.11) *"determining the status of a system, a process* *or an activity"*, where this may include condition or performance monitoring when considering an asset. This document further states that this term is also known as predictive maintenance.

Table 5.5 illustrates the clauses within the ISO 55001 and ISO 55002 documents applicable to Maintenance.

Table 5.5: Maintenance Requirements in ISO 55000

Clause	Description including ISO 55002 cross references
6.2.1	Establishing AM objectives. According to ISO 55002 (6.2.1.3d), when establishing asset objectives, typical issues addressed includes asset conditions.
7.5	The organisation need to determine its information requirements to support its assets, AM, AMS and the achievement of its organisational objectives. According to ISO 55002 (7.5.2c), this may include information regarding an asset's physical attributes and condition, which forms part of condition monitoring.
9.1	The organisation should develop processes to provide for the systematic measurement, monitoring, analysis and evaluation of the organisation's assets, AMS and AM activity on a regular basis. According to ISO 55002 (9.1.1.1a) and 9.1.1.2j), an organisation should set up performance metrics and indicators and proactive indicators (which may include indicators for condition monitoring).
10.1	When a nonconformity or incident occurs in its assets, asset management or asset management system the organisation shall take action to control and correct it. This addresses corrective maintenance.
10.2	The organisation shall establish processes to proactively identify potential failures in asset performance and evaluate the need for preventive action

Continued on next page

Table 5.5 – *Continued from previous page*

Clause	Description including ISO 55002 cross references
10.3	An organisation shall continually improve the suitability, adequacy and effectiveness of its AM and AMS. According to ISO 55002 (10.3.2a and b), this may include corrective and preventive action, respectively.

This section cross-referenced the guidelines of ISO 55002 with the ISO 55001 requirements and integrated them with selected PAM areas. The following section integrates Lean thinking with ISO 55001 requirements for the specific PAM Areas.

5.3 Lean Tools Associated with Important PAM Areas

This section explores and categorises the different Lean principles and tools which are to be used to support the ISO requirements specific to each of the PAM areas chosen in Chapter 4.

Figure 5.1 provides a summary of the Lean tools described in Chapter 2, which is used to match relevant tools with ISO 55001 requirements categorised in section 5.2. Figure 5.1 should be read from left to right, where each Lean concept listed on the column to the right is used as a Lean tool to its respective match. For example, Kanban (1.1.1) is a JIT Maintenance Lean practice, but is also used as a tool for a visual control (1.1.5.4), continuous flow (2.1.2.10), and Lean pull (2.1.3.4). Also, Kanban uses visual control, work standardisation and quick changeover techniques as tools to create a JIT maintenance system. Furthermore, in order to avoid redundancy, when tools are listed for a Lean concept, it is not listed again, where the table should be read from left to right and top to bottom. For example, visual control (1.1.1.1) acts as a tool for Kanban, but is also listed as a Lean Maintenance JIT practice (1.1.5). Visual control uses tools 1.1.5.1 - 1.1.5.9, which is only listed once and not again when listed as a tool for Kanban (1.1.1).

Lean Concept	Lean Bundle	Lean Practice	Lean Tool	
1. Maintenance	1.1 JIT	1.1.1 Kanban	1.1.1.1 Visual Control	
			1.1.1.2 Work Standardisation	
			1.1.1.3 Quick changeover techniques	
		1.1.2 SMED	1.1.2.1 Work Standardisation	
		1.1.3 Work Standardisation	1.1.3.1 Takt time	
			1.1.3.2 Work sequence	
			1.1.3.3 Standard WIP	
		1.1.4 Takt time	1.1.4.1 Work Standardisation	
		1.1.5 Visual Control	1.1.5.1 5S	
			1.1.5.2 Shadow Tool Board	
			1.1.5.3 Inventory indicators	
			1.1.5.4 Kamishabi	
			1.1.5.5 Kanban	
			1.1.5.6 Andon	
			1.1.5.7 One-piece flow	
			1.1.5.8 Standardised work	
			1.1.5.9 Jidoka	
		1.1.6 Distributed MRO Storeroom	1.1.6.1 Inventory Standardisation	
			1.1.6.2 ABC Analysis	
		1.1.7 CMMS	1.1.7.1 Work Order	
	1.2 TPM	1.2.1 Autonomous Maintenance	1.2.1.1 5 S's	
			1.2.1.2 Visual Control	
			1.2.1.3 Cleaning and Lubrication standards	
		1.2.2 Planned Maintenance	1.2.2.1 Maintenance schedule	
		1.2.3 a) Root Cause Analysis	1.2.3.1 Cause and Effect Diagram	
			1.2.3.2 Five Whys	
			1.2.3.3 Tree diagram	
			1.2.3.4 Fault Tree Analysis	
			1.2.3.5 Brainstorming	
		1.2.3 b) Problem Solving	1.2.3.5 PDCA	
			1.2.3.6 SBCE	
		1.2.4 OEE	1.2.4.1 Eliminating six main losses	1.2.4.1.1 Brainstorming
		1.2.5 Work Order System	1.2.5.1 Waste Elimination	
		2.1.1 Lot size reductions		
2. Production	2.1 JIT	2.1.2 JIT/Continuous flow improvement	2.1.2.1 Finished-Goods Supermarket	
			2.1.2.2 Takt time	
			2.1.2.3 Pitch	2.1.2.3.1 Work Standardisation
			2.1.2.4 Buffer and safety inventories	
			2.1.2.5 Lights-Out Manufacturing	2.1.2.5.1 Work Standardisation
			2.1.2.6 Agile Manufacturing	
			2.1.2.7 One-piece flow or pull production	
			2.1.2.8 In-process supermarkets	
			2.1.2.9 FIFO lanes	2.1.2.9.1 Work Standardisation
			2.1.2.10 Kanban	
			2.1.2.11 Heijunka	2.1.2.11.1 Heijunka box
				2.1.2.11.2 Work Standardisation
			2.1.2.12 Paced Withdrawal	
			2.1.2.13 Runner	
			2.1.2.14 Value Stream Mapping	2.1.2.14.1 Waste Elimination
			2.1.2.15 PDCA	
			2.1.2.16 Jidoka	2.1.2.16 Autonomation
		2.1.3 Pull system	2.1.3.1 Similar process speed	2.1.3.1.1 Work Standardisation
			2.1.3.2 Finished-Goods Supermarket	
			2.1.3.3 One-piece flow plant layout	
			2.1.3.4 Kanban	
			2.1.3.5 Heijunka	2.1.3.5.1 Heijunka box
				2.1.3.5.2 Work Standardisation
			2.1.3.6 Production Scheduling	
		2.1.4 Cellular manufacturing	2.1.4.1 Work Cells	
			2.1.4.2 Counter clockwise flow direction	
			2.1.4.3 Sequential process arrangement	
			2.1.4.4 Closely positioned equipment	
			2.1.4.5 U-, C-, L-, S- or V- cell shapes	
		2.1.5 Cycle time reduction	2.1.5.1 Takt time	
			2.1.5.2 Pitch	
			2.1.5.3 Line balancing	
		2.1.6 Focussed factory production system	2.1.6.1 Work Cells	
		2.1.7 Agile manufacturing strategies	2.1.7.1 Buffer, safety inventory or de-coupling	
			2.1.7.2 IT Systems	
			2.1.7.3 Pull System	
		2.1.8 Quick changeover tecniques	2.1.8.1 SMED	2.1.8.1.1 Work Standardisation
		2.1.9 Bottleneck removal	2.1.9.1 TOC	
		2.1.10 Reengineerd production processes		
	2.2 TPM	2.2.1 Preventive maintenance	2.2.1.1 Condition monitoring	
			2.2.1.2 Maintenance schedule	
		2.2.2 Predictive maintenace	2.2.2.1 Condition monitoring	
			2.2.2.2 New process equipment or technologies	
		2.2.3 Maintenance optimisation	2.2.3.1 Reliability centred maintenance	2.2.3.1.1 MTBF
			2.2.3.2 Risk-based maintenance	
		2.2.4 Planning and scheduling strategies		
		2.2.5 New process equipment or technologies		
3. Strategic	3.1 Policy Deployment	3.1.1 Hoshin Kanri	3.1.1.1 PDCA	
			3.1.1.2 Standardisation	

Figure 5.1: Summary of Lean Tools and Practices

5.3.1 Lean Tools in Support of ISO 55000 Asset Information and Knowledge Requirements

To identify the different Lean tools and principles applicable to supporting ISO 55001 asset information and knowledge requirements, it is important to first have a basic understanding of the relationship between Lean and the flow of information. The application of Lean tools to the flow of intangible assets, such as data, is not as apparent as applying it to tangible assets. Figure 5.2 compares a value stream applied to a manufacturing process with the value stream applied to information management.

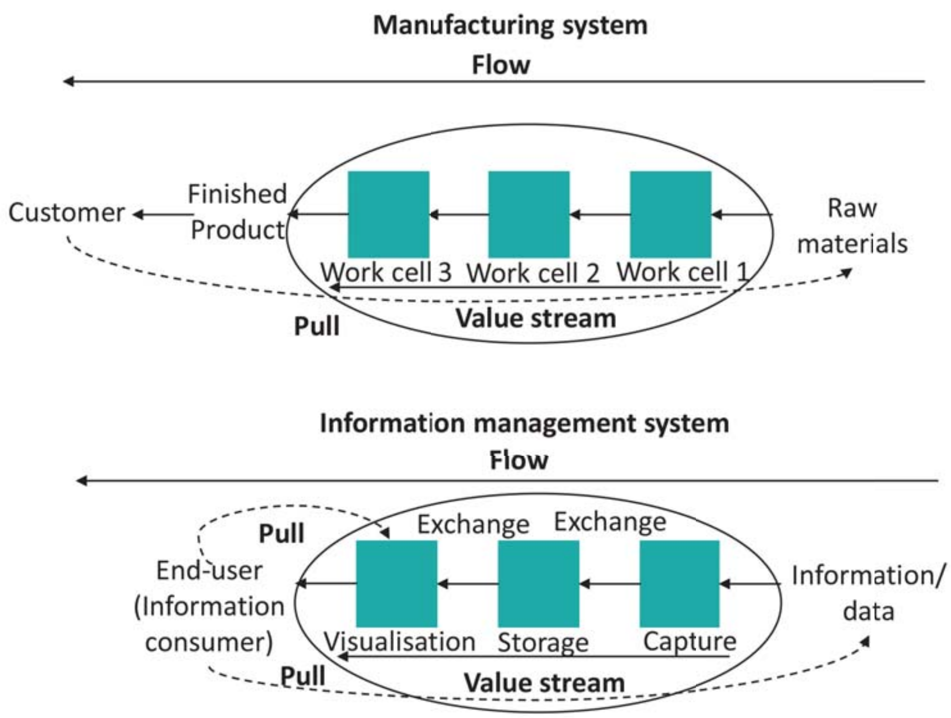


Figure 5.2: A comparison of the value stream of a manufacturing process and the value stream of information management.
Adapted from Hicks (2007, p.238)

From Figure 5.2, it is clear that in the value stream of an information management system, there is intrinsic value in data and the way in which data is organised, represented, exchanged and visualised.

According to (Hicks, 2007), the five Lean principles are applied to an information management system as follows:

Step 1: Specify Value

Value will be created when valuable information is managed optimally and when users understand the direct or indirect benefit to be received from the generated data.

Step 2: Map

Map includes mapping the activities and processes necessary to deliver valuable data.

Step 3: Flow

Flow includes streamlining the information management process and ensuring that consistent, accurate and complete information is accessible in real-time.

Step 4: Pull

Pull includes ensuring that only necessary and requested data is provided to the end-user.

Step 5: Continuous Improvement

Continuous improvement includes continuously reviewing and improving data quality and flow and integrating it with all business processes in order to aid strategic decision-making.

When considering waste within the context of information management, it can be defined as any additional action or inactivity that is a result of the end-user not being able to access accurate, up-to-date data immediately (Hicks, 2007).

Table 5.6 matches the Lean Practices and Tools summarised in Figure 5.1 with the ISO 55001 requirements related to Asset Information and Knowledge identified in Table 5.1.

Value Stream Mapping (2.1.2.14) involves mapping the information flow from supplier to customer. In doing so, it will assist in defining the organisation's internal and external information flow. It will also assist in determining stakeholder requirements for recording financial and non-financial information, as stakeholders should be involved in mapping the external information flow of the organisation. This will support achieving requirements 4.1 and 4.2 in the ISO 55001 document.

Table 5.6: Lean Tools and Principles to Support Asset Information and Knowledge Requirements in ISO 55000

Cl	Lean Principles and Tools
4.1	2.1.2.14
4.2	2.1.2.14
7.5 (b)	2.1.3.6, 2.1.2.14, 2.1.2.15, 1.1.3
7.5 (c)	1.2.2, 2.1.2.14, 2.1.2.15, 2.1.3.6, 1.1.6.2, 1.1.3
7.5 (e)	3.1.1
7.6.1	3.1.1
7.6.2	2.1.2.14, 1.1.3
7.6.3	1.1.5.1
8.3 c)	2.1.2.14
9.1 (b)	2.1.2.14, 2.2.3.1.1, 1.2.4, 1.2.5, 2.1.2.2, 2.1.2.3, 1.1.2, 2.2.3.1.1
9.2	N/A
9.3	N/A
10.1 e)	N/A
10.2	2.2.1.1, 2.2.2.2

ISO 55001 (7.5b) addresses the determination of information requirements to support its assets, asset management (AM), the asset management system (AMS) and the achievement of organisational objectives. ISO 55001 (7.5b) requires an organisation to determine the attributive and quality requirements of its identified information. ISO 55002 (7.5.3a) states that when determining its information requirements, the organisation should consider the value of the information to enable decision-making. ISO 55002 (7.5.3c) requires an organisation to get input from relevant stakeholders when determining the types of information needed for decision-making. This can be supported by a VSM (2.1.2.14), as its main purpose is to determine the information stream that brings value to the organisation and eliminating all non-value-adding activities, where stakeholder should be included in defining the value stream. ISO 55002 (7.5.3d) requires an organisation to establish and continuously improve controls, specifications and level of accuracy of data. This can be supported by applying work standardisation (1.1.3) and PDCA

(2.1.2.15) to establish and improve controls and specifications, respectively. ISO 55001 (7.5b) further requires an organisation to determine how and when information is to be collected, analysed and evaluation. This can be achieved by viewing data as the product to be "produced" and using VSM (2.1.2.14) to map the flow of data and production scheduling (2.1.3.6) to plan exactly when data is to be generated, collected, analysed or evaluated. When determining an organisations' data requirements, ISO 55002 (7.5.3k) requires an organisation to consider the flow of data and its integration to planning, operational and reporting technology systems, which should be aligned with the size, complexity and capability of the organisation. This can be supported through the application of VSM (2.1.2.14), as the flow of information throughout the organisation is mapped and studied, in collaboration with employees from all departments.

When considering information management, ISO 55001 (7.5c) requires an organisation to specify, implement and maintain processes for managing its information. VSM (2.1.2.14) and production scheduling (2.1.3.6) will enable the organisation to specify its processes for managing information, while PDCA (2.1.2.15), work standardisation (1.1.3) and planned maintenance (1.2.2) will support its implementation and maintenance. An example of using planned maintenance to maintain an organisation's information management processes is periodically performing maintenance on its IT systems to ensure it is at all times up to date and valid. ISO 55002 (7.5.3l) requires an organisation to specifically maintain the appropriate quality and timeliness of the information and emphasise the importance of prioritising data, as its collection can be costly. ABC Analysis (1.1.6.2) will enable organisation to rank the importance of data, which can be used as a focus point for prioritisation.

ISO 55001 (7.5e) requires an organisation to ensure consistency and traceability between financial and technical and all non-financial data. It further states that is should be consistent to the extent that all legal and regulatory requirement as well as stakeholders' requirements and organisational objectives are met. Hoshin Kanri (3.1.1) is a strategic Lean tool that will enable the organisation to focus on the organisation's objectives and legal, regulatory and stakeholder requirements, while planning its day to day tasks and ensuring that all levels of the organisation work towards the same goals. In other words, it will ensure vertical and horizontal alignment.

ISO 55001 (7.6.1) requires an organisation to document information as stipulated in The ISO 55000 Family of Standards, for applicable legal and regulatory requirements and for the effectiveness of the AMS. Hoshin Kanri (3.1.1) can be used as a tool to align documenting information according to the ISO 55000 Family of Standards and applicable legal and regulatory requirements. Furthermore, ISO

55001 (7.6.2) requires an organisation to consider specific attributes when creating and updating documented information. According to ISO 55002 (7.6), when creating and updating documented information, an organisation need to put controls in place to ensure that the information is appropriate and consistent. The appropriateness of information can be confirmed by referring to the information flow in the VSM (2.1.2.14) and information consistency can be obtained through the application of work standardisation (1.1.3). ISO 55001 (7.6.3) requires an organisation to control the documented information to ensure availability and protection. Lean's 5 S's (1.1.5.1) can be used to ensure documented information is organised and available.

ISO 55001 (8.3c) states that when an organisation outsources any activities, they need to determine the processes and scope for sharing knowledge and information with its contracted service providers. This can be determined by applying Lean's VSM (2.1.2.14) to the organisation's information flow.

ISO 55001 (9.1) addresses establishing processes for performance monitoring. According to ISO 55002 Requirement 9.1.1.1, this specifically refers to an organisation's assets, AMS and AM activity. Even though this requirement does not specifically mention information, knowledge or reporting in the ISO 55001 document, it is addressed numerous times in the ISO 55002 document.

ISO 55002 (9.1.1.1d) states that when the organisation develops these processes, it should consider the use of documented information to facilitate corrective action and decision making. This process can be established through a VSM (2.1.2.14). ISO 55002 (9.1.1.2e) states that when establishing processes for monitoring performance, it should address the organisation's ability to compile and report information to those responsible for the AMS and asset activities. By mapping out a VSM (2.1.2.14), an organisation will be able to realise its ability to aggregate and report on information, as each step of the information flow is investigated in detail. ISO 55002 (9.1.1.2f) further states that the processes for monitoring performance should address the quality, reliability and completeness of financial and non-financial asset information. The Lean tools studied in this thesis does not involve processes to monitor performance and address quality and completeness of financial and non-financial information. Calculating MTBF (2.2.3.1.1), where failure in the context of information is failing to provide accurate or valid information, can be used to monitor the reliability of the organisation's information.

ISO 55002 (9.1.2.5) and ISO 5002 (9.1.2.6) requires consistency, traceability and accuracy regarding asset related financial and non-financial terminology throughout all organisational functions. The Lean tools investigated in this study will not satisfy these requirements.

ISO 55002 (9.1.1.4) requires an organisation to make use of data to determine trends and obtain information on asset performance, in order to determine if an organisation's policy and objectives are achieved and also to determine areas for corrective action or improvement. Lean tools that can be used to facilitate corrective action and decision making include the calculation and use of information related to OEE (1.2.4), takt time (2.1.2.2), pitch (2.1.2.3), the efficiency of the work order system (1.2.5), SMED (1.1.2) or MTBF (2.2.3.1.1).

Requirement 9.2 and 9.3 in the ISO 55001 document addresses conducting internal audits and reviewing the organisation's AMS at planned intervals, respectively. According to ISO 55002 (9.2.1), the information obtained through the internal audits should be provided to top management. ISO 55002 (9.3.5) requires an organisation to retain information as proof that reviews were conducted and to communicate the results of the reviews to relevant stakeholders. The Lean tools studied in this thesis will not specifically assist in achieving these requirement.

ISO 55001 (10.1) addresses nonconformity and corrective action, where ISO 55001 (10.1e) addresses retaining documenting information in support of the nature of nonconformities or incidents that might have occurred and the results of corrective actions taken. The Lean tools studied in this thesis does not provide methods for effectively retaining documented information. Requirement 10.2 addresses preventive action, where ISO 55002 (10.2e) requires an organisation to use appropriate sources of information when establishing and maintaining preventive action. Appropriate sources of information when considering preventive action is by applying condition monitoring (2.2.1.1) on assets or extracting information from technology (2.2.2.2) that can predict the condition of the organisation's assets.

5.3.2 Lean Tools and Principles in Support of ISO 55000 Asset Lifecycle Management Requirements

The primary goal of ALCM is optimising profit generated by an organisation's assets through their lifecycle. The integration of Lean thinking with the ALM process will enhance this objective, as it eliminates all non-value-adding activities and their associated costs and enhances value-adding activities. For example, by increasing an asset's OEE in the "operation" phase of the ALM cycle by eliminating the six main losses, the asset may produce more products in the same time period, which can lead to increased profits. Table 5.7 matches the Lean Practices and Tools summarised in Figure 5.1 with the ISO 55001 requirements related to ALM identified in Section 5.2 Table 5.2. From Table 5.7, it can be seen that the Lean principles and tools used mostly to support ALM ISO 55000 requirements is related to TPM.

Table 5.7: Lean Tools and Principles in support of Asset Lifecycle Management ISO 55000 Requirements

Cl	Lean Principles and Tools
4.3	N/A
5.2	3.1.1
6.2.1	3.1.1, 2.1.2.15
6.2.2 b)	1.2.4, 1.2.1, 1.2.2, 1.2.3, 2.2, 2.1.2.15
6.2.2 i)	N/A
9.1 d)	1.1.3

ISO 55001 (4.3) requires an organisation to determine the scope of the AMS. According to ISO 55002 (4.3b), this should include information on external contractors which meets the requirements of the AMS for the activities in different asset life cycle stages. The Lean tools studied in this thesis is not adequate to support this requirement.

ISO 55001 (5.2) requires an organisation to establish an AM policy, which, according to ISO 55002 (5.2d), should include commitments to decision-making criteria regarding asset life cycle costs. The first step of Lean's Hoshin Kanri (3.1.1) can be used to determine organisational policies, where the following steps focusses on achieving these policies. It would therefore be able to support this requirement.

ISO 55001 (6.2.1) addresses establishing AM objectives, which typically includes goals regarding life cycle cost and life expectancy (ISO 55002 (6.2.1.3d)). Hoshin Kanri (3.1.1) will enable an organisation to establish objectives aligned with the organisation's AM policy, which should consider decision-making criteria regarding asset life cycle costs. PDCA (2.1.2.15) can be used as a bottom-up approach to establish AM objectives regarding life cycle cost and life expectancy. ISO 55001 (6.2.2) addresses planning to achieve the AM objectives, which was established in the previous requirement. When considering asset lifecycle management, ISO 55001 (6.2.2b) states that the organisation should determine and document methods and processes for managing the organisation's assets over their lifecycle. To recap, The ALM steps includes planning, evaluate and design, create and procure, operate, maintain, modify and dispose. When considering each step of the ALM process, OEE (1.2.4) can be used to determine how effective an asset is operating and eliminate the six main losses associated with unnecessary equipment down time. Autonomous maintenance (1.2.1), planned maintenance

(1.2.2), root cause analysis and problem solving (1.2.3), preventive maintenance, predictive maintenance, planning and scheduling strategies (2.2.4), maintenance optimisation and/or new process equipment and technologies (all 2.2) can be used to maintain the asset, where applicable PDCA (2.1.2.15) events can be used to identify improvement opportunities to modify or upgrade the asset in order to possible extend its life. ISO 55001 (6.2.2i) addresses the financial and non-financial implications of the AMP, where life cycle costs should be considered. None of the Lean tools studied in this thesis will assist in determining the financial implications of the different life cycle phases of assets.

ISO 55001 (9.1d) addresses analysing, evaluating and reporting on financial and non-financial AM performance. According to ISO 55002 (9.1.2.5), establishing a common understanding on how asset portfolios, asset systems and individual assets are broken down in support of asset lifecycle management, may be useful. Lean's work standardisation (1.1.3) may be useful to standardise how these are broken down, which will provide a basis for establishing a common understanding. If this is not standardised, it may run a risk of creating confusion among relevant individuals.

5.3.3 Lean Tools and Principles in Support of ISO 55000 Risk and Opportunity Requirements

The integration of Lean thinking and RM would result in a RM process that is more efficient and effective, as each step within the RM framework will be streamlined and waste eliminated. For example, in non-lean organisations with a strict hierarchical structure, the workforce employed at lower levels are often not allowed to make decisions, especially when risk is involved. This can lead to non-value added processing, defects and waiting in the RM process. The application of Lean to these types of organisation's would eliminate these wastes. Table 5.8 matches the Lean Practices and Tools summarised in Figure 5.1 with the ISO 55001 requirements related to Risk and Opportunity identified in Section 5.2 Table 5.3. From this table, it is apparent that the Lean tools used most to support risk and opportunity requirements in ISO 55001 is related to TPM, problem solving and root cause analysis.

Table 5.8: Lean Tools and Principles in support of Risk and Opportunity ISO 55000 Requirements

Cl	Lean Principles and Tools
4.1	1.2.3 a)
4.3	N/A
5.1	2.2.3.2, 3.1.1
5.2	3.1.1
6.1 a)	1.2.3 a), 1.2.3.6, 2.2.1, 2.2.2, 2.2.3, 1.1.5
6.1 b)	3.1.1, 1.2.4, 2.2.3.1.1
6.2.2 k)	1.2.3, 2.2.3.2
7.3	1.1.5
7.5 a)	2.1.2.14
8.1	1.2.3, 2.2.3.2
8.3	1.2.3
9.1 d)	1.2.4, 1.2.5, 2.2.3.1.1
9.2	N/A
9.3 f)	1.2.3
9.3 e)	2.1.2.15, 2.1.2.14
10.1	1.2.3 a)
10.3	1.2.3 a)

ISO 55001 (4.1) states that an organisation shall determine internal and external issues that may affect its ability to achieve the intended outcome of its AMS. RCA (1.2.3 a)) can be used to detect internal and external risks. According to ISO 55002 (4.1.2.3j), when an organisation is evaluating its internal context, it may include evaluating its risk management plans. The Lean tools studied in this thesis is not adequate to help an organisation evaluate its risk management plans. ISO 55001 (4.3) addressed determining the scope of the AMS, where, according to ISO 55002 (4.3d), this may include an organisation's accountability for certain risks beyond the operation or use of its assets. None of the Lean tools studied in this thesis will assist in determining an organisation's accountability for certain risks beyond an assets useful life.

ISO 55001 (5.1) requires top management to demonstrate leadership and commitment with respect to the AMS. Commitment can be demonstrated by addressing asset related risks and including them into the organisation's Risk Management (RM) processes (ISO 55002 (5.i). It can also be demonstrated by aligning AM and the AMS to the organisation's approach to RM (ISO 55002 (5.1k)). Asset related risks can be addressed by performing risk-based maintenance (2.2.3.2) on relevant assets, which can also be a means of integrating AM with RM. Hoshin Kanri (3.1.1) can be used to align asset-related activities with the organisation's Risk Management process. ISO 55001 (5.2) requires an organisation to establish an AM policy, which, according to ISO 55002 (5.2d), should include commitments to decision-making criteria regarding benefits and risks of assets. The first step of Lean's Hoshin Kanri (3.1.1) can be used to establishing organisational policies, where the following steps focusses on achieving these policies. It would therefore be able to support this requirement.

ISO 55001 (6.1) focusses mainly on incorporating the needs of the organisation's stakeholders and risks and opportunities related to the organisation's internal and external issues in the organisation's AMP. The organisation need to plan a) actions to address risks and opportunities, while considering how they can change with time and b) how to integrate and implement the actions determined in a) into its AMS processes and evaluate their effectiveness. Cause and effect diagrams (1.2.3.1), the five whys (1.2.3.2), tree diagram (1.2.3.3), brainstorming (1.2.3.5) and SBCE (1.2.3.6) can be used to determine the root causes of risks and a fault tree analysis (1.2.3.4) can be used to determine the likelihood of their occurrence, which will be needed to determine which actions are applicable to address these risks. Preventive maintenance (2.2.1), predictive maintenance (2.2.2), maintenance optimisation (2.2.3) or visual control (1.1.5) can be used as actions to implement to prevent risks from occurring, where applicable. Hoshin Kanri (3.1.1) can be used to align actions to mitigate risks with the organisation's AMS. OEE (1.2.4) and MTBF (2.2.3.1.1) can be used to calculate the effectiveness of actions taken to mitigate risks of downtime and failure.

ISO 55001 (6.2.2) addresses planning to achieve AM objectives, where processes to address risks and opportunities associated with managing the assets, should be established. According to ISO 55001 (6.2.2k) risks and opportunities should be identified and assessed and appropriate treatment and monitors for managing these risks should be implemented. Requirement ISO 55002 (6.2.2.3b) states that when identifying risks and opportunities, potential events, their causes, likelihood and consequences and should be identified. This can be achieved through root cause analysis and problem solving (1.2.3). ISO 55002 (6.2.2.3h) states that when determining relevant treatment of risks, it should be established whether risks should be addressed directly, avoided, reduced, tolerated or transferred. Risk-based maintenance (2.2.3.2) can be used to satisfy this requirement, where relevant.

ISO 55001 (7.3) requires relevant individuals to be aware of the risks and opportunities that their work present, and how they relate to each other. Awareness can be created through visual control (1.1.5), such as Andon. ISO 55001 (7.5) addresses the determination of the asset's, AM and AMS information requirements. According to ISO 55002 (7.5.2h), the organisation should determine its asset information requirements related to its RM process. This can be achieved by applying VSM (2.1.2.14) to the organisation's RM process. ISO 55002 (7.5.3b) states that the organisation should align its information requirements to suit the level of risk an asset poses. There are no Lean tools that can specifically assist in determining information requirements appropriate to the risk an asset pose.

ISO 55001 (8.1) requires an organisation to plan, implement and control processes to meet necessary requirements for treating and monitoring risks, using the approach described in ISO 55001 (6.2.2). The Lean tools to satisfy this process has already been established. ISO 55001 (8.3) addresses assessing and controlling risks associated with outsourcing any activities that can have an impact on achieving AM objectives. Root cause analysis and problem solving tools (1.2.3) can be used to identify risks, their root cause and likelihood.

ISO 55001 (9.1d) states that an organisation should evaluate and report on the effectiveness of its risk and opportunity management processes. ISO 55002 (9.1.2.1) states that this can be done in the form of internal and external audits. OEE (1.2.4) and MTBF (2.2.3.1.1) can be calculated to determine the effectiveness of equipment. If an asset's OEE is high, it states that its downtime is minimised, which is measure of how effectively the risk of downtime is managed. In contrast, if equipment's MTBF is high, it indicates a high failure rate, which illustrates that risk of failure is not being controlled effectively. If an organisation uses a work order system to address risks (1.2.5), the effectiveness of the work order system can be calculated based on the time it takes for a work order to be processed.

ISO 55001 (9.2) requires an organisation to conduct internal audits at planned intervals, where the focus of these audits should be based on the risk an asset or the AMS poses. None of the Lean tools studied in this thesis provides a basis for internal audits. ISO 55001 (9.3f) addresses periodic review of the changes in the profile on risk and opportunity. This includes periodically reassessing the risks certain assets hold. Root cause analysis and problem solving (1.2.3)) can assist in supporting this requirement. ISO 55001 (9.3e) required an organisation to periodically review opportunities for continual improvement. This can be done through PDCA (2.1.2.15) and Value Stream Mapping (2.1.2.14).

ISO 55001 (10.1) required an organisation to assess the risk of corrective action, should a nonconformity of incident occur. This can be done through root cause analysis tools (1.2.3 a)). ISO 55001 (10.3) addresses continuous improvement of its AM and the AMS. According to ISO 55002 (10.3.4), when opportunities for continuous improvement is identified, possible risks to be incurred should be performed. RCA (1.2.3 a)) tools can be used to determine possible risks as a result of implementing continuous improvement activities.

5.3.4 Lean Tools and Principles in Support of ISO 55000 Reliability Engineering Requirements

Reliability is the basis for the effective implementation of Lean in an organisation. It is futile to make a system as efficient as possible, if the reliability of the assets in the system is poor. For this reason, Lean has different practices and tools specifically focussed on reliability, for example TPM. Table 5.9 matches the Lean Practices and Tools summarised in Figure 5.1 with the ISO 55001 requirements related to Reliability identified in Section 5.2 Table 5.4.

Table 5.9: Lean Tools and Principles in support of Reliability Engineering ISO 55000 Requirements

Cl	Lean Principles and Tools
4.2	2.1.2.14
6.2.1	2.1.2.14, 3.1.1, 2.1.2.15
9.1	2.1.2.15

ISO 55001 (4.2) requires an organisation to determine the expectations of customers and users regarding reliability. When conducting a VSM (2.1.2.14), the first step is specifying value from the standpoint of the end customer. This may require determining customer expectations regarding reliability.

ISO 55001 (6.2.1) includes the establishment of AM objectives. According to ISO 55002 (6.2.1.3b), these AM objectives should include reliability parameters. When implementing a VSM (2.1.2.14), the customer as expectation of reliability will be determined. This can act as a basis for establishing AM objectives regarding reliability, as a Lean organisation's focus should always be on creating value for the end-user. Hoshin Kanri (3.1.1) and PDCA (2.1.2.15) can be used as top-down and bottom up tools for creating AM objectives, respectively.

ISO 55001 (9.1) addresses developing processes for the systematic measurement, monitoring and evaluation of the organisation's assets, AMS and AM activity regularly. According to ISO 55002 (9.1.2.4), when considering continuous improvement, the organisation can gain knowledge on new AM technology and practices, which may include reliability and predictive technologies to assess the procurement or modification of assets. None of the Lean tools studied in this thesis can assist in gaining knowledge on new technology. PDCA (2.1.2.15) can be implemented, where its focus can be on the improvement of reliability through new technology.

5.3.5 Lean Tools and Principles in Support of ISO 55000 Maintenance Requirements

According to Mostafa *et al.* (2015*b*), the non-value adding activities within maintenance can be reduced through the implementation of Lean tools. Mostafa *et al.* (2015*b*) mentioned the most popular Lean tools found in literature for maintenance activities includes VSM, 5S, visual control, TPM, OEE, work standardisation, inventory management, the elimination of Lean's seven wastes, SMED, kaizen, CMMS and takt time. Table 5.10 matches the Lean Practices and Tools summarised in Figure 5.1 with the ISO 55001 requirements related to Maintenance. From this table, it can be concluded that the Lean tools mentioned most as sufficient for the support of ISO 55001 Maintenance requirements is aligned with Mostafa *et al.* (2015*b*)'s findings.

Table 5.10: Lean Tools and Principles in support of Maintenance ISO 55000 Requirements

Cl	Lean Principles and Tools
6.2.1	2.2.3.1, 3.1.1, 2.1.2.15
7.5	2.2.3.1
9.1	2.2.3.1
10.1 a)	2.2.3.1
10.1 b)	1.2.3
10.2	2.2.1, 2.2.2, 2.2.3.1
10.3	2.1.2.15, 1.2.5, 2.2.3.1.1, 1.2.4, 2.2.3

ISO 55001 (6.2.1) states that an organisation should establish AM objectives, which, according to ISO 55002 (6.2.3.1d), should include objectives related to asset conditions. The application of RCM (2.2.3.1) to assets will help define which conditions an asset need be in order to perform optimally, which can serve as a basis for determining objectives regarding asset conditions. As mentioned previously Hoshin Kanri (3.1.1) and PDCA (2.1.2.15) can be used as top-down and bottom-up approaches for the establishment of AM objectives.

ISO 55001 (7.5) addresses the determination of the asset's AM and AMS information requirements. According to ISO 55002 (7.5.2c), the organisation should determine its asset information requirements related to an asset's physical attributes and condition, which falls within the scope of condition monitoring. By performing RCM (2.2.3.1) on relevant assets, physical asset operational requirements will be determined, which can serve as a basis for determining which information need be obtained regarding an asset's physical attributes and condition to minimise downtime.

ISO 55001 (9.1) addresses developing processes for the systematic measurement, monitoring and evaluation of the organisation's assets, AMS and AM activity regularly. According to ISO 55002 (9.1.1.1 a), this may include setting proactive indicators such as condition or capacity indicators. The application of RCM (2.2.3.1) will help determine condition indicators when establishing physical asset operational requirements.

ISO 55001 (10.1) addresses corrective action, should nonconformity or an incident occur. ISO 55001 (10.1a) states that the organisation should act, control and correct incidents or nonconformity and deal with the consequences. If RCM (2.2.3.1) is applied, where applicable, maintenance tactics on certain assets might be corrective. This will help the organisation to take appropriate action, as the possibility of the occurrence of failure has already been considered and corrective action already defined. Furthermore, ISO 55001 (10.1b) requires an organisation to review the nonconformity or incident, determine its cause, determine the potential of reoccurence. This can be achieved through RCA and problem solving (1.2.3). ISO 55001 (10.2) states that an organisation need to establish processes to proactively identify possible failures and evaluate whether preventive action need be taken. This requirement can be supportive by preventive (2.2.1) and predictive maintenance (2.2.2). RCM (2.2.3.1) can be used to determine the feasibility of using preventive action, should failure occur.

ISO 55001 (10.3) requires an organisation to continually improve the adequacy, suitability and effectiveness of its corrective and preventive action. This can be done through the implementation of PDCA (2.1.2.15) to corrective and preventive action. The calculation of OEE (1.2.4), MTBF (2.2.3.1.1) and the efficiency of the organisation's work order system (1.2.5) can be used as part of the PDCA cycle as metrics to determine the effectiveness of corrective and preventive action, as it incorporate equipment availability, failure rate and how efficiently corrective and preventive action is being actioned, where applicable. If OEE is high, it states that equipment downtime is low, which indicates an effective maintenance system. If MTBF is low, the number of equipment failures are low, which also indicates an effective maintenance system. Continually performing RCM and RBM (2.2.3) will also enable an organisation to review the suitability of corrective or preventive action on its assets, where applicable.

5.4 Proposed Framework

In this study, the framework aims to combine and interlink the results of Section 5.2 and 5.3 in the form of a matrix in order to provide a structured guide on supporting ISO 55000 through the use of Lean principles and tools. This is consistent with the provided definitions of a conceptual framework. The rest of this section will provide a description on the development of the layout of the proposed framework.

Y-Axis

The y-axis represents the ISO 55001 clauses related to this study. It combines the results of the first column in Table 5.1, 5.2, 5.3 and 5.5 of Section 5.2 in ascending order.

X-Axis

The x-axis represents three focal points to this study:

1. PAM focus areas
2. ISO 55002 clauses
3. Lean principles and tools

The *PAM focus area* columns list the PAM areas applicable to this study: Asset Information and Knowledge, Asset Lifecycle Management, Risk and Opportunity, Maintenance and Reliability. Each PAM focus area is categorised in two: (1) ISO 55002 clauses and (2) Lean principles and tools.

The *ISO 55002 clauses* column on the x-axis records applicable ISO 55002 clauses investigated in column 2 of Table 5.1, 5.2, 5.3 and 5.5 in Section 5.2. The purpose of this column is to provide clarity about the relevance of the PAM focus area to the ISO 55001 clause on the y-axis. For example, Requirement 9.1 in the ISO 55001 document addresses the establishment of processes for performance monitoring. Even though this clause does not mention asset, information and reporting in the ISO 55001 document, it is mentioned numerously in the ISO 55002 document. For example, ISO 55002 9.1.1.1 d) states that documented information should be used to facilitate corrective action and decision-making.

The *Lean tools and principles* column on the x-axis illustrates relevant Lean principles and tools with the potential of supporting the ISO 55001 clause listed on the y-axis, investigated in Table 5.6, 5.7, 5.8, 5.9 and 5.10 in Section 5.3.

The resulting proposed framework is illustrated in Appendix A. The framework is supported by a similar table as Table 5.1.

5.5 Chapter Summary

The purpose of this chapter is to develop a framework for implementing Lean principles and tools to support the requirements in the ISO 55001 document. It seeks to cross-reference the guideline presented in the ISO 55002 document and to integrate parts of the standard text with Lean principles and tools. The resulting framework is presented in Appendix A.

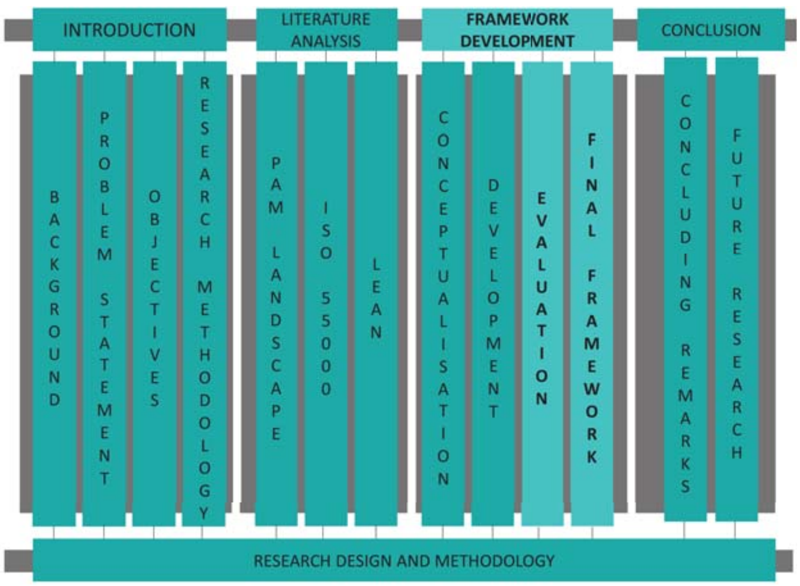
Chapter 6

Framework Validation

Chapter Outcome

1. Provide an explanation on the methodology used to validate the proposed framework.
2. Discuss the results of the review conducted by experts within the fields of Lean, PAM or ISO 55000.
3. Modify the developed framework in accordance with expert input.

Chapter Route Map



6.1 Overview

Chapter 5 develops a framework illustrating the Lean tools and practices to be used to support requirements in the ISO 55000 Family of Standards related to specific PAM areas, chosen in Chapter 4. This will enable an organisation to better their processes and procedures related to PAM and aid ISO 55000 compliance through the use of Lean principles and tools. This chapter adresses the validation of the proposed framework.

According to Bryman and Bell (2014), in many ways, validation is the most essential criterion in research. He states that the goal of validation is to determine *"whether or not a measure of concept really measures the concept it is intended to measure"*– Bryman and Bell(2014, p.38). He further concludes that validity presumes reliability, as an unreliable measure cannot be valid. In addition, Robinson (1998, p.53) defines validation as '*the process of ensuring that the model is sufficiently accurate for the purpose at hand*', where the key phrase within this definition is *sufficiently accurate*, as no model is ever 100 percent accurate.

In Chapter 3, face validation is identified for validating the proposed framework, and are described in detail in the following section.

6.2 Validation Methodology

As stated in Chapter 3, qualitative research methodology is used to validate this study, which follows the method of face validation.

According to Bornstein (2011, pg.2), face validity is *"an estimate of the degree to which a measure is clearly and unambiguously tapping the construct it purports to assess."* Sargent (2013) further defines face validation as a method used where experts within the field under study are asked whether the conceptual model or its behaviour is reasonable and poses sufficient accuracy for its intended purpose. This aims to address the correctness of the conceptual model and reasonability of the model's input-output relationship. Consistent with this the Bryman and Bell (2014) definition of face validity, where they state that face validity is established by asking individuals with experience or expertise in a field whether the measure captures the concept that forms the point of focus.

In addition, Borenstein (1998) states that face validity is a cost-effective and timely manner of which to ensure that the perception of a problem is consistent between the framework-developer and framework-user. It thus acts as a method to revise and refine the conceptual framework to ensure alignment with the potential user's requirements.

According to researchers such as Drost (2011), due to its subjective nature, face validity is regarded as a weak form of validation. Mostert (2004) however points out that if face validity is not established, chances are low that any other validity criteria will prove viable. Other researchers in the field of PAM have succesfully applied face validity in their research, such as Beecham *et al.* (2005), Hardesty and Bearden (2004), Flynn (2016), Walker (2015), Kriege *et al.* (2016) and Jooste (2014).

As the provided definitions state, for a framework to be valid, it need be reviewed by an expert panel. This is confirmed by Teddlie and Tashakkori (2010), which states that the use of experts in face validity will improve its quality. Lauesen and Vinter (2001) also addresses the use of experts over non-experts, where they found that the ability of experts to predict techniques to prevent requirements defects were very high when put into practice.

For the purpose of this study, face validation is used to investigate the potential of the proposed framework to assist organisations in determining which Lean tools can be used to achieve the requirements set out in the ISO 55000 Family of Standards and aid compliance. As the concept of the framework is defined, it can be presented to an expert panel in the field of PAM, ISO 55000 and Lean. This proves the use of face valdation for this study to be appropriate. It is however recommended that in the future other forms of validation is also applied to the proposed framework, in order to strenghten its validity.

6.3 Background of Expert Panel

Lauesen and Vinter (2001) and Kitchenham *et al.* (2002) recommend using an expert panel that consists of participants with different backgrounds and from different industries. Experts are therefore selected from a population of experienced practitioners and researchers in the areas of PAM, ISO 55000 and Lean. Ten suitable participants were identified, of which four were willing to participate in the study. Researchers such as Walker (2015) and Kriege *et al.* (2016) makes use of a panel of four or less experts for face validity, which concludes that the use of four participants is sufficient for the validation of the proposed framework.

Participant 1 (P1) has more than ten years of experience within the field of PAM and led numerous organisations accross a range of sectors closer to PAS 55 and ISO 55000 compliance. These sectores includes but is not limited to power and utilites, defence, manufacturing, telecoms, transportation and the built environment. In her AM career, P1 has taken up roles such as a Project Development Manager, Asset Development Planner, Asset Performance Development and Change Manager and a Senior Asset Management Consultant and is currently self-employed as an Asset Management and Business Change Professional. She was also a Chair Member of the Next Generation Institute of Asset Management for three year and a committee member for five. She is still involved in AM improvement projects in collaboration with the IAM. During her tenure in the Railway Industry, she was on the project team involved in two large scale Lean projects, which was succesfully implemented.

Participant 2 (P2) is a Professional Mechanical Engineer with experience within different PAM Fields. He started his career in the automotive industries, where he rotated through process, design, finance and maintenance. His career became more focussed on process improvement, and he obtained his Six Sigma Black Belt (BB) and Master Black Belt (MBB). His success within different organisations in the automotive industry led to the Railway industry to lead Maintenance Six Sigma projects. P2 is currently still working in the Railway Industry as a Reliability Process Manager. Due to Participant P2's experience within PAM, he serves the profile to participate in the validation process.

Participant 3 (P3) is an internationally recognised expert in PAM, with over 35 years of experience within numerous industries such as power generation, mining, heavy manufacturing and pharmaceuticals. He is a member of the Technical Committee for Asset Management Systems, who is responsible for the development of the ISO 55000 Family of Standards. He is also a member of the Institute of Asset Management (IAM) UK, Southern African Asset Management Association (SAAMA), a board member of the Association of Maintenance Professionals (AMP) and an endorsed IAM PAS 55 assessor. P3 serves as a supplier to the IAM and provides PAM, including ISO 55000, consulting services to international clients.

Participant 4 (P4) received his Bachelors' degree in Industrial Engineering at the University of Stellenbosch in 1998, whereafter he started working for Mercedes–Benz SA as a Continuous Improvement Specialist. At Mercedes Benz, P4 focussed on streamlining their production system through the implementation of Lean practices and tools. In 2006, P4 received his Lean certicifation and Six Sigma green belt. In 2006, he was also part of various TPM projects in Germany, representing Mercedes–Benz SA. In 2009, P4 started working for South African Breweries as a Manufacturing Development Consultant, where he was responsible for the identification, coordination and active participation in strategic and systematic value chain improvement initiatives using various Lean tools. He is currently employed at Nestle SA as a Market Lean Manager, where is primary focus is on the creation and empowerment of teams accross different funcational departments with the common goal of improving the way in which the value stream satisfies consumers and customers.

6.4 Success Criteria

In order to have a measure against which the proposed framework can be arbitrated, it is important to define criteria for success. According to Mohamed and Lim (1999), criteria are the set of principles or standards by which judgement is made. In the context of this study, the establishment of criteria provides principles which can be used to lead the data collection process and which the outcome of face validation can be measured against. If the framework meets the established criteria, the framework proves to be valid *by the face of it*.

Davis (1989) did a study on improving measures for predicting and explaining the use of information technology. His main focus was on two theoretical constructs, *perceived usefulness* and *perceived ease of use*, which he states are two fundamental determinants of system use. Even though his main focus was on IT systems, it can be applied to all type of systems. For the purpose of this study, the system is the proposed framework.

Davis (1989, p.320) defines perceived usefulness as *'the degree to which a person believes that using a particular system would enhance his or her job performance'*. Thus, if a system proves high in perceived usefulness, the user believes in a positive use-performance relationship. If however a system is regarded as useful, but its application too dificult, the user may regard the benefits presented by the system as being outweighed by the effort to use the system. This brings us to his next criterion, *ease of use*.

Davis (1989, p.320) defines perceived ease of use as *'the degree to which a person believes that using a particular system would be free of effort.'*. He states that if a system is perceived as easy to use, it is more likely to be accepted by the user.

In addition to *perceived usefulness* and *perceived ease of use*, Beecham *et al.* (2005) regards *understandability* and *flexibility* also as imperative criterion when evaluation the validity of a model. He states that in order for a model to be *understandable*, there should be no ambiguity in its interpretation, where the framework functionality and structure should be clear, well defined and logical. Furhtermore, a framework with high flexibility has the potential to be tailored to any environment, depending on individual needs. Beecham *et al.* (2005) also addresses the importance of testing the *strengths* and *weaknesses* of the model in order to direct future model development.

The most important criterion for success is determining if the framework meets its objectives, which is to provide a framework to be used in solving the problem statement and achieving the research objectives.

In summary, in order for the framework to prove face valid, it should be perceived as useful, easy to use, understandable, flexible and solve the problem statement. Its strenghts and weaknesses should also be evaluated in order to make improvements.

6.5 Data Collection and Questionnaire Development

Semi-structured interviews are used for data collection. According to DiCicco-Bloom and Crabtree (2006), a face-to-face in-depth interview is the more common interview format used when the researcher seeks to foster learning about individual experiences and perspectives regarding a set of issues. Sturges and Hanrahan (2004) did a study where they compared face-to-face interviews with telephonic interviews in qualitative research and concluded it to be equally effective. They state that even though face-to-face interviews are generally used to conduct in-depth semi-structured interviews, the use of telephonic interviews may increase the sample of the study, especially when the geographical locations of participants are not in close proximity to the researcher.

In addition to telephonic interviews, Hanna (2012) studied the use of modern software, such as Skype, as a viable research medium for overcoming issues such as distance and access. He states that even though technical difficulties might hinder the interview experience, it is regarded as closest to the interactive experience in face-to–face interviews. In this study, the researcher conducts, where possible, face-to-face interviews. If geographically not viable, Skype interviews are conducted. If technical difficulties however are experienced, or if preferred by the participant, telephonic interviews are conducted.

Open-ended questions are questions for which the answer categories are provided by the respondent rather than the interviewer. These type of questions work best when the range of possible responses exceed what a researcher can provide and if the researcher aims to find out more about a specific topic. It is important for the interviewee to have a great amount of knowledge on the topic under discussion, as it is very demanding on respondents less educated on the subject matter (Frey, 2004). One advantage of open–ended questions is that it can provide researchers new or different insights on a specific topic, as they often have bias views obtained from past research papers. Open–ended questions have the ability to provide new perceptions about a situations that the researcher may have never considered (Clow and James, 2014).

In contrast, when considering closed-ended questions, participants are provided with a set of answers preselected by the interviewer. These questions are more difficult to write, as the interviewer needs to know the scope of answers respondents may provide. Closed-ended questions are normally used in quantitative studies, as it can easily be statistically analysed (Fink, 2003). There are three different forms of closed-ended questions: dichotomous question, multiple-choice questions and scaled-response questions. Dichotomous questions are most appropriate when the outcome of the study requires statistical analysis. It however lacks insight on the opinion of the respondent, as the respondent is only limited to two responses. Multiple choice questions are normally used for demographic variables, but is inadequate when additional insight into participant responses is required. Scale-response questions are closest to capturing the detail of respondent's answers (Clow and James, 2014). In order to provide a framework of value, the researcher provides questions to experts within the areas of Lean, ISO 55000 and PAM, with the aim of collecting as much data as possible in order to effectively determine the validity of the framework. If the framework proves invalid, participant responses need be sufficient in order to adapt the framework to prove face valid. This is more likely to be achieved through open-ended questions rather than closed-ended questions. Closed-ended questions are used where applicable, and is presented in the form of a rating scale in order to maximise respondent input.

The appropriate number of intervals to use in a rating scale has been a subject of debate for many years. Peterson (2000) state that even though it is a widely held believe that the correct number of rating scale categories should be between 5 and 9, it is not an agreed-upon standard. He further states that the amount of rating scale categories depend on the type of interview being conducted, the capability of participants, the nature of the objects to be scaled and the way in wich the collected data will be analysed. When conducting telephonic interviews, a maximum of five rating scale categories are desired, as more may confuse respondees due to factors related to visualisation, memory or fatigue. Personal interviews allow the greatest amount of rating scale categories, especially if participants are given a copy of the questionnaire. The ability of the participants to comprehend the different and amount of rating scale categories should also be considered. Furthermore, if the data obtained need be analysed by sophisticated statistical techniques, a minimum of seven rating scale categories may be required (Peterson, 2000).

There have also been great debate about the use of even or uneven numbers in rating scales. Weller and Romney (1988) state that whether the number of rating scale categories are even or odd is completely up to the researcher. The benefit of using en even number is that it can easily be categorised, because there are no equivocal responses. In contrast, respondees might feel like they are forces to choose against or in favour of a certain concept, when, in fact, they feel neutral about it. The main reason researchers prefer to use an odd number of rating scale categories is to avoid this inconvenience (Weller and Romney, 1988). The five-point scale is selected for the closed-ended questions in this study to allow for a neutral stance, where there is an equal number of positive and negative categories. An example of this is shown in Figure 6.1.

How would you rate *the ease of understanding* the framework?

Very Poor ☐ Poor ☐ Fair ☐ Good ☐ Very Good ☐

Figure 6.1: Ordinal Scale used in Questionnaire

Participants were invited to participate in the survey via email. Upon accepting the request, they were sent the document provided in Appendix B before the interview. This document includes the context of the problem, the developed framework, an explanation on the framework and the open- and closed-ended questions to be covered in the interview. Before the interview commenced, permission was asked to record responses of the participants via voice recording in order to capture responses effectively. Participants were ensured that their identities be kept anonymous, where desired. Participant responses is provided in Appendix C.

6.6 Interview Results

This section aims to conclude the validity of the proposed framwork by comparing participant responses to the success criteria covered in Section 6.4. To recap, in order for the framework to prove valid, it should be useful, easy to use, understandable, flexible, and achieve the research objectives. An analysis on the strenghts and weaknesses of the proposed framework should also be conducted. Depending on the outcome of the analysis, the developed framework is modified accordingly in order to improve its validity.

6.6.1 Perceived Usefulness

In order to determine if participants consider the developed framework *useful*, they are asked if they deem the framework to be of value to the PAM environment and if they would utilise the framework (Appendix C Question 7).

According to P1, *'a lot of organisations do not know where to start implementing the requirement within the Standard and this framework will assist them'*

P3 regards the value of the framework as '*significant*' and states that it provides a *'significant contribution to the body of knowledge surrounding the implementation* *of ISO 55000'*. He also states that the researcher is doing '*very important*' work and that he would '*absolutely utilise*' the developed framework. P1 further states that she considers the framework to be a *'very valuable tool'*.

Both P1 and P3 mentions the difficulty of implementing the Standard and that organisations normally do not know where to start. This framework will provide them with the necessary focus and structure to start their implementation journey.

P4 regards the framwork as very '*specific*', which he believes will simplify the implementation strategy for the business.

Even though P2 would utilise the framework when implementing ISO 55000, he does mention that he would find a process more useful and recommends it for future research. P4 also mentions that if a change management process were to be integrated in the framework, it would ease the implementation process even further.

6.6.2 Perceived Ease of Use

In order to determine whether the framework is easy to use, participants are asked to rate the structure and comprehensiveness of the framework. If the framework is not structured in a way that is understandable to participants, it will be difficult to implement. In addition, if the framework is not comprehensive enough and misses information, time will be wasted trying to fill in the missing gaps. *Ease of Understanding* the framework, covered in Section 6.6.3, also plays a role in determining if the framework is easy to use.

P1, P2 and P4 rates the structure of the framework as *Good*, where P3 rates it as *Fair*.

P1 states that she especially likes that fact that the ISO 55002 clauses are included in the framework. According to P2, he would rate the structure of the framework as *Very Good* if the Lean tools is written out in the framework as opposed to being cross-referenced to another table. He also suggests explaining the structure of the table summarising the Lean parctices and tools (Table 1 of Appendix B) clearer.

According to P3, the structure of the framework can be improved by using more colours to emphasise the different PAM focus areas. He also suggests adding more information on the relevance of the specific Lean tools to the ISO 55000 clauses by adding a third column for each PAM focus area and inserting colour coding or using a rating system. If this is in place, he would rate the structure of the framework as *Good*.

P4 states that he especially like the fact that the framework is segmented in the different PAM focus areas. It makes it *'clear from the beginning'*. He would however give it a rating of *Very good* if the researcher made it *pop out* more through the use of capital letters or colour coding. He furthermore suggests the PAM focus areas to be part of the overall numbering system of the framework, to keep consistency.

When considering the comprehensiveness of the proposed framework, P1, P2, and P3 gives a rating of *Good*, while P4 gives a rating of *Very Good*.

According to P1, she would give the comprehensiveness of the framework a rating of *Very Good* if *AM Planning and Strategy* and *AM Decision-Making* were added as PAM focus areas. She does however admit that she understands that there is *'no one right reason'* in determining which PAM areas should be focused on and the methodology used by the researcher to decide on PAM focus areas is *'sound'* and *'logical'*. She further adds that she would be happy if these areas be recommended for future research. In addition, P3 states that he would have given a rating of *Very Good* if *Focussed Improvement* were added to the PAM focus areas, as he believes that it is the most applicable to Lean.

6.6.3 Understandability

In order to determine if the framework is easily understandable, participants is asked to rate the ease of understanding the framework.

P1, P2 and P4 rates the ease of understanding the framework as *Good*, while P3 rates it as *Very Good*. All participants state that the framework is very comprehensive, with a great amoung of detail. P1 does state that, at times, this makes it slightly hard to follow. She however adds that the way it is set out is very logical and only encompasses the critical elements of the fields under study, so the amount of detail cannot necessarily be reduced.

6.6.4 Flexibility

Participants are asked to provide a rating on the flexibilty/adaptability of the proposed framework. Three out of four participants rates it as *Good* and above, and one participant rates it as *Fair*

P1 rates it as *Very Good*. P2 rates it as *Good*, P3 rates it as *fair* and P4 rates it between *Good* and *Very Good*.

P3 states that the reason he is giving it a rating of *Fair*, is because organisations might be confused on the applicability of the implentation of the Lean tools in their organisation and how it would advance PAM. If the framework has a third column indicating the relevance of specific Lean tools to PAM or the specific ISO 55000 clauses, he would give it a rating of *Good*.

P4 states that he cannot give the framework a rating of *Very Good* for flexibility, as it has not yet been applied in practice. He is therefore more comfortable rating it between *Good* and *Very Good*.

Furthermore, as each participant comes from a different industry, and they all declare that they would utilise the proposed framework, they framework can be regarded as *flexible*.

6.6.5 The Potential of the Framework to Address the Stated Problem

In order to determine the potential of the framework to address the problem statement, participants is asked the following question:

Considering the research methodology that was followed, what is your opinion on the potential of the proposed framework as a tool to advance Physical Asset Management in an organisation and support ISO 55000 accreditation?

All participants agree that the framework sets out what it intends to.

P1 states that the framework is very useful in illustrating the synergy between Lean, AM and the ISO 55000 Family of Standards. P4 confirms the gap in determining which tools to use in support of ISO 55000 implementation and state that the correlations in the framework is correct and will bridge the gap.

P3 specifically states that the framework succesfully achieves its objectives, and that he considers it to be of great value within the AM industry. P2 states that the developed framework *'clearly points you in the right direction'* when considering how Lean practices support the ISO 55000 requirements. P3 considers the research methodology followed as *'logical'*, while P4 considers it to be *'one hundred percent sound'*.

6.6.6 Framework Strenghts and Weaknesses

Participants are asked to provide their opinion on the strenghts and weaknesses of the framework and the methodology that was followed.

According to P1, the strengths in the framework lies in the benefit it holds for organisations when trying to correlate Lean and AM, as there is little research done in this specific field.

P2 and P4 considers the comprehensiveness and detail of the framework to be its greatest strenght. P4 also states another strength of the framework to be its pragmatism and the fact that it is not *'pie in the sky'*. P3 believes the framework's greatest strength is its provision of orientation and cross-referencing.

When considering the framework weaknesses, P1 believes its greatest weakness to be that it does not include AM Strategy and Planning and AM Decision-making as PAM focus points. After the researcher provided a detailed explanation on how the PAM areas of focus were determined, P1 agreed that the methodology followed is *logical* and *sound* and that everyone will have a different opinion on which PAM areas to focus. This is proven by the fact that P3 considers Focussed Improvement as an imporant PAM area to focus on, and does not necessarily regard the elimination of AM Strategy and Planning and AM Decision-Making as a framework weakness. Due to the broad scope PAM encompass, and time constraints of this dissertation, the researcher had to narrow down the PAM areas to focus on and all participants regarding the methodology used to determine these areas as correct.

P2 states that the frameworks' greatest weakness is the fact that the Lean practices and tools used are more reactive than proactive. He does however comment that this may be due to the clauses being more focussed on reactive strategies rather than proactive strategies. He also states that he would prefer the framework to be in the form of a process and suggests that, in the future, a process be derived from the framework.

According to P3, a weakness of the framework is that it is not specific enough in the sense that it does not specify exactly how the chosen Lean practices and tools are relevant to the chosen clauses. He suggests inserting an additional column where this is indicated through a rating scale or colour coding.

P4 suggests a weakness of the framework to be the fact that the sequence of which the Lean tools should be implemented is not indicated on the framework. He states that numerous organisations regards Lean as a *big monster* with *a lot of legs* and do not know where to start when wanting to implement Lean. He also states that certain Lean initiatives will not be successful if other Lean initiatives are not in place. For example, Lean production will not reach its full potential if Lean maintenance is not implemented first. The main aim of this study is to correlate Lean practices and tools to ISO 55000 clauses in a framework and not to provide a process on the steps in which Lean should be implemented. This is therefore out of the scope of this project. Even though this will not be illustrated in the final framework, Chapter 2 provides in-depth literature on the different Lean tools and concepts and their implementation sequence.

6.6.7 Face Validation Summary and Conclusion

Due to time and resource constraints, Face Validation is used for the purpose of this thesis. Semi-structured interviews is conducted with four experts with different backgrounds and from different industries in order to determine the face validity of the proposed framework. The success criterion used to determine the frameworks' validity includes perceived usefulness, understandability, flexibility and objective-orientated.

All four participants considers the framework to be of *value* to the PAM environment and states that they would utilise the framework if they were to implement ISO 55000. For these reasons, there exists sufficient support that the success criterion of perceived usefulness is met.

The structure, comprehensiveness and ease of understanding the proposed framework is collectively investigated to conclude the frameworks' ease of use. A summary of participant responses regarding these three factors is illustrated in Figure 6.2. Each participant gives a rating between 1 and 5, where 1 – Very Poor, 2 – Poor, 3 – Fair, 4 – Good and 5 – Very Good.

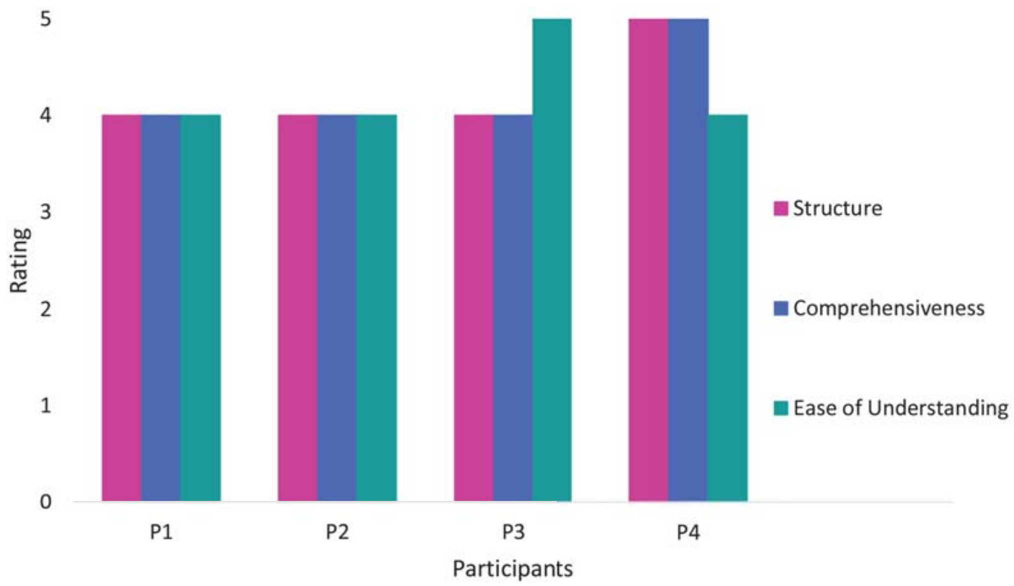


Figure 6.2: The Ease of Using the Proposed Framework

The average rating of all participant responses is 4 - *Good*. This concludes the success criterion of ease of use to be met. The researcher however wants the framework to be as valid as possible. Therefore, when considering ease of use, the following improvements are made in order to increase the validity of the proposed framework:

- Write out Lean tools
- Add emphasis - colour and/or capital letters
- Add third column to indicate the relevance of the Lean tool to the clause
- Include PAM focus areas to the numbering system

If these improvements incorporated, all ratings is between 4 and 5, with the overall average rating increased to 4.25.

When considering the understandability of the proposed framework, all participants rates the framework between 4 and 5, as illustrated in Figure 6.2. This concludes the success criterion of understandability to be met.

Participant ratings related to the flexibility of the framework can be seen in Figure 6.3.

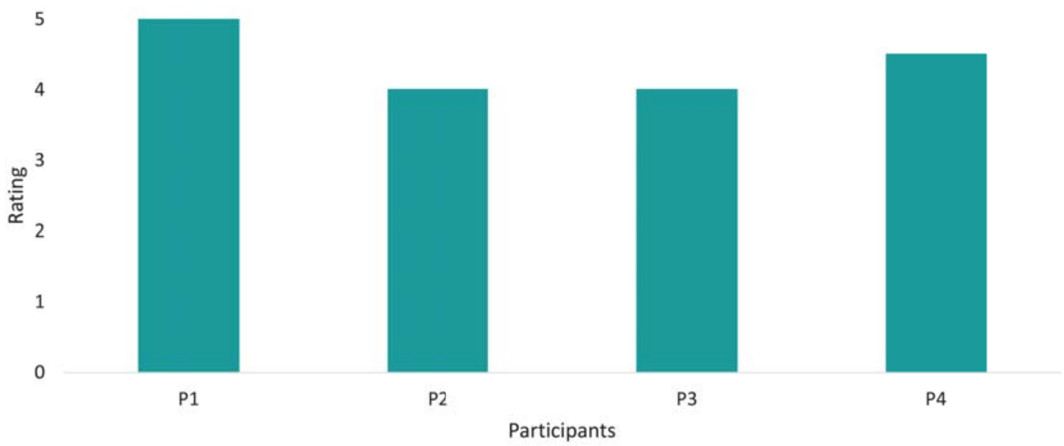


Figure 6.3: The Flexibility of the Proposed Framework

The average rating of the participants is 4.1 - *Good*. The framework therefore can be regarded as flexible and the success criterion is met. However, when the researcher implements the above mentioned improvements, the average overall rating increases to 4.4.

All participants considers the potential of the framework to address the problem statement as *high* and the research methodology used *sound* and *logical*. The perceptions of the participants provide supporting confidence that the proposed framework meets the success criterion of objective-orientated.

Despite concerns regarding the framework, there exists sufficient support that all success criteria regarding the face validity of the proposed framework is met.

6.7 Proposed Changes to Framework

In Section 6.6, the face validity of the proposed framework is reported. In this section, improvements are made to the proposed framework in order to increase its practicality in the working environment.

The improvements includes:

1. Writing out Lean tools in the framework;
2. Emphasising different PAM focus areas through colour coding and capital letters;
3. Including PAM focus areas to the overall numbering system of the proposed framework.
4. Inserting a third column to indicate the relevance of the Lean tools to PAM

The improved and final framework can be seen in Appendix D. The rest of this section describes the framework improvements.

Improvement 1 in the above mentioned list is addressed by inserting an additional column, which contains written out Lean tools. Improvements 2 and 3 is addressed by providing each PAM focus area a unique number and colour. Note that the Lean reference numbers are still illustrated on the framework, in order to keep consistency of the framework's numbering system.

To indicate the relevance of each Lean tool to PAM within the context of the clauses, each Lean tool is matched with one of the four fundamentals of AM, as defined by the ISO 55000 document and as discussed in Chapter 2. This is illustrated in column *ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)* on the framework. To recap, this includes:

1. Value;
2. Alignment;

3. Leadership and
4. Assurance.

In order to uphold consistency, the AM values is illustrated on the framework in the form of the number of which it is indicated on Page 3 in the ISO 55000 document. The rest of this section gives a brief explanation on the alignment of Lean practices and tools and AM fundamentals, as indicated on the proposed framework. It is important to note that, for the purpose of this framework, this strongly depends on the context of which each Lean practice or tool is used to support its respective ISO 55001 clause.

The use of VSM (2.1.2.14) to determine the internal and external context of the organisation (ISO 55001 4.1) provides assurance that the scope of the AMS integrates effectively with the organisation's information system. This is aligned with ISO 55000 (2.4.2b). The utilisation of VSM (2.1.2.14) to determine the information requirements of stakeholders establish a basis for consistent decision-making and also influence the design and scope of the organisations' AMS and objectives to stakeholders' satisfaction. It furthermore illustrated leadership through the consultation with stakeholders regarding AM. This is consistent with Fundamental 2.4.2a(1), 2.4.2a(3), 2.4.2b and 2.4.2c(3) of the ISO 55000 document.

The use of production scheduling (2.1.3.6), VSM (2.1.2.14), a pull system (2.1.3), PDCA (2.1.2.15), work standardisation (1.1.3) and ABC analysis (1.1.6.2) to determine attribute requirements of identified information and to determine how and when information should be collected, analysed and evaluated gives assurance that the asset will fulfill its required purpose (ISO 55000 Fundamental 2.4.2d). This fundamental is also at the core of the specification, implementation and maintenance of processes for managing information through the use of VSM (2.1.2.14), PDCA (2.1.2.15), work standardisation (1.1.3), planned maintenance (1.2.2), and ABC analysis (1.1.6.2).

To support ISO 55001 (7.5e), Hoshin Kanri (3.1.1) is used to ensure horisontal and vertical consistency, traceability and alignment. This supports Fundamental 2.4.2b in the ISO 55000 document.

The use of VSM (2.1.2.14) and work standardisation (1.1.3) for the consistency and appropriateness of asset information assures that assets will fulfill their purpose, which is consistent with Fundamental 2.4.2 d) in the ISO 55000 document. Lean's 5S's is used to organise data for availability and protection. This also assures optimum asset performance in order to meet organisational objectives.

The use of VSM (2.1.2.14) to determine the scope of which information and knowledge is shared with contracted service providers (ISO 55001 8.3c) assists in controlling the risk of outsourcing activities with the potential of impacting the achievement of AM objectives. This is aligned with assuring that assets fulfill their purpose (ISO 55000 Fundamental 2.4.2d).

By using VSM (2.1.2.14) to determine an organisation's ability to compile and report on information (ISO 55002 9.1.1.2e) and to facilitate corrective action (ISO 55002 9.1.1.1d), it assures that the organisation is capable of achieving its AM objectives. This is consistent with Fundamental 2.4.2 b) 1) and 2.4.2 b) 3) in the ISO 55000 document.

The calculation of MTBF (2.2.3.1.1) on an organisation's IT systems, monitors the reliability of the organisation's information (as per ISO 55002 91.1.2f). This is aligned with Fundamental 2.4.2 d) 3) in the ISO 55000 document, as it monitors AM processes.

The use of information related to OEE (1.2.4), takt time (2.1.2.2), pitch (2.1.2.2), the efficiency of the work order system (1.2.5), SMED (1.1.2) or MTBF (2.2.3.1.1) to determine areas for corrective action and improvement or to determine if organisational objectives are met are aligned with ISO 55000 (2.4.2d(2) and 2.4.2d(3)), as it implements processes to assure capability and continual improvement.

When information obtained through condition monitoring (2.2.1.1) or new technology (2.2.2.2) is used as a basis for preventive action (as per ISO 55002 10.2e), it assures optimum performance of assets. This is based on the fundamental that all assets should fulfill their required purpose (ISO 55000 2.4.2d).

The use of Hoshin Kanri (3.1.1) do develop an AM Policy related to the commitment to decision-making criteria regarding asset life cycle costs (as per ISO 55002 5.2d), enables vertical and horisontal alignment and illustrates the organisations' commitment to using a life-cycle approach to realise value from organisational assets, as per ISO 55000 (2.4.2 a(1)), 2.4.2 a2), 2.4.2 b1) and 2.4.2 b2).

The formulation of AM objectives related to asset life-cycle costs and asset life expectancy (as per ISO 55002 (5.2d) through the use of Hoshin Kanri (3.1.1) and PDCA (2.1.2.15) assures that the organisaiton use a life-cycle management approach to realise value from its assets, which is aligned with ISO 55000 (2.4.2 a(2)). It also ensures the integration of AM processes with functional management processes, as stated in ISO 55000 (2.4.2b(2)). The use of Hoshin Kanri (3.1.1) as a top-down approach to establish AM objectives connects the purpose of organisational assets with the AM policy, which is consistent with the organisational plan. This is aligned with with ISO 55000 (2.4.2d(1)). Furthermore, the use of PDCA as a bottom-up approach to establish asset life-cycle objectives is also aligned with ISO 55000 (2.4.2d(1)).

When considering achieving AM objectives related to asset life-cycle management (as per ISO 55001 6.2.2b), each Lean tool is implemented with the goal of assuring assets perform according to their intended purpose. The use of OEE (1.2.4), autonomous maintenance (1.2.1), planned maintenance (1.2.2), RCA (1.2.3 a)), problem solving (1.2.3 b)) and TPM (2.2) to maintain assets is aligned with ISO 55000 (2.4.2 d(1) and 2.4.2d(2)) and the use of PDCA (2.1.2.15) to identify improvement opportunities is aligned with ISO 55000 (2.4.2d(3)) .

The use of work standardisation to standardise how assets are broken down in support of asset lifecycle management is aligned with ISO 55000 (2.4.2b(3)), which covers the specification, design and implementation of a supporting AMS.

The use of RCA (1.2.3 a)) to detect internal and external issues to the organisation (ISO 55001 (4.1)) ensures a risk-based approach to achieving AM objectives. This is consistent with ISO 55000 (2.4.2 b(1)). Furthermore, the demonstration of AM leadership through perfoming Risk-based Maintenance and aligning AM to the organisation's RM approach is aligned with ISO 55000 2.4.2 c). The establishment of an AM policy that incorporates commitments to decision-making criteria related to risk (ISO 55002 5.2d) through Hoshin Kanri (3.1.1) ensures the implementation of risk-based decision-making processes, which is aligned with Fundamental 2.4.2 b(1) in the ISO 55000 document.

The implementation of Lean tools to address and mitigate risks and opportunities (ISO 55002 6.1a) aligns with ISO 55000 Fundamental ISO 55000 (2.4.2b(1), 2.4.2b(3) and 2.4.2d(3)). Furthermore, the use of Hoshin Kanri (3.1.1) to integrate risk and opportunity management actions with the AMS supports ISO 55000 (2.4.2b(1) and 2.4.2d(1)) and the calculation of OEE (1.2.4) and MTBF (2.2.3.1.1) to monitor their effectiveness supports ISO 55000 (2.4.2d(2) and 2.4.2d(3)).

Lean tools used to identify risks and opportunities, potential events, their causes, likelihood and consequences (ISO 55002 6.2.2.3b) conforms to ISO 55000 Fundamental 2.4.2(1), 2.4.2b(3) and 2.4.2d(3), as it enables the implementation of aupporting risk-based decision-making processes and processes for monitoring risks and opportunities, respectively. The use of Risk-based maintenance (2.2.3.2) to determine the organisation's strategy to the treatment of risks also supports fundamental 2.4.2b(1) and 2.4.2d(3) in the ISO 55000 document.

Creating awareness of risks (ISO 55001 7.3) through visual control (1.1.5) demonstrates management leadership (ISO 55000 2.4.2c) and provides necessary resources to assure high competency of personnel (ISO 55000 2.4.2d(4)). Furthermore, by applying VSM (2.1.2.14) to the organisation's RM process to identify information requirements, support is given to ensure successfull RM execution. This aligns with ISO 55000 (2.4.2b(3)).

Lean tools used to plan, implement and control processes to meet necessary requirements related to risk and opportunity (ISO 55002 (8.1.4) supports ISO 55000 (2.4.2d). The Lean tools used to monitor the effectiveness of the RM process is aligned with ISO 55000 (2.4.2d(3)). Furthermore, the Lean tools used to assess the changes in profile on risk and opportunity (ISO 55001 9.3f) and to periodically review opportunities for continual improvement (ISO 55001 9.3e) supports the implementation of processes for monitoring and continual improvement (ISO 55000 2.4.2d(3)). The assessment of possible risks encountered when applying corrective action (ISO 55001 10.1) or implementing oppoortunities (ISO 55002 10.3.4) also supports the implementation of processes for monitoring.

The determination of the customers' perspective regarding reliability through VSM (2.1.2.14) sets a basis for decision-making processes that reflects stakeholder needs (ISO 55000 2.4.2a(3)) and illustrates leadership and commitment through consultation with stakeholders regarding AM (ISO 55000 2.4.2c(3)). Furthermore, the use of VSM (2.1.2.14) to determine AM objectives also illustrated leadership, as stakeholders are consulted in order to discuss their expectations regarding PAM parameters. The use of Hoshin Kanri (3.1.1) and PDCA (2.1.2.15) to establish AM objectives ensures top-down and bottom-up alignment, which is consistent with fundamentals 2.4.2a(1) and 2.4.2b(1) in the ISO 55000 document.

The use of PDCA (2.1.2.15) to identify new process equipment and technology is consistent with implementing processes for monitoring reliability (ISO 55000 2.4.2d(3)).

The use of RCM (2.2.3.1), Hoshin Kanri (3.1.1) and PDCA (2.1.2.15) to determine AM objectives regarding asset conditions (as stipulated in ISO 55002 (6.2.3.1 d) enables bottom-up and top-down alignment, which is consistent with Fundamentals 2.4.2a(1) and 2.4.2b(1).

Through the applicaiton of RCM (2.2.3.1) to determine an assets' information requirements related to its physical attributes, a basis is set for the implementation of processes for monitoring the assets physical stance in order to prematurely detect failure. This is directly aligned with fundamental 2.4.2d(3) in the ISO 55000 document.

When RCM (2.2.3.1) is used to set condition indicators to measure, monitor and evaluate the organisation's assets (as per ISO 55002 9.1.1.1a), it provides assurance that the assets will fulfill their required purpose (ISO 55000 2.4.2d). Furthermore, the application of RCM (2.2.3.1) to identify corrective action should a nonconformity or incident occur (ISO 55001 10.1a, sets a basis for continual improvement in the event of an accident (SO 55000 2.4.2d(2)). By applying preventive maintenance (2.2.1), predictive maintenance (2.2.2) and reliability-centred maintenance (2.2.3.1), probability of asset failure decreases (as required by ISO 55001 (10.2)), which assures that assets will fulfil their required purpose and supports fundamental 2.4.2d in the ISO 55000 document.

The implementation of Lean tools to continuously improve the suitability and effectiveness of the organisations' corrective and preventive action (ISO 55001 (10.3) assures the implementation of continual improvement (as per fundamental 2.4.2d(3) in the ISO 55000 document) so that assets can fulfill their required purpose (as per fundamental 2.4.2d(1) in the ISO 55000 document).

6.8 Chapter Summary

In Chapter 6, the validity of the proposed framework is addressed through face validation by conducting semi-structured interviews with participants obtained through purposive sampling. The chapter first provides literature about face validation, whereafter the face validation methodology specific to this thesis is described in detail. This includes (1) the recruitment process followed to obtain an expert panel for the evaluation of the proposed framework, (2) the success criteria against which the framework is evaluated and (3) the development of the questionnaire covered in the semi-structured interviews. To summarise, the attributive requirements which the framework needs to portray to be regarded as *valid* includes useful, easy to use, understandable, flexible, and objective-orientated.

After the methodology of face validation is clearly defined, expert input is provided and their evaluation of the proposed framework against each success criteria described in detail. Based on expert input, conclusions are made about the achievement of each success criteria, which proves successful for all. The proposed framework can thus be deemed as valid and succesfully achieves its objectives.

Finally, improvements are made to the proposed framework, based on expert input.

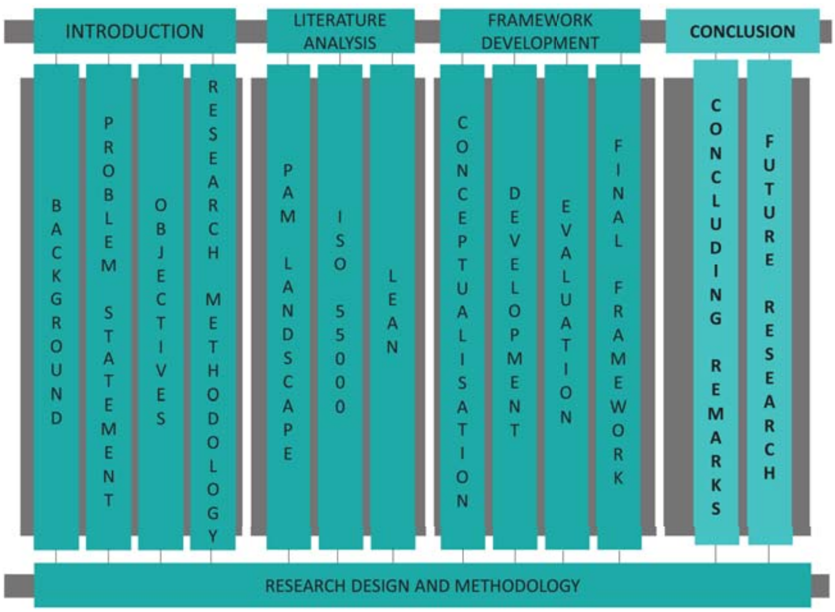
Chapter 7

Closure

Chapter Outcome

1. Provides a concise summary about the research conducted.
2. Answer the central research question.
3. Determine this thesis' potential benefits to PAM and society
3. Provide recommendations for future research

Chapter Route Map



7.1 Overview

The study stems from an opportunity identified for assisting organisations to prepare for ISO 55000 compliance, particularly through the use of Lean practices and tools. It proposes a framework that provides cross-referencing between IS0 55001, ISO 55002 and ISO 55000 and integrates these with Lean principles and tools.

The study consists of seven chapters: (1) an introduction, (2) a literature review of PAM and Lean and an overview of the ISO 55000 Family of Standards, (3) a description of the research methodology and design, (4) The selection of PAM focus areas, (5) framework development, (6) framework validation and (7) a conclusion to this study. This section provides a summary of how each chapter contributes to achieving the research objectives.

Chapter 1 provides an introduction to this study with a brief background in PAM, ISO 55000, Lean and their possible integration. Thereafter, the problem statement is provided and researchs questions are posed as follows:

1. What can be done to create a standard framework addressing *how* organisations can prepare for ISO 55000 accreditation?
2. How can Lean principles and tools be used to support the process of becoming ISO 55000 compliant?
3. How can a framework be structured to provide guidance on the use of Lean principles and tools to support the requirements set out in the ISO 55000 Suite of Standards?

After the research problem is stated, the studies' research objectives and delimitations are listed, which is followed by a summary of the research design and methodology and thesis layout.

Chapter 2 aims to provide extensive literature on the key concepts within the study. It first explores the PAM landscape in detail, where it provides definitions on physical assets and PAM and investigates its building blocks. Secondly, it provides a summary on the ISO 55000 of Standards, which is categorised in the six critical areas of AM, as defined by ISO 55000 as: context of the organisation, planning, support, operation, performance evaluation and improvement. Lastly, in-depth literature is provided on the Lean landscape, where key Lean principles, fundamentals and tools are investigated and categorised according to Lean maintenance and Lean production.

Chapter 3 details the research methodology and design of this research. It investigates the elements of inquiry, research approach and research design. When describing the elements of inquiry, this thesis' philosophical worldview, strategy of inquiry and research method is examined. The philosophical worldview of this research concludes to be that of pragmatism, because it focuses on the importance of the research question and the researcher has freedom of choice when choosing methods to solve the research question. Furthermore, its strategy of inquiry and research method follows a qualitative approach. When describing the research design of this research, the data collections methods and tools, sample selection, research process and approach to data analysis are detailed. Chapter 3 concludes with possible ethical implications addressed during the study.

Due to the broad scope of PAM, *Chapter 4* aims to conduct a quantitative analysis on the literature provided in Chapter 2 for the purpose of narrowing the focus of the research down to key PAM areas. The key focus areas include Asset Information and Knowledge, Asset Lifecycle Management, Risk and Opportunity Management, Reliability Engineering and Maintenance. It also provides further literature on each selected PAM focus area.

Chapter 5 develops a framework to illustrate which Lean principles and tools can be used to support the requirements set out in the ISO 55001 document. First, the ISO 55001 and ISO 55002 clauses applicable to each PAM focus area is identified. Secondly, the Lean principles and tools applicable to each clause is identified. Finally, the proposed framework is developed, illustrated in Appendix A.

Chapter 6 aims to determine the validity of the proposed framework through face validation by conducting semi-structured interviews with experts in the fields under study. It first provides literature on face validation and describes the methodology followed in detail, which includes (i) information on the chosen expert panel and their recruitment, (ii) the success criteria against which the framework is evaluated and (ii) the development of the questionnaire used during the interviews. Secondly, it evaluates the expert input against each success criteria. According to expert input, the proposed framework is useful, easy to use, understandable, flexible and objective-orientated, with an overall rating of *Good* when considering its validity. Finally, improvements are made to the framework in order to increase its validity.

This section outlined each chapter of this study. The following section aims to conclude the study by answering its research question.

7.2 Research Conclusions

Effective AM is imperative to any organisation, as it enables organisations to realise value from their assets. The ISO 55000 Series for the effective management of physical assets aims to provide a standardised framework illustrating what an AMS should consist of. The problem is that this document only provides organisations with *what* to do and not *how* it should be done. This thesis aims to bridge this gap. Lean and AM has similar principles, of which one of the most important principle is to create value for the organisation and its stakeholders. The implementation of Lean principles and tools can therefore provide support to the clauses set out in the ISO 55000 Family of Standards. This study proposes a framework which serves as a comprehensive and structured guide on supporting the requirements of the ISO 55000 documents through the use of Lean principles and tools.

Objectives 1 to 3 is satisfied in Chapter 2, which provides literature about PAM and Lean, as well as an overview of the ISO 55000 Family of Standards. In Chapter 3 objective 4 is achieved by detailing the research design and methodology of this thesis. Objective 5 and 6 is met in Chapter 4, which selects PAM focus areas and provides literature on each. Chapter 2 and Chapter 4 answers the first research question, as it investigates literature on the key concepts of this study, which leads the rest of this study. It provides thus an understanding on what need be done to create a standard framework addressing *how* organisations can prepare for ISO 55000 accreditation.

In Chapter 5, each Lean principle and tools is analysed in order to determine *how* they can be used to support the process of becoming ISO 55000 compliant. This answers the second research question of this thesis. Chapter 5 furthermore develops a framework that provides orientation and direction on the Lean principles and tools to be used for the support of the clauses set out in the ISO 55001 document. It also provides cross-referencing between the ISO 55001 and ISO 55002 document for clarification and ease of use. It can thus be concluded that the primary objective of this thesis (Objectives 7-9 in Table 1.1) is met.

According to an expert panel, the proposed framework achieves its desired intention, which includes usefulness, easy to use, understandable, flexible and objective-orientated. The framework was consequently modified according to expert input during the conduction of face validition of the proposed framework. Chapter 6 therefore satisfies Objectives 10 and 11 of Table 1.1.

Considering the feedback from the expert panel, it can be stated that the developed framework would be able to provide organisations direction on *how* to support the requirements set out in the ISO 55000 Suite of Standards for the effective management of physical assets through the use of Lean practices and tools. This answers the third research question and concludes the achievement of this thesis' final objective (Objective 12 in Table 1.1).

Although the objectives of this research have been successfully achieved, some limitations are evident.

7.3 Recommendations for Future Research

Through the course of this study, opportunities for future research were identified through the limitations imposed on this study or through expert feedback received during the validation process. The following recommendations may add value to address in the future and may contribute to this research:

- Due to resource constraints, such as time, funding and access, the framework could not physically be implemented in order to determine its validity. It is recommended that in future the framework be applied in the industry in real-world situations to determine the difficulty of its implementation and to test if its established face validity holds true.
- The framework is validated using four experts with backgrounds in different industries. This sample size can be increased to encompass a wider spectrum of credible experts to improve the frameworks' generalisability and to determine its true external validity.
- According to expert input, it would be of great value if the framework further be developed into a procedural process which incorporates training packets, practical examples and change management.
- Due to time and scope limitations of this study, the framework only focuses on the clauses in the ISO 55000 Family of Standards applicable to pre-determined PAM and Lean focus areas. It is recommended that in the future, this be expanded to encompass a broader scope of PAM and Lean. According to expert input, the incorporation of AM Strategy and Planning, AM Decision-Making, Focused Improvement and Lean Quality will especially be of great value for future research.

7.4 Potential Benefits to the field of PAM and Society

This framework benefits the field of PAM by providing a framework to bring organisations closer to ISO 55000 accreditation through the use of Lean principles and tools, which can increase the efficiency, effectiveness and safety of their PAM systems. As a result, this benefits society in creating assurance of safe production systems and continuous increased value to the end-user, as this is Lean's sole purpose.

According to the expert input, the proposed framework adds significant value to the PAM domain, specifically to the body of knowledge surrounding the implementation of ISO 55000.

7.5 Chapter Summary

This chapter concludes this study by providing an overview of the research conducted, answering the central research questions and concluding the achievement of its research objectives. After investigation, it is concluded that the research objectives illustrated in Chapter 1, Table 1.1 is achieved successfully. This chapter further concludes the value this research provides to the PAM domain and society and stipulates recommendations for future research.

Appendices

Appendix A

A Framework for Implementing Lean Practices and Tools to Support ISO 55000 Compliance

The proposed framework is illustrated in Figure A.2. As mentioned before, the proposed framework should be read with the ISO 55000 Family of Standards and Figure A.1 at hand.

Lean Concept	Lean Bundle	Lean Practice	Lean Tool	
1. Maintenance	1.1 JIT	1.1.1 Kanban	1.1.1.1 Visual Control	
			1.1.1.2 Work Standardisation	
			1.1.1.3 Quick changeover techniques	
		1.1.2 SMED	1.1.2.1 Work Standardisation	
		1.1.3 Work Standardisation	1.1.3.1 Takt time	
			1.1.3.2 Work sequence	
			1.1.3.3 Standard WIP	
		1.1.4 Takt time	1.1.4.1 Work Standardisation	
		1.1.5 Visual Control	1.1.5.1 5S	
			1.1.5.2 Shadow Tool Board	
			1.1.5.3 Inventory indicators	
			1.1.5.4 Kamishabi	
			1.1.5.5 Kanban	
			1.1.5.6 Andon	
			1.1.5.7 One-piece flow	
			1.1.5.8 Standardised work	
			1.1.5.9 Jidoka	
	1.2 TPM	1.1.6 Distributed MRO Storeroom	1.1.6.1 Inventory Standardisation	
			1.1.6.2 ABC Analysis	
		1.1.7 CMMS	1.1.7.1 Work Order	
		1.2.1 Autonomous Maintenance	1.2.1.1 5 S's	
			1.2.1.2 Visual Control	
			1.2.1.3 Cleaning and Lubrication standards	
		1.2.2 Planned Maintenance	1.2.2.1 Maintenance schedule	
		1.2.3 a) Root Cause Analysis	1.2.3.1 Cause and Effect Diagram	
			1.2.3.2 Five Whys	
			1.2.3.3 Tree diagram	
			1.2.3.4 Fault Tree Analysis	
			1.2.3.5 Brainstorming	
		1.2.3 b) Problem Solving	1.2.3.5 PDCA	
			1.2.3.6 SBCE	
		1.2.4 OEE	1.2.4.1 Eliminating six main losses	1.2.4.1.1 Brainstorming
		1.2.5 Work Order System	1.2.5.1 Waste Elimination	
		2.1.1 Lot size reductions		
2. Production	2.1 JIT	2.1.2 JIT/Continuous flow improvement	2.1.2.1 Finished-Goods Supermarket	
			2.1.2.2 Takt time	
			2.1.2.3 Pitch	2.1.2.3.1 Work Standardisation
			2.1.2.4 Buffer and safety inventories	
			2.1.2.5 Lights-Out Manufacturing	2.1.2.5.1 Work Standardisation
			2.1.2.6 Agile Manufacturing	
			2.1.2.7 One-piece flow or pull production	
			2.1.2.8 In-process supermarkets	
			2.1.2.9 FIFO lanes	2.1.2.9.1 Work Standardisation
			2.1.2.10 Kanban	
			2.1.2.11 Heijunka	2.1.2.11.1 Heijunka box
				2.1.2.11.2 Work Standardisation
			2.1.2.12 Paced Withdrawal	
			2.1.2.13 Runner	
			2.1.2.14 Value Stream Mapping	2.1.2.14.1 Waste Elimination
			2.1.2.15 PDCA	
			2.1.2.16 Jidoka	2.1.2.16 Autonomation
		2.1.3 Pull system	2.1.3.1 Similar process speed	2.1.3.1.1 Work Standardisation
			2.1.3.2 Finished-Goods Supermarket	
			2.1.3.3 One-piece flow plant layout	
			2.1.3.4 Kanban	
			2.1.3.5 Heijunka	2.1.3.5.1 Heijunka box
				2.1.3.5.2 Work Standardisation
			2.1.3.6 Production Scheduling	
		2.1.4 Cellular manufacturing	2.1.4.1 Work Cells	
			2.1.4.2 Counter clockwise flow direction	
			2.1.4.3 Sequential process arrangement	
			2.1.4.4 Closely positioned equipment	
			2.1.4.5 U-, C-, L-, S- or V- cell shapes	
		2.1.5 Cycle time reduction	2.1.5.1 Takt time	
			2.1.5.2 Pitch	
			2.1.5.3 Line balancing	
		2.1.6 Focussed factory production system	2.1.6.1 Work Cells	
		2.1.7 Agile manufacturing strategies	2.1.7.1 Buffer, safety inventory or de-coupling	
			2.1.7.2 IT Systems	
			2.1.7.3 Pull System	
		2.1.8 Quick changeover tecniques	2.1.8.1 SMED	2.1.8.1.1 Work Standardisation
		2.1.9 Bottleneck removal	2.1.9.1 TOC	
		2.1.10 Reengineerd production processes		
	2.2 TPM	2.2.1 Preventive maintenance	2.2.1.1 Condition monitoring	
			2.2.1.2 Maintenance schedule	
		2.2.2 Predictive maintenace	2.2.2.1 Condition monitoring	
			2.2.2.2 New process equipment or technologies	
		2.2.3 Maintenance optimisation	2.2.3.1 Reliability centred maintenance	2.2.3.1.1 MTBF
			2.2.3.2 Risk-based maintenance	
		2.2.4 Planning and scheduling strategies		
		2.2.5 New process equipment or technologies		
3. Strategic	3.1 Policy Deployment	3.1.1 Hoshin Kanri	3.1.1.1 PDCA	
			3.1.1.2 Standardisation	

Figure A.1: Summary of Lean Principles and Tools

ISO 55001	Asset Information and Knolwedge		Asset Lifecycle Management		Risk and Opportunity		Reliability Engineering		Maintenance	
Cl	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools
4.1	4.1.2.3 e)	2.1.2.14				1.2.3 a)				
4.2	4.2.4	2.1.2.14					4.2.4	2.1.2.14		
5.1					5.1 i), 5.1 k)	2.2.3.2, 3.1.1				
5.2			5.2 d)	3.1.1	5.2 d)	3.1.1				
6.1 a)					6.1	1.2.3 a), 1.2.3.6				
						2.2.1, 2.2.2, 2.2.3				
						1.1.5				
6.1 b)					6.1	3.1.1, 1.2.4, 2.2.3.1.1				
6.2.1			6.2.1.3 d)	3.1.1, 2.1.2.15			6.2.1.3 b)	2.1.2.14, 3.1.1, 2.1.2.15	6.2.3.1 d)	2.2.3.1
										3.1.1, 2.1.2.15
6.2.2 b)			6.2.2	1.2.4, 1.2.1	6.2.2.3 b)	1.2.3 a), 1.2.3 b)				
				1.2.2, 1.2.3 a), 1.2.3 b)	6.2.2.3 h)	2.2.3.2				
				2.1.2.15,2.2						
6.2.2 k)					6.2.2.3 b), 6.2.2.3 h)	1.2.3, 2.2.3.2				
7.3					7.3 d)	1.1.5				
7.5 a)					7.5.2 h)	2.1.2.14				
7.5 b)	7.5.3 a), 7.5.3 c)	2.1.3.6, 2.1.2.14								
	7.5.3 d), 7.5.3 k)	2.1.2.15, 1.1.3								
7.5 c)		2.1.2.14, 2.1.2.15, 1.1.3, 1.2.2							7.5.2 c)	2.2.3.1
	7.5.3 l)	1.1.6.2								
7.5 e)	7.5.3 g)	3.1.1								
7.6.1	7.6	3.1.1								
7.6.2	7.6	2.1.2.14, 1.1.3								
7.6.3	7.6	1.1.5.1								
8.1					8.1.4	1.2.3, 2.2.3.2				
8.3					8.3.4	1.2.3				
8.3 c)	8.3.2 c)	2.1.2.14								
9.1						1.2.3 a), 1.2.3 b)	9.1.2.4	2.1.2.15	9.1.1.1 a)	2.2.3.1
9.1 b)	9.1.1.1 d), 9.1.1.2 e)	2.1.2.14								
	9.1.1.2 f)	2.2.3.1.1								
	9.1.1.4	1.2.4, , 2.1.2.2, 2.1.2.3, 1.2.5								
		1.1.2, 2.2.3.1.1								
9.1 d)			9.1.2.5	1.1.3	9.1.2.1	1.2.4, 1.2.5, 2.2.3.1.1				
9.2										
9.3					9.3.2 f)	1.2.3 a), 1.2.3 b)				
10.1					10.1.1 b)	1.2.3 a)				
10.1 a)									10.1.1 a), 10.1.3	2.2.3.1
10.1 b)										1.2.3
10.1 e)										
10.2	10.2 e)	2.2.1.1, 2.2.2.2							10.2	2.2.1, 2.2.2, 2.2.3.1
10.3					10.3.4 d)	1.2.3 a)			10.3.2 a), 10.3.2 b)	2.1.2.15, 1.2.5, 2.2.3.1.1,
										1.2.4, 2.2.3

Figure A.2: Proposed Framework for implementing Lean Practices and Tools to Support ISO 55000 Compliance

Appendix B

Interview Questions

A Framework for Implementing Lean Practices and Tools to Support ISO 55000 Compliance for Physical Asset Management

Jeanne-Marie de Villiers

September 2016

Introduction

Background

- B. Eng (Industrial) – University of Stellenbosch
- M.Eng (Engineering Management) – University of Stellenbosch
- Member of the Asset Care Research Group of the University of Stellenbosch

Purpose of the Interview:
Validation of Master's research thesis

Purpose of the Study
The purpose of this study is to determine how lean tools can be structured in a framework to support the requirements set out in the ISO 55000 Suite of Standards for the effective management of physical assets.

Important Consideration and Information

- This interview will be handled confidentially; the participants will not be identifiable in any way if consent is not provided.

- You can choose whether to be in this study or not. If you volunteer to be in this study, you may withdraw at any time without consequences of any kind. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so.

- Supervisors/coordinators for this study are:

  Dr J.L. Jooste (email: wyhan@sun.ac.za)
  Prof C.J. Fourie (email: cjf@sun.ac.za)

- Please feel free to ask any questions regarding the study or this interview.

Context and Problem

Effective Physical Asset Management (PAM) is imperative to the success and safety of any organisation. This is apparent when considering cases such as the explosion of the Piper Alpha, Britain's biggest oil and gas producing platform. This explosion killed 167 people and occurred due to a lack of safety and maintenance precautions. This realisation led to the development of the highly anticipated ISO 55000 series, an international standard covering the management of physical assets, launched in 2014. Becoming ISO 55000 compliant is the next step in ensuring a company's PAM is up to standard and to avoid the numerous losses associated with poor PAM. However, there is no general model which organisations can take to determine what needs to be done to prepare for ISO 55000. There is also a lack of skills and expertise on how to change the current state of AM within an organisation to adhere to ISO 55000 requirements and receive accreditation.

Lean and PAM have similar fundamentals – creating value for an organisation and its stakeholders. Therefore, lean practices and tools have the potential to advance AM within an organisation and aid ISO 55000 accreditation. This points to the following empirical research question:

"How can lean tools be structured in a framework to support the requirements set out in the ISO 55000 Suite of Standards for the effective management of physical assets?"

The literature study of this research included a review of the PAM Landscape, The ISO 55000 Suite of Standards and Lean. As PAM constitutes a very broad scope, a selection model was used to determine the most important PAM areas, identified through various PAM definitions, The Global Forum on Maintenance and Asset Management (GFMAM), the ISO 55000 Suite of Standards and research students. In the selection model, each subject area was given a rating between 1 and 3, where 1 is low importance and 3 is high importance.

Through the selection model, the scope of research was narrowed to the following PAM areas:

- Asset Information and Knowledge
- Asset Lifecycle Management
- Risk and Opportunity Management
- Reliability Engineering
- Maintenance

The Framework with which this research aims to solve the problem statement was formulated in three consecutive steps. Firstly, the ISO 55000 Family of Standards were investigated and specific requirements were identified as applicable to the above mentioned five PAM areas of focus.

Secondly, a table (Table 1 Page 3) was created, listing the numerous lean tools and practices investigated in the literature study. It should be read from left to right, where each lean concept listed on the column to the right is used as a lean tool to its respective match. For example, Kanban (1.1.1) is a JIT Maintenance Lean practice, but is also used as a tool for a visual control (1.1.5.4), continuous flow (2.1.2.10), and lean pull (2.1.3.4). Also, Kanban uses visual control, work standardisation and quick changeover techniques as tools to create a JIT maintenance system. Furthermore, to avoid redundancy, when tools are listed for a lean concept, it is not listed again, where the table should be read from left to right and top to bottom. For example, visual control (1.1.1.1) acts as a tool for Kanban, but is also listed as a Lean Maintenance JIT practice (1.1.5). Visual control uses tools 1.1.5.1 - 1.1.5.9, which is only listed once and not again when listed as a tool for Kanban (1.1.1).

Finally, the lean practices and tools summarised in step two were evaluated against the requirements chosen in step one and their ability to support these requirements assessed. The final framework is illustrated in Figure 2 Page 4, which is followed by an explanation of its structure and the logic followed in determining which lean tools are adequate to support the ISO 55000 requirements within the scope of this research.

Table 1: Lean Tools

Lean Concept	Lean Bundle	Lean Practice	Lean Tool	
1. Maintenance	1.1 JIT	1.1.1 Kanban	1.1.1.1 Visual Control	
			1.1.1.2 Work Standardisation	
			1.1.1.3 Quick changeover tecniques	
		1.1.2 SMED	1.1.2.1 Work Standardisation	
		1.1.3 Work Standardisation	1.1.3.1 Takt time	
			1.1.3.2 Work sequence	
			1.1.3.3 Standard WIP	
		1.1.4 Takt time	1.1.4.1 Work Standardisation	
		1.1.5 Visual Control	1.1.5.1 5S	
			1.1.5.2 Shadow Tool Board	
			1.1.5.3 Inventory indicators	
			1.1.5.4 Kamishabi	
			1.1.5.5 Kanban	
			1.1.5.6 Andon	
			1.1.5.7 One-piece flow	
			1.1.5.8 Standardised work	
			1.1.5.9 Jidoka	
	1.2 TPM	1.1.6 Distributed MRO Storeroom	1.1.6.1 Inventory Standardisation	
			1.1.6.2 ABC Analysis	
		1.1.7 CMMS	1.1.7.1 Work Order	
		1.2.1 Autonomous Maintenance	1.2.1.1 5 S's	
			1.2.1.2 Visual Control	
			1.2.1.3 Cleaning and Lubrication standards	
		1.2.2 Planned Maintenance	1.2.2.1 Maintenance schedule	
		1.2.3 a) Root Cause Analysis	1.2.3.1 Cause and Effect Diagram	
			1.2.3.2 Five Whys	
			1.2.3.3 Tree diagram	
			1.2.3.4 Fault Tree Analysis	
			1.2.3.5 Brainstorming	
		1.2.3 b) Problem Solving	1.2.3.5 PDCA	
			1.2.3.6 SBCE	
		1.2.4 OEE	1.2.4.1 Eliminating six main losses	1.2.4.1.1 Brainstorming
		1.2.5 Work Order System	1.2.5.1 Waste Elimination	
		2.1.1 Lot size reductions		
2. Production	2.1 JIT	2.1.2 JIT/Continuous flow improvement	2.1.2.1 Finished-Goods Supermarket	
			2.1.2.2 Takt time	
			2.1.2.3 Pitch	2.1.2.3.1 Work Standardisation
			2.1.2.4 Buffer and safety inventories	
			2.1.2.5 Lights-Out Manufacturing	2.1.2.5.1 Work Standardisation
			2.1.2.6 Agile Manufacturing	
			2.1.2.7 One-piece flow or pull production	
			2.1.2.8 In-process supermarkets	
			2.1.2.9 FIFO lanes	2.1.2.9.1 Work Standardisation
			2.1.2.10 Kanban	
			2.1.2.11 Heijunka	2.1.2.11.1 Heijunka box
				2.1.2.11.2 Work Standardisation
			2.1.2.12 Paced Witdrawal	
			2.1.2.13 Runner	
			2.1.2.14 Value Stream Mapping	2.1.2.14.1 Waste Elimination
			2.1.2.15 PDCA	
			2.1.2.16 Jidoka	2.1.2.16 Autonomation
		2.1.3 Pull system	2.1.3.1 Similar process speed	2.1.3.1.1 Work Standardisation
			2.1.3.2 Finished-Goods Supermarket	
			2.1.3.3 One-piece flow plant layout	
			2.1.3.4 Kanban	
			2.1.3.5 Heijunka	2.1.3.5.1 Heijunka box
				2.1.3.5.2 Work Standardisation
			2.1.3.6 Production Scheduling	
		2.1.4 Cellular manufacturing	2.1.4.1 Work Cells	
			2.1.4.2 Counter clockwise flow direction	
			2.1.4.3 Sequential process arrangement	
			2.1.4.4 Closely positioned equipment	
			2.1.4.5 U-, C-, L-, S- or V- cell shapes	
		2.1.5 Cycle time reduction	2.1.5.1 Takt time	
			2.1.5.2 Pitch	
			2.1.5.3 Line balancing	
		2.1.6 Focussed factory production system	2.1.6.1 Work Cells	
		2.1.7 Agile manufacturing strategies	2.1.7.1 Buffer, safety inventory or de-coupling	
			2.1.7.2 IT Systems	
			2.1.7.3 Pull System	
		2.1.8 Quick changeover tecniques	2.1.8.1 SMED	2.1.8.1.1 Work Standardisation
		2.1.9 Bottleneck removal	2.1.9.1 TOC	
		2.1.10 Reengineerd production processes		
	2.2 TPM	2.2.1 Preventive maintenance	2.2.1.1 Condition monitoring	
			2.2.1.2 Maintenance schedule	
		2.2.2 Predictive maintenance	2.2.2.1 Condition monitoring	
			2.2.2.2 New process equipment or technologies	
		2.2.3 Maintenance optimisation	2.2.3.1 Reliability centred maintenance	2.2.3.1.1 MTBF
			2.2.3.2 Risk-based maintenance	
		2.2.4 Planning and scheduling strategies		
		2.2.5 New process equipment or technologies		
3. Strategic	3.1 Policy Deployement	3.1.1 Hoshin Kanri	3.1.1.1 PDCA	
			3.1.1.2 Standardisation	

Table 2: A Framework of Lean Practices and Tools to Support ISO 55000 Compliance

ISO 55001	Asset information and knowledge		Asset Lifecycle Management		Risk and Opportunity		Reliability Engineering		Maintenance	
Cl	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools	ISO 55002	Lean Tools
4.1	4.1.2.3 e)	2.1.2.14				1.2.3.5				
4.2	4.2.4	2.1.2.14					4.2.4	2.1.2.14		
5.1					5.1 i), 5.1 k)	2.2.3.2, 3.1.1				
5.2			5.2 d)	3.1.1	5.2 d)	3.1.1				
6.1 a)					6.1	1.2.3 a), 1.2.3.6				
						2.2.1, 2.2.2, 2.2.3				
						1.1.5				
6.1 b)					6.1	3.1.1, 1.2.4, 2.2.3.1.1				
6.2.1			6.2.1.3 d)	3.1			6.2.1.3 b)	2.1.2.14	6.2.3.1 d)	2.2.3.1
6.2.2 b)			6.2.2	3.1, 1.2.4, 1.2.1	6.2.2.3 b)	1.2.3 a), 1.2.3 b)				
				1.2.2, 1.2.3 a), 1.2.3 b)	6.2.2.3 h)	2.2.3.2				
				2.1.2.15,2.2						
6.2.2 k)					6.2.2.3 b), 6.2.2.3 h)	1.2.3, 2.2.3.2				
7.3					7.3 d)	1.1.5				
7.5 a)					7.5.2 h)	2.1.2.14				
7.5 b)	7.5.3 a), 7.5.3 c)	2.1.3.6, 2.1.2.14, 2.1.3			7.5.3 b)	1.2.3.4, 1.2.3.5				
	7.5.3 d), 7.5.3 k)	2.1.2.15, 1.1.3, 1.1.6.2								
7.5 c)		2.1.2.14, 2.1.2.15, 1.1.3, 1.2.2							7.5.2 c)	2.2.3.1
	7.5.3 l)	1.1.6.2								
7.5 e)	7.5.3 g)	3.1.1								
7.6.1	7.6	3.1.1								
7.6.2	7.6	2.1.2.14								
7.6.3	7.6	1.1.5.1								
8.1					8.1.4	1.2.3 a), 1.2.3 b), 2.2.3.2				
8.3					8.3.4	1.2.3 a), 1.2.3 b)				
8.3 c)	8.3.2 c)	2.1.2.14								
9.1							9.1.2.4	2.1.2.15	9.1.1.1 a)	2.2.3.1
9.1 b)	9.1.1.1 d), 9.1.1.2 e)	2.1.2.14								
	9.1.1.2 f)	2.2.3.1.1								
	9.1.1.4	1.2.4, , 2.1.2.2, 2.1.2.3, 1.2.5								
		1.1.2, 2.2.3.1.1								
9.1 d)			9.1.2.5	1.1.3	9.1.2.1	1.2.4, 1.2.5, 2.2.3.1.1				
9.2					9.2.2	1.2.4.2				
9.3					9.3.2 f)	1.2.3 a), 1.2.3 b)				
10.1					10.1.1 b)	1.2.3 a)				
10.1 a)									10.1.1 a), 10.1.3	2.2.3.1
10.1 b)										
10.1 e)										
10.2	10.2 e)	2.2.1.1, 2.2.2.2							10.2	2.2.1, 2.2.2, 2.2.3.1
10.3					10.3.4 d)	1.2.3 a)			10.3.2 a), 10.3.2 b)	2.1.2.15, 1.2.5, 2.2.3.1.1,
										1.2.4, 2.2.3

Framework Explanation

The proposed framework should be read with the Lean practices and tools summary (Figure 1) and ISO 55001 and ISO 55002 documents at hand.

The developed framework takes the form of a table, with the y-axis representing the ISO 55001 clauses applicable to each of the chosen PAM subject areas. Each ISO 55001 clause is matched with an ISO 55002 clause and lean practice or tool on the x-axis. The matched ISO 55002 clauses provide information on why the specific ISO 55001 clause is related to the PAM subject group it is categorized under. For example, Requirement 9.1 in the ISO 55001 document addresses the establishment of processes for performance monitoring. Even though this clause does not mention asset, information and reporting in the ISO 55001 document, it is mentioned numerously in the ISO 55002 document. For example, ISO 55002 9.1.1.1 d) states that documented information should be used to facilitate corrective action and decision-making.

The rest of this section will describe the logic behind the lean practices and tools chosen to support respective ISO 55001 clauses, where reference will be given to content within the ISO 55002 document, where applicable.

Lean practices and tools to support ISO 55000 requirements related to Asset, Information and Knowledge

Value Stream Mapping involves mapping the information flow from supplier to customer. In doing so, it will assist in defining the organisation's internal and external information flow. It will also assist in determining stakeholder requirements for recording financial and non-financial information, as stakeholders should be involved in mapping the external information flow of the organisation. This will support achieving requirements 4.1 and 4.2 in the ISO 55001 document.

ISO 55001 7.5 b) addresses the determination of information requirements to support its assets, asset management (AM), the asset management system (AMS) and the achievement of organizational objectives. ISO 55001 7.5 b) requires an organisation to determine the attributive and quality requirements of its identified information. ISO 55002 7.5.3 a) states that when determining its information requirements, the organization should consider the value of the information to enable decision-making. ISO 55002 7.5.3 c) requires an organisation to get input from relevant stakeholders when determining the types of information needed for decision-making. This can be supported by a VSM, as its main purpose is to determine the information stream that brings value to the organisation and eliminating all non-value-adding activities, where stakeholder should be included in defining the value stream. ISO 55002 7.5.3 d) requires an organisation to establish and continuously improve controls, specifications and level of accuracy of data. This can be supported by applying work standardisation and PDCA to establish and improve controls and specifications, respectively. ISO 55001 7.5 b) further requires an organisation to determine how and when information is to be collected, analyzed and evaluation. This can be achieved by viewing data as the product to be "produced" and using VSM to map the flow of data and production scheduling to plan exactly when data is to be generated, collected, analyzed or evaluated. When determining an organisations' data requirements, ISO 55002 7.5.3 k) requires an organisation to consider the flow of data and its integration to planning, operational and reporting technology systems, which should be aligned with the size, complexity and capability of the organization. This can be supported through the application of VSM, as the flow of information throughout the organisation is mapped and studied, in collaboration with employees from all departments.

When considering information management, ISO 55001 7.5 c) requires an organisation to specify, implement and maintain processes for managing its information. VSM and production scheduling will enable the organisation to specify its processes for managing information, while PDCA, work standardization and planned maintenance will support its implementation and maintenance. An example of using planned maintenance to maintain an organization's information management processes is periodically performing maintenance on its IT systems to ensure it is at all times up to date and valid. ISO 55002 7.5.3 l) requires an organisation to specifically maintain the appropriate quality and timeliness of the information and emphasize the importance of prioritizing data, as its collection can be costly. ABC Analysis will enable organisation to rank the importance of data, which can be used as a focus point for prioritization. ISO 55001 7.5 e) requires an organisation to ensure consistency and traceability between financial and technical and all non-financial data. It further states that is should be consistent to the extent that all legal and regulatory requirement as well as stakeholders' requirements and organisational objectives are met. Hoshin Kahnri is a strategic lean tool that will enable the organisation to focus on the organization's objectives and legal, regulatory and stakeholder requirements, while planning its day to day tasks and ensuring that all levels of the organisation work towards the same goals. In other words, it will ensure vertical and horizontal alignment.

ISO 55001 7.6.1 requires an organisation to document information as stipulated in The ISO 55000 Family of Standards, for applicable legal and regulatory requirements and for the effectiveness of the AMS. Hoshin Kahnri can be used as a tool to align documenting information according to the ISO 55000 Family of Standards and applicable legal and regulatory requirements. Furthermore, ISO 55001 7.6.2 requires an organisation to consider specific attributes when creating and updating documented information. According to ISO 55002 7.6, when creating and updating documented information, an organisation need to put controls in place to ensure that the information is appropriate and consistent. The appropriateness of information can be confirmed by referring to the information flow in the VSM and information consistency can be obtained through the application of work standardization. ISO 55001 7.6.3 requires an organisation to control the documented information to ensure availability and protection. Lean's 5 S's can be used to ensure documented information is organized and available.

ISO 55001 8.3 c) states that when an organisation outsources any activities, they need to determine the processes and scope for sharing knowledge and information with its contracted service providers. This can be determined by applying lean's VSM to the organisation's information flow.

ISO 55001 9.1 addresses establishing processes for performance monitoring. According to ISO 55002 Requirement 9.1.1.1, this specifically refers to an organisation's assets, AMS and AM activity. Even though this requirement does not specifically mention information, knowledge or reporting in the ISO 55001 document, it is addressed numerous times in the ISO 55002 document.

ISO 55002 9.1.1.1 d) states that when the organisation develops these processes, it should consider the use of documented information to facilitate corrective action and decision making. This process can be established through a VSM. ISO 55002 9.1.1.2 e) states that when establishing processes for monitoring performance, it should address the organisation's ability to compile and report information to those responsible for the AMS and asset activities. By mapping out a VSM, an organization will be able to realise its ability to aggregate and report on information, as each step of the information flow is investigated in detail. ISO 55002 9.1.1.2 f) further states that the processes for monitoring performance should address the quality, reliability and completeness of financial and non-financial asset information. The lean tools studied in this thesis does not involve processes to monitor performance and address quality and completeness of financial and non-financial information. Calculating MTBF, where failure in the context of information is failing to provide accurate or valid information, can be used to monitor the reliability of the organisation's information.

ISO 55002 9.1.2.5 and ISO 5002 9.1.2.6 requires consistency, traceability and accuracy regarding asset related financial and non-financial terminology throughout all organizational functions. The lean tools investigated in this study will not satisfy these requirements.

ISO 55002 9.1.1.4 requires an organisation to make use of data to determine trends and obtain information on asset performance, in order to determine if an organisation's policy and objectives are achieved and also to determine areas for corrective action or improvement. Lean tools that can be used to facilitate corrective action and decision making include the calculation and use of information related to OEE, takt time, pitch, the efficiency of the work order system, SMED or MTBF.

Requirement 9.2 and 9.3 in the ISO 55001 document addresses conducting internal audits and reviewing the organisation's AMS at planned intervals, respectively. According to ISO 55002 9.2.1, the information obtained through the internal audits should be provided to top management. ISO 55002 9.3.5 requires an organisation to retain information as proof that reviews were conducted and to communicate the results of the reviews to relevant stakeholders. The lean tools studied in this thesis will not specifically assist in achieving these requirement.

ISO 55001 10.1 addresses nonconformity and corrective action, where ISO 55001 10.1 (e) addresses retaining documenting information in support of the nature of nonconformities or incidents that might have occurred and the results of corrective actions taken. The lean tools studied in this thesis does not provide methods for effectively retaining documented information. Requirement 10.2 addresses preventive action, where ISO 55002 10.2 (e) requires an organization to use appropriate sources of information when establishing and maintaining preventive action. Appropriate sources of information when considering preventive action is by applying condition monitoring on assets or extracting information from technology that can predict the condition of the organisation's assets.

Lean practices and tools to support ISO 55000 requirements related to Asset Lifecycle Management

ISO 55001 4.3 requires an organisation to determine the scope of the AMS. According to ISO 55002 4.3 b), this should include information on external contractors which meets the requirements of the AMS for th activities in different asset life cycle stages. The lean tools studied in this thesis is not adequate to support this requirement.

ISO 55001 5.2 requires an organisation to establish an AM policy, which, according to ISO 55002 5.2 d), should include commitments to decision-making criteria regarding asset life cycle costs. The first step of lean's Hoshin Kahnri can be used to determine organisational policies, where the following steps focusses on achieving these policies. Therefore, it would be able to support this requirement.

Requirement 6.2.1 addresses establishing AM objectives, which typically includes goals regarding life cycle cost and life expectancy (ISO 55002 6.2.1.3 d)). Hoshin Kahnri will enable an organisation to establish objectives aligned with the organisation's AM policy, which should consider decision-making criteria regarding asset life cycle costs. PDCA can be used as a bottom-up approach to establish AM objectives regarding life cycle cost and life expectancy. Requirement 6.2.2 addresses planning to achieve the AM objectives, which was established in the previous requirement. When considering asset lifecycle management, Requirement 6.2.2 b) states that the organisation should determine and document methods and processes for managing the organisation's assets over their lifecycle. The ALM process was studied in Section 2.1.2. To recap, these steps included planning, evaluate and design, create and procure, operate, maintain, modify and dispose. When considering each step of the ALM process, OEE can be used to determine how effective an asset is operating and eliminate the six main losses associated with unnecessary equipment down time. Autonomous maintenance, planned maintenance, root cause analysis and problem solving, preventive maintenance, predictive maintenance, planning and scheduling strategies, maintenance optimisation and/or new process equipment and technologies can be used to maintain the asset, where applicable PDCA events can be used to identify improvement opportunities to modify or upgrade the asset in order to possible extend its life. Requirement 6.2.2 i) addresses the financial and non-financial implications of the AMP, where life cycle costs should be considered. None of the lean tools studied in this thesis will assist in determining the financial implications of the different life cycle phases of assets.

Requirement 9.1 d) addresses analysing, evaluating and reporting on financial and non-financial AM performance. According to ISO 55002 9.1.2.5, establishing a common understanding on how asset portfolios, asset systems and individual assets are broken down in support of asset lifecycle management, may be useful. Lean's work standardisation may be useful to standardise how these are broken down, which will provide a basis for establishing a common understanding. If this is not standardised, it may run a risk of creating confusion among relevant individuals.

Lean practices and tools to support ISO 55000 requirements related to Risk and Opportunity

ISO 55001 4.1 states that an organisation shall determine internal and external issues that may affect its ability to achieve the intended outcome of its AMS. Brainstorming and RCA can be used to detect internal and external risks. According to ISO 55002 4.1.2.3 j), when an organisation is evaluating its internal context, it may include evaluating its risk management plans. The lean tools studied in this thesis is not adequate to help an organisation evaluate its risk management plans. ISO 55001 4.3 addressed determining the scope of the AMS, where, according to ISO 55002 4.3 d), this may include an organisation's accountability for certain risks beyond the operation or use of its assets. None of the lean tools studied in this thesis will assist in determining an organisation's accountability for certain risks beyond an assets useful life.

ISO 55001 5.1 requires top management to demonstrate leadership and commitment with respect to the AMS. Commitment can be demonstrated by addressing asset related risks and including them into the organisation's Risk Management (RM) processes (ISO 55002 5.1 i)). It can also be demonstrated by aligning AM and the AMS to the organisation's approach to RM ((ISO 55002 5.1 k)). Asset related risks can be addressed by performing risk-based maintenance on relevant assets, which can also be a means of integrating AM with RM. Hoshin Kanri can be used to align asset-related activities with the organisation's Risk Management process. ISO 55001 5.2 requires an organisation to establish an AM policy, which, according to ISO 55002 5.2d), should include commitments to decision-making criteria regarding benefits and risks of assets. The first step of lean's Hoshin Kanri can be used to establishing organisational policies, where the following steps focusses on achieving these policies. Therefore, it would be able to support this requirement.

ISO 55001 6.1 focusses mainly on incorporating the needs of the organisation's stakeholders and risks and opportunities related to the organisation's internal and external issues in the organisation's AMP. The organisation need to plan a) actions to address risks and opportunities, while considering how they can change with time and b) how to integrate and implement the actions determined in a) into its AMS processes and evaluate their effectiveness. Cause and effect diagrams, the five whys, tree diagram, brainstorming and SBCE can be used to determine the root causes of risks and a fault tree analysis can be used to determine the likelihood of their occurrence, which will be needed to determine which actions are applicable to address these risks. Preventive maintenance, predictive maintenance, maintenance optimisation or visual control can be used as actions to implement to prevent risks from occurring, where applicable. Hoshin kahnri can be used to align actions to mitigate risks with the organisation's AMS. OEE and MTBF can be used to calculate the effectiveness of actions taken to mitigate risks of downtime and failure.

ISO 55001 6.2.2 addresses planning to achieve AM objectives, where processes to address risks and opportunities associated with managing the assets, should be established. According to ISO 55001 6.2.2 k) risks and opportunities should be identified and assessed and appropriate treatment and monitors for managing these risks should be implemented. Requirement ISO 55002 6.2.2.3 b) states that when identifying risks and opportunities, potential events, their causes, likelihood and consequences and should be identified. This can be achieved through root cause analysis and problem solving. ISO 55002 6.2.2.3 h) states that when determining relevant treatment of risks, it should be established whether risks should be addressed directly, avoided, reduced, tolerated or transferred. Risk-based maintenance can be used to satisfy this requirement, where relevant.

ISO 55001 7.3 requires relevant individuals to be aware of the risks and opportunities that their work present, and how they relate to each other. Awareness can be created through visual control, such as Andon. Requirement 7.5 addresses the determination of the asset's, AM and AMS information requirements. According to ISO 55002 7.5.2 h), the organisation should determine its asset information requirements related to its RM process. This can be achieved by applying VSM to the organisation's RM process. ISO 55002 7.5.3 b) states that the organisation should also consider the information requirements to suit the level of risk an asset poses. There are no lean tools that can specifically assist in determining information requirements appropriate to the risk an asset pose.

ISO 55001 8.1 requires an organisation to plan, implement and control processes to meet necessary requirements for treating and monitoring risks, using the approach described in ISO 55001 6.2.2. The lean tools to satisfy this process has already been established. ISO 55001 8.3 addresses assessing and controlling risks associated with outsourcing any activities that can have an impact on achieving AM objectives. Root cause analysis and problem solving tools can be used to identify risks, their root cause and likelihood.

ISO 55001 9.1 d) states that an organisation should evaluate and report on the effectiveness of its risk and opportunity management processes. ISO 55002 9.1.2.1 states that this can be done in the form of internal and external audits. OEE and MTBF can be calculated to determine the effectiveness of equipment. If an asset's OEE is high, it states that its downtime is minimised, which is measure of how effectively the risk of downtime is managed. In contrast, if equipment’s MTBF is high, it indicates a high failure rate, which illustrates that risk of failure is not being controlled effectively. If an organisation uses a work order system to address risks, the effectiveness of the work order system can be calculated based on the time it takes for a work order to be processed.

ISO 55001 9.2 requires an organisation to conduct internal audits at planned intervals, where the focus of these audits should be based on the risk an asset or the AMS poses. None of the lean tools studied in this thesis provides a basis for internal audits. ISO 55001 9.3 f) addresses periodic review of the changes in the profile on risk and opportunity. This includes periodically reassessing the risks certain assets hold. Root cause analysis and problem solving can assist in supporting this requirement. ISO 55001 9.3 e) required an organisation to periodically review opportunities for continual improvement. This can be done through PDCA and Value Stream Mapping.

ISO 55001 10.1 required an organisation to assess the risk of corrective action, should a nonconformity of incident occur. This can be done through root cause analysis tools. ISO 55001 10.3 addresses continuous improvement of its AM and the AMS. According to ISO 55002 10.3.4), when opportunities for continuous improvement is identified, possible risks to be incurred should be performed. RCA tools can be used to determine possible risks as a result of implementing continuous improvement activities.

Lean practices and tools to support ISO 55000 requirements related to Reliability Engineering

ISO 55001 4.2 requires an organisation to determine the expectations of customers and users regarding reliability. When conducting a value stream, the first step is specifying value from the standpoint of the end customer. This may require determining customer expectations regarding reliability.

ISO 55001 6.2.1 includes the establishment of AM objectives. According to ISO 55002 6.2.1.3 b), these AM objectives should include reliability parameters. When implementing a value stream, the customer as expectation of reliability will be determined. This can act as a basis for establishing AM objectives regarding reliability, as a lean organisation's focus should always be on creating value for the end-user. Hoshin Kanri and PDCA can be used as top-down and bottom up tools for creating AM objectives, respectively.

ISO 55001 9.1 addresses developing processes for the systematic measurement, monitoring and evaluation of the organisation’s assets, AMS and AM activity regularly. According to ISO 55002 9.1.2.4, when considering continuous improvement, the organisation can gain knowledge on new AM technology and practices, which may include reliability and predictive technologies to assess the procurement or modification of assets. None of the lean tools studied in this chapter can assist in gaining knowledge on new technology. PDCA can be implemented, where its focus can be on the improvement of reliability through new technology.

Lean practices and tools to support ISO 55000 requirements related to Maintenance

ISO 55001 6.2.1 states that an organisation should establish AM objectives, which, according to ISO 55002 6.2.3.1 d), should include objectives related to asset conditions. The application of RCM to assets will help define which conditions an asset need be in order to perform optimally, which can serve as a basis for determining objectives regarding asset conditions. As mentioned previously Hoshin Kanri and PDCA can be used as top-down and bottom-up approaches for the establishment of AM objectives.

ISO 55001 7.5 addresses the determination of the asset's AM and AMS information requirements. According to ISO 55002 7.5.2 c), the organisation should determine its asset information requirements related to an asset's physical attributes and condition, which falls within the scope of condition monitoring. By performing RCM on relevant assets, physical asset operational requirements will be determined, which can serve as a basis for determining which information need be obtained regarding an asset's physical attributes and condition to minimise downtime.

ISO 55001 9.1 addresses developing processes for the systematic measurement, monitoring and evaluation of the organisation’s assets, AMS and AM activity regularly. According to ISO 55002 9.1.1.1 a), this may include setting proactive indicators such as condition or capacity indicators. The application of RCM will help determine condition indicators when establishing physical asset operational requirements.

ISO 55001 10.1 addresses corrective action, should nonconformity or an incident occur. ISO 55001 10.1 a) states that the organisation should act, control and correct incidents or nonconformity and deal with the consequences. If RCM is applied, where applicable, maintenance tactics on certain assets might be corrective. This will help the organisation to take appropriate action, as the possibility of the occurrence of failure has already been considered and corrective action already defined.

ISO 55001 10.2 states that an organisation need to establish processes to proactively identify possible failures and evaluate whether preventive action need be taken. This requirement can be supportive by preventive and predictive maintenance. RCM can be used to determine the feasibility of using preventive action, should failure occur.

ISO 55001 10.3 requires an organisation to continually improve the adequacy, suitability and effectiveness of its corrective and preventive action. This can be done through the implementation of PDCA to corrective and preventive action. The calculation of OEE, MTBF and the efficiency of the organisation's work order system can be used as part of the PDCA cycle as metrics to determine the effectiveness of corrective and preventive action, as it incorporate equipment availability, failure rate and how efficiently corrective and preventive action is being actioned, where applicable. If OEE is high, it states that equipment downtime is low, which indicates an effective maintenance system. If MTBF is low, the number of equipment failures are low, which also indicates an effective maintenance system. Continually performing RCM and RBM will also enable an organisation to review the suitability of corrective or preventive action on its assets, where applicable.

Validation

1. What is your background regarding Lean, ISO 55000 and/or Physical Asset Management?

2. Considering the research methodology that was followed, what is your opinion on the *potential* of the proposed framework as a tool to advance Physical Asset Management in an organisation and support ISO 55000 accreditation?

3. In your opinion, what are the *strengths* of the proposed framework and methodology that was followed?

4. In your opinion, what are the *weaknesses* of the proposed framework and methodology that was followed?

5. Please comment on the following *structural aspects* of the proposed framework:

6. In your opinion, what *improvements* can be made to the proposed framework?

7. In your opinion, what value do you believe the proposed framework would add to the PAM environment? Would you utilise the framework? If not, please substantiate as to why you would not.

8. Do you have any additional comments?

Appendix C

Responses from Participants

A Framework for Implementing Lean Practices and Tools to Support ISO 55000 Compliance for Physical Asset Management

Jeanne-Marie de Villiers

September 2016

Questions and Participant Responses

1. **What is your background regarding Lean, ISO 55000 and/or Physical Asset Management?**

P1: *I have been involved in the field of Physical Asset Management for 10 years now. I started at the London Underground (LU), where I worked as a project development manager and oversaw project lifecycle activities and capital delivery for many asset replacement and refurbishment projects. I then started the role of an Asset Development Planner within the same organization, where I lead the improvement of Physical Asset Management across LU to obtain PAS 55 certification. Thereafter, I moved to a different department within LU, where I developed tools and systems for the effective collaboration between the maintenance, projects and operations departments. After 5 years at LU, I moved to an AM Consultancy firm, where I worked as an AM consultant for eight months, where after I was offered the position of a Senior AM consultant at eAsset Management. At eAsset Management, my main role was to assist organisations in becoming ISO 55 000 compliant through training and GAP assessments. In—between, I worked at the Institute of Asset Management on a voluntary basis for six years, where I am currently a Chair Member at the Next Generation Institute of Asset Management working on professional development projects.*

P2: *P2 sent the researcher his Biography to assist with this question.*

P2 started his career at Ford Motor Company, with a degree in Mechanical Engineering, where he spent a few years rotating through different positions, including maintenance, in order to gain a Chartered Engineering status. He soon became involved in process improvement, where he set up the first Statistical Process Control (SPC) application in the plant, run by the workforce, and gained the position as a Quality Supervisor. In this position, P2 was mainly responsible for end—of—line teams performing condition monitoring, visual appearance and quality tests, where he achieved a 23% annual drop in warranty claims. With his success as a Quality Supervisor, he started working as an internal quality consultant in Ford's world-class Engineering Quality Improvement Programme and achieved his Sig Sigma Master Black Belt (MBB). Network Rail approached P2 to head their Maintenance Six Sigma Programme, which he accepted, and managed to save the organisation up to 1.6 Million GBP/ Annum signed-off Savings. P2 is also trained in Lean techniques and has assisted Network Rail staff in running a number of lean workshops. P2 is currently Network Rail's Reliability Process Manager, with his main focus being on Design for Reliability (DFR), where he incorporates a raft of reliability tools throughout the design process. P2 is currently also assisting Network Rail in satisfying certain requirements set out in the ISO 55000 Family of Standards.

P3: *To assist in this question, P3 provided the researcher website links which contains information on his background and working history. P3 is an internationally recognised global AM consultant, with over 30 years of experience in the industry. He is the co-founder and director of an internationally—recognised organisation that serves as a supplier to the Institute of Asset Management. He is also a co—founder and adviser of the Asset Care Research Group of the University of Stellenbosch and hosts numerous short courses on Physical Asset Management and ISO 55000 across the world. He is a member of the Technical Committee for Asset Management Systems, who was responsible for the development of the ISO 55000 family of standards. He is furthermore also an endorsed PASS 55 consultant/assessor, a member of the Institute of Asset Management (IAM), Southern African Asset Management Association (SAAMA) and a board member of the Association of Maintenance Professionals (AMP).*

P4: *In 1998, I received my Bachelor's degree in Industrial Engineering from the University of Johannesburg, where after I started working for Mercedes-Benz South Africa as a Continuous Improvement Specialist. At Mercedes Benz, my key focus was on streamlining their production system using lean tools, such as line balancing and optimising line speed. In 2006 I received my lean certification and had the opportunity to represent Mercedes SA in Germany, where I did numerous projects in Total Productive Maintenance. To enhance my understanding of Lean and the complexity of certain manufacturing problems, I received my green belt in Six Sigma also in 2006. In 2009, I started working for South African Breweries as a Manufacturing Development Consultant, where I was responsible for the identification, coordination and active participation in strategic and systematic value chain improvement initiatives using various lean tools, such as waste elimination, overall equipment effectiveness (OEE) and autonomous maintenance. I am currently employed at Nestle SA as a Market Lean Manager, where my primary purpose is to create and empower teams across different functional departments with the common goal of improving the manner which the value stream satisfies consumers and customers.*

2. **Considering the research methodology that was followed, what is your opinion on the *potential* of the proposed framework as a tool to advance Physical Asset Management in an organisation and support ISO 55000 accreditation?**

P1: *I consider it to be a very useful framework in showing the synergy between lean and Asset Management and how the different lean tools can support ISO 55000 accreditation.*

P2: *When considering how lean tools support PAM and applicable ISO 55000 requirements, the developed framework clearly points you in the right direction and as such, sets out exactly what it intends to.*

P3: *You have followed a very logical and sound research methodology and the framework achieves its objectives, which is to illustrate the lean tools applicable to satisfying certain ISO 55000 requirements. It has great potential within the AM industry.*

P4: In my opinion, the research methodology you followed is one hundred percent sound. The ISO 55000 standard is not definitive as to what tools you need to use. The correlations in the framework that you developed is correct and will assist in bridging that gap.

3. **In your opinion, what are the *strengths* of the proposed framework and methodology that was followed?**

P1: *It is very good to have identified a synergy between lean and AM. There is not much out there on this specific topic. The framework holds a lot of benefit to organisations.*

P2: *The framework encompasses a great amount of powerful lean tools.*

P3: *It provides orientation and cross-referencing.*

P4: *Firstly, your framework is very detailed and you have incorporated all the relevant Lean practices and tools. Secondly, with the numerous years of experience I have in lean and in the Physical Asset Management environment, I can for sure say that the lean tools that you have chosen are very pragmatic. It is not "pie in the sky".*

4. In your opinion, what are the *weaknesses* of the proposed framework and methodology that was followed?

P1: *I would have included Asset Management Strategy and Planning and Asset Management Decision-Making to your Physical Asset Management focus areas. However, the methodology you used to choose you Physical Asset Management focus areas is very logical and sound. What you have developed is a good starting point and I would suggest Asset Management Strategy and Planning and Asset Management Decision-Making be added at a later stage. There is no one right answer on which Physical Asset Management areas to focus on.*

P2: *The tools are more reactive than proactive. However, this might be due to the way the clauses are written. Focus should be given on more upstream processes. Even though it is useful having a framework illustrating the different lean tools and practices that supports the different ISO 55000 clauses, I would prefer it to be in the form of a process. This can perhaps be a recommendation for future research.*

P3: *Not specific enough in the sense that it does not specify exactly in how the chosen lean practices or tools are relevant to the clause. It would also be useful if you could include practical examples on how the various lean techniques reinforce Asset Management, but I do understand that it might not be within the scope of your thesis.*

P4: *Organisations see lean as a "big monster" with a lot of legs which is almost unachievable. There are certain lean concepts that must be in place as a basis before any other lean tools can be implemented. For example, lean maintenance tools must be implemented before lean production tools are even considered. Only when lean maintenance and lean production is perfected, can lean quality tools be considered. Also, lean maintenance cannot be effective if the 5 S's are not in place. The fact that your framework does not illustrate the sequence of which the lean tools should be implemented is a weakness for me.*

5. Please comment on the following *structural aspects* of the proposed framework:

P1:

- *How would you rate the ease of understanding the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  The framework has a lot of detail, which makes it slightly hard to follow. However, the way it is set out is very logical, so I would say good.

- *What is your impression on the structure of the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  I especially liked the fact that you also incorporated the ISO 55002 Clauses.

- *How would you rate the flexibility / adaptability of the framework (ability to apply relevant steps to different environments in different organisations)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☐ Very Good ☒

- *How would you rate the comprehensiveness of the framework (referring to many or most of the relevant aspects)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  I would nearly give a rating of five, but because it does not include Asset Management Strategy and Planning and Asset Management Decision Making as a Physical Asset Management focus areas, I give it a rating of 4.

P2:

- *How would you rate the ease of understanding the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  It would be easier to read if the lean tools are written out in the framework as opposed to referencing it to another table.

- *What is your impression on the structure of the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  I would make Table 1 simpler or clearly explain how it should be interpreted. For example, the fact that certain tools are mentioned twice is confusing. I would find a way to eliminate that or explain it clearly.

- *How would you rate the flexibility / adaptability of the framework (ability to apply relevant steps to different environments in different organisations)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

- *How would you rate the comprehensiveness of the framework (referring to many or most of the relevant aspects)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  There is a great amount of confusion in the working environment on what lean exactly encompass. It is important that you define exactly what you believe lean is. There are a lot of lean practices and tools in your table that I do not regard as lean. When I consider your definition on lean, which is to eliminate waste and increase value, I do believe that the list of tools in your Framework is very comprehensive.

P3:

- *How would you rate the ease of understanding the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☐ Very Good ☒

- *What is your impression on the structure of the framework?*
  Very Poor ☐ Poor ☐ Fair ☒ Good ☐ Very Good ☐

  If you use more colour to emphasise the different Physical Asset Management areas and add more information on the relevance of the specific lean tools to the ISO 55000 clauses, I would give it a rating of 4.

- *How would you rate the flexibility / adaptability of the framework (ability to apply relevant steps to different environments in different organisations)?*

  Very Poor ☐ Poor ☐ Fair ☒ Good ☐ Very Good ☐

  If you add a column illustrating the relevance of the lean tool to Physical Asset Management, I would give it a rating of 4.

- *How would you rate the comprehensiveness of the framework (referring to many or most of the relevant aspects)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  The framework is very comprehensive when considering the lean tools and ISO 55000 clauses that it incorporates.

P4:

- *How would you rate the ease of understanding the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

- *What is your impression on the structure of the framework?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☐

  What you have managed to do when structuring your framework, and what I quite liked about it, is you categorised it according to your focus Physical Asset Management areas, which makes it quite clear from the beginning. I would have given it a "Very Good" rating if these areas were emphasised a bit more – put in capital letters, different colours and numbered. Just make it "pop out" more. You are very specific in your numbering system with the lean tools and ISO 55001 and ISO 55002 clauses. If this is incorporated throughout your Framework, I would give you a rating of 5.

- *How would you rate the flexibility / adaptability of the framework (ability to apply relevant steps to different environments in different organisations)?*
  Very Poor ☐ Poor ☐ Fair ☐ Good ☒ Very Good ☒

The lean tools that you use and the clauses in general are very generic and you can use it worldwide. I cannot give you a rating of five, because it has not been applied to any organisation yet. Therefore, I give you a 4.5.

- *How would you rate the comprehensiveness of the framework (referring to many or most of the relevant aspects)?*

  Very Poor ☐ Poor ☐ Fair ☐ Good ☐ Very Good ☒

6. **In your opinion, what *improvements* can be made to the proposed framework?**

P1: *All the previous mentioned comments. However, I do understand that it might be out of the scope of your project. I would be happy if you could recommend them for future research. I also recommend for future research that this framework be developed into a process, where training packets and practical examples are incorporated.*

P2: *My previous mentioned comments. Write out the lean tools rather than referencing it in another table. I do understand that the clauses cannot be written out, so writing out the lean tools will be your best bet in simplifying the framework.*

P3: *My comments you've got. Make it bigger, use symbols or colour coding to illustrate the relevance of the lean tools, use more colour in general. I will give you examples on how we use colour coding on our posters to emphasize certain concepts.*

P4: *All the above mentioned.*
In summary, this includes: Emphasizing your different Physical Asset Management focus areas more through capital letters/ colour and keeping your numbering system consistent in your framework. I would also illustrate the sequence of which the lean tools should be implemented and incorporate change management somehow in your framework.

7. **In your opinion, what value do you believe the proposed framework would add to the PAM environment? Would you utilise the framework? If not, please substantiate as to why you would not.**

P1: *I would definitely use the developed framework and consider it to be a very valuable tool. I think that a lot of organisations do not know where to start implementing the requirements within the Standard and this will assist them greatly.*

P2: *As mentioned earlier, the framework definitely points you in the right direction when considering becoming ISO 5000 compliant. I would use the framework as a guideline to determine which tools to use to possibly support ISO 55000 compliance. Especially if you make my recommended changes. I would, however, find a process more useful.*

P3: *Significant Value. Significant contribution to the body of knowledge surrounding the implementation of ISO 55000. I think you are doing important work. I would definitely utilise it, absolutely. Even just relating Lean with Physical Asset Management, there is not much out there. Most organisations are on some kind of Asset Management improvement journey. If you give them any toolkit, focus or structure to improve it, it is very useful.*

P4: *I would use the proposed framework in the sense that it gives a very clear outline as to which tools to use against which clause. It is very specific in that regard, which simplifies the implementation strategy for the business. I think the only thing that I would add, which might be out of your scope, is illustrating how you deliver it to those who execute it in the field and the change management within the organisation. The most critical element of the introduction to any new initiative is the change management that goes with the initiative. If you can, in some way, bring change management into your framework, it will help greatly.*

8. Do you have any additional comments?

P1: *No*

P2: *No*

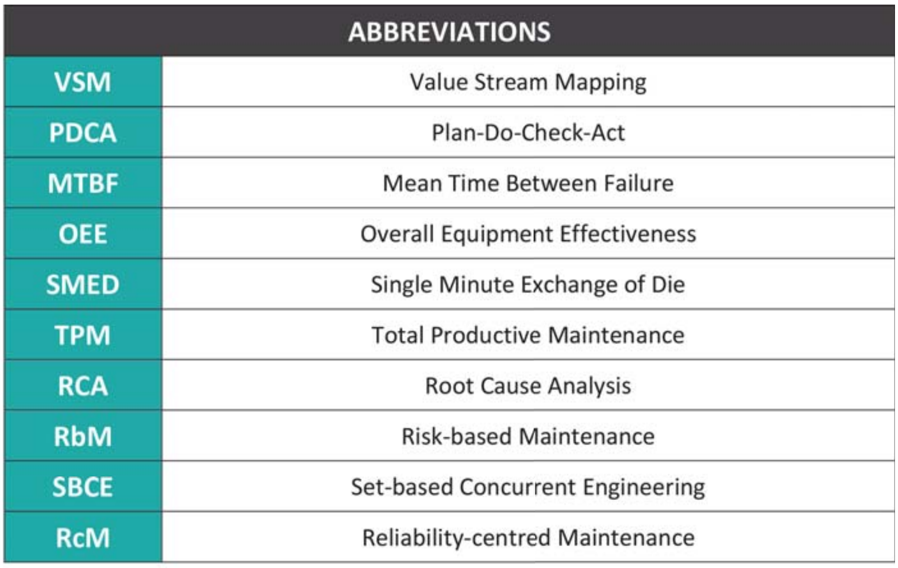
P3: *No*

P4: *No*

Appendix D

Final Framework

Due to space constraints, the Final Framework, illustrated in Figure D.3, D.4, D.5, D.6 and D.7 is divided in five. This should be read with the summary of lean principles and tools, illustrated in Figure D.2, and the ISO 55000 Family of Standards at hand. Figure D.1 lists the abbreviations in Figure D.2.



ABBREVIATIONS	
VSM	Value Stream Mapping
PDCA	Plan-Do-Check-Act
MTBF	Mean Time Between Failure
OEE	Overall Equipment Effectiveness
SMED	Single Minute Exchange of Die
TPM	Total Productive Maintenance
RCA	Root Cause Analysis
RbM	Risk-based Maintenance
SBCE	Set-based Concurrent Engineering
RcM	Reliability-centred Maintenance

Figure D.1: Lean Abbreviations

Lean Concept	Lean Bundle	Lean Practice	Lean Tool	
1. Maintenance	1.1 JIT	1.1.1 Kanban	1.1.1.1 Visual Control	
			1.1.1.2 Work Standardisation	
			1.1.1.3 Quick changeover techniques	
		1.1.2 SMED	1.1.2.1 Work Standardisation	
		1.1.3 Work Standardisation	1.1.3.1 Takt time	
			1.1.3.2 Work sequence	
			1.1.3.3 Standard WIP	
		1.1.4 Takt time	1.1.4.1 Work Standardisation	
		1.1.5 Visual Control	1.1.5.1 5S	
			1.1.5.2 Shadow Tool Board	
			1.1.5.3 Inventory indicators	
			1.1.5.4 Kamishabi	
			1.1.5.5 Kanban	
			1.1.5.6 Andon	
			1.1.5.7 One-piece flow	
			1.1.5.8 Standardised work	
			1.1.5.9 Jidoka	
	1.2 TPM	1.1.6 Distributed MRO Storeroom	1.1.6.1 Inventory Standardisation	
			1.1.6.2 ABC Analysis	
		1.1.7 CMMS	1.1.7.1 Work Order	
		1.2.1 Autonomous Maintenance	1.2.1.1 5 S's	
			1.2.1.2 Visual Control	
			1.2.1.3 Cleaning and Lubrication standards	
		1.2.2 Planned Maintenance	1.2.2.1 Maintenance schedule	
		1.2.3 a) Root Cause Analysis	1.2.3.1 Cause and Effect Diagram	
			1.2.3.2 Five Whys	
			1.2.3.3 Tree diagram	
			1.2.3.4 Fault Tree Analysis	
			1.2.3.5 Brainstorming	
		1.2.3 b) Problem Solving	1.2.3.5 PDCA	
			1.2.3.6 SBCE	
		1.2.4 OEE	1.2.4.1 Eliminating six main losses	1.2.4.1.1 Brainstorming
		1.2.5 Work Order System	1.2.5.1 Waste Elimination	
		2.1.1 Lot size reductions		
2. Production	2.1 JIT	2.1.2 JIT/Continuous flow improvement	2.1.2.1 Finished-Goods Supermarket	
			2.1.2.2 Takt time	
			2.1.2.3 Pitch	2.1.2.3.1 Work Standardisation
			2.1.2.4 Buffer and safety inventories	
			2.1.2.5 Lights-Out Manufacturing	2.1.2.5.1 Work Standardisation
			2.1.2.6 Agile Manufacturing	
			2.1.2.7 One-piece flow or pull production	
			2.1.2.8 In-process supermarkets	
			2.1.2.9 FIFO lanes	2.1.2.9.1 Work Standardisation
			2.1.2.10 Kanban	
			2.1.2.11 Heijunka	2.1.2.11.1 Heijunka box
				2.1.2.11.2 Work Standardisation
			2.1.2.12 Paced Withdrawal	
			2.1.2.13 Runner	
			2.1.2.14 Value Stream Mapping	2.1.2.14.1 Waste Elimination
			2.1.2.15 PDCA	
			2.1.2.16 Jidoka	2.1.2.16 Autonomation
		2.1.3 Pull system	2.1.3.1 Similar process speed	2.1.3.1.1 Work Standardisation
			2.1.3.2 Finished-Goods Supermarket	
			2.1.3.3 One-piece flow plant layout	
			2.1.3.4 Kanban	
			2.1.3.5 Heijunka	2.1.3.5.1 Heijunka box
				2.1.3.5.2 Work Standardisation
			2.1.3.6 Production Scheduling	
		2.1.4 Cellular manufacturing	2.1.4.1 Work Cells	
			2.1.4.2 Counter clockwise flow direction	
			2.1.4.3 Sequential process arrangement	
			2.1.4.4 Closely positioned equipment	
			2.1.4.5 U-, C-, L-, S- or V- cell shapes	
		2.1.5 Cycle time reduction	2.1.5.1 Takt time	
			2.1.5.2 Pitch	
			2.1.5.3 Line balancing	
		2.1.6 Focussed factory production system	2.1.6.1 Work Cells	
		2.1.7 Agile manufacturing strategies	2.1.7.1 Buffer, safety inventory or de-coupling	
			2.1.7.2 IT Systems	
			2.1.7.3 Pull System	
		2.1.8 Quick changeover tecniques	2.1.8.1 SMED	2.1.8.1.1 Work Standardisation
		2.1.9 Bottleneck removal	2.1.9.1 TOC	
		2.1.10 Reengineerd production processes		
	2.2 TPM	2.2.1 Preventive maintenance	2.2.1.1 Condition monitoring	
			2.2.1.2 Maintenance schedule	
		2.2.2 Predictive maintenace	2.2.2.1 Condition monitoring	
			2.2.2.2 New process equipment or technologies	
		2.2.3 Maintenance optimisation	2.2.3.1 Reliability centred maintenance	2.2.3.1.1 MTBF
			2.2.3.2 Risk-based maintenance	
		2.2.4 Planning and scheduling strategies		
		2.2.5 New process equipment or technologies		
3. Strategic	3.1 Policy Deployment	3.1.1 Hoshin Kanri	3.1.1.1 PDCA	
			3.1.1.2 Standardisation	

Figure D.2: Final Summary of Lean Principles and Tools

ISO 55001	1) ASSET INFORMATION AND KNOWLEDGE			
Cl	**ISO 55002**	**Lean Table Reference**	**Lean Practice or Tool**	**ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)**
4.1	4.1.2.3 e)	2.1.2.14	VSM	2.4.2 b)
4.2	4.2.4	2.1.2.14	VSM	2.4.2 a)1), 2.4.2 a)3), 2.4.2 a)3), 2.4.2 b)
7.5 b)	7.5.3 a), 7.5.3 c)	2.1.3.6	Production Scheduling	2.4.2 d)
		2.1.2.14	VSM	
	7.5.3 d), 7.5.3 k)	2.1.2.15	PDCA	
		1.1.3	Work Standardisation	
7.5 c)		2.1.2.14	VSM	2.4.2 d)
		2.1.2.15	PDCA	
		1.1.3	Work Standardisation	
		1.2.2	Planned Maintenance	
	7.5.3 l)	1.1.6.2	ABC Analysis	
7.5 e)	7.5.3 g)	3.1.1	Hoshin Kanri	2.4.2 b)
7.6.1	7.6	3.1.1	Hoshin Kanri	2.4.2 b)
7.6.2	7.6	2.1.2.14	VSM	2.4.2 d)
		1.1.3	Work Standardisation	
7.6.3	7.6	1.1.5.1	5S	2.4.2 d)
8.3 c)	8.3.2 c)	2.1.2.14	VSM	2.4.2 d)

Figure D.3: Final Framework for implementing Lean Practices and Tools to Support ISO 55000 Asset Information and Knowledge Clauses

ISO 55001	2) ASSET LIFECYCLE MANAGEMENT			
Cl	**ISO 55002**	**Lean Table Reference**	**Lean Practice or Tool**	**ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)**
5.2	5.2 d)	3.1.1	Hoshin Kanri	2.4.2 a)1), 2.4.2 a)2), 2.4.2 b)1), 2.4.2 b)2)
6.2.1	6.2.1.3 d)	3.1.1	Hoshin Kanri	2.4.2 a)2), 2.4.2 b)2), 2.4.2 d)1)
		2.1.2.15	PDCA	
6.2.2 b)	6.2.2	1.2.4	OEE	2.4.2 d)2)
		1.2.1	Autonomous Maintenance	
		1.2.2	Planned Maintenance	
		1.2.3 a)	Root Cause Analysis	
		1.2.3 b)	Problem Solving	
		2.2	TPM	
		2.1.2.15	PDCA	2.4.2 d)3)

Figure D.4: Final Framework for implementing Lean Practices and Tools to Support ISO 55000 Asset Lifecycle Management Clauses

ISO 55001	3) RISK AND OPPORTUNITY			
Cl	ISO 55002	Lean Table Reference	Lean Practice or Tool	ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)
4.1		1.2.3 a)	RCA	2.4.2 b)1)
5.1	5.1 i), 5.1 k)	2.2.3.2	RbM	2.4.2 c)
		3.1.1	Hoshin Kanri	
5.2	5.2 d)	3.1.1	Hoshin Kanri	2.4.2 b)1)
6.1 a)	6.1	1.2.3 a)	Root Cause Analysis	2.4.2 b)1), 2.4.2 b)3), 2.4.2 d)3)
		2.2.1	Preventive Maintenance	
		1.2.3.6	SBCE	
		2.2.2	Predictive Maintenance	
		2.2.3	Maintenance Optimisation	
		1.1.5	Visual Control	
6.1 b)	6.1	3.1.1	Hoshin Kanri	2.4.2 b)1), 2.4.2 d)1)
		1.2.4	OEE	2.4.2 d)2), 2.4.2 d)3)
		2.2.3.1.1	MTBF	
6.2.2 b)	6.2.2.3 b)	1.2.3 a)	RCA	2.4.2 b)1), 2.4.2 b)3), 2.4.2 d)3)
		1.2.3 b)	Problem Solving	
	6.2.2.3 h)	2.2.3.2	RbM	2.4.2 b)1), 2.4.2 d)3)
6.2.2 k)	6.2.2.3 b), 6.2.2.3 h)	1.2.3	RCA and Problem Solving	2.4.2 b)1), 2.4.2 d)3)
		2.2.3.2	RbM	
7.3	7.3 d)	1.1.5	Visual Control	2.4.2 c), 2.4.2 d)4)
7.5 a)	7.5.2 h)	2.1.2.14	VSM	2.4.2 b)3)
8.1	8.1.4	1.2.3	RCA and Problem Solving	2.4.2 d) 3)
		2.2.3.2	RbM	
8.3	8.3.4	1.2.3	RCA and Problem Solving	
9.1 d)	9.1.2.1	1.2.4	OEE	2.4.2 d)1), 2.4.2 d)3)
		1.2.5	Work Order System	
		2.2.3.1.1	MTBF	
9.3 f)	9.3.2 f)	1.2.3 a)	Root Cause Analysis	2.4.2 d)3)
		1.2.3 b)	Problem Solving	
9.3 e)	9.3.2 e)	2.1.2.14	VSM	
		2.1.2.15	PDCA	
10.1	10.1.1 b)	1.2.3 a)	Root Cause Analysis	2.4.2 d)3)
10.3	10.3.4 d)	1.2.3 a)	Root Cause Analysis	2.4.2 d)3)

Figure D.5: Final Framework for implementing Lean Practices and Tools to Support ISO 55000 Risk and Opportunity Clauses

ISO 55001	4) RELIABILITY ENGINEERING			
Cl	ISO 55002	Lean Table Reference	Lean Practice or Tool	ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)
4.2	4.2.4	2.1.2.14	VSM	2.4.2 a)3), 2.4.2 c)3)
6.2.1	6.2.1.3 b)	2.1.2.14	VSM	2.4.2 a)3), 2.4.2 c)3)
		3.1.1	Hoshin Kanri	2.4.2 a)1) and 2.4.2 b)1)
		2.1.2.15	PDCA	
9.1	9.1.2.4	2.1.2.15	PDCA	2.4.2 d)3)

Figure D.6: Final Framework for implementing Lean Practices and Tools to Support ISO 55000 Reliability Engineering Clauses

ISO 55001	5) MAINTENANCE			
CI	**ISO 55002**	**Lean Table Reference**	**Lean Practice or Tool**	**ISO 55000 Clause (Relevance of Lean Practice or Tool to PAM)**
6.2.1	6.2.3.1 d)	2.2.3.1	RcM	2.4.2 a)1) and 2.4.2 b)1)
		3.1.1	Hoshin Kanri	
		2.1.2.15	PDCA	
7.5 c)	7.5.2 c)	2.2.3.1	RcM	2.4.2 d)3)
9.1	9.1.1.1 a)	2.2.3.1	RcM	2.4.2 d)
10.1 a)	10.1.1 a), 10.1.3	2.2.3.1	RcM	2.4.2 d)2
10.1 b)		2.2.3.1	RcM	2.4.2 d)2
10.2	10.2	2.2.1	Preventive Maintenance	2.4.2 d)
		2.2.2	Predictive Maintenance	
		2.2.3.1	RcM	
10.3	10.3.2 a), 10.3.2 b)	2.1.2.15	PDCA	2.4.2 d)1), 2.4.2 d)3)
		1.2.5	Work Order System	
		2.2.3.1.1	MTBF	
		1.2.4	OEE	
		2.2.3	Maintenance Optimisation	

Figure D.7: Final Framework for implementing Lean Practices and Tools to Support ISO 55000 Maintenance Clauses

List of References

Ackoff, R. (1999). *From Data to Wisdom*. John Wiley & Sons.

Alukal, G. (2007). Lean Kaizen in the 21st Century. *Quality Progress*, vol. 40, no. 8, p. 69.

Amadi-Echendu, J. (2004). Managing physical assets is a paradigm shift from maintenance. In: *Engineering Management Conferenct*, pp. 1156–1160.

American Society for Quality (2014). A Plan for Improvement. *Quality*, vol. 53, no. 1, p. 24.

Armistead, C. and Meakins, M. (2002). A Framework for Practising Knowledge Management. *Long Range Planning*, vol. 35, no. 1, pp. 49–71.

Arunraj, N. and Maiti, J. (2007). Risk-based maintenance - Techniques and applications. *Journal of Hazardous Materials*, vol. 142, no. 2007, pp. 653–661.

Askin, R.G. and Goldberg, J.B. (2002). *Design and Analysis of Lean Production Systems*. John Wiley & Sons, Inc.

Bakri, A.H., Rahim, A.R.A., Yusof, N.M. and Ahmad, Y. (2012). Boosting Lean Production via TPM. *International Congress on Interdisciplinary Business and Social Science*, vol. 65, no. 2012, pp. 485–491.

Balzer, W.K. (2010). *Lean Higher Education*. CRC Press, New York.

Baskarada, S., Gao, J. and Koronios, A. (2006). Agile Maturity Model Approach to Assessing and Enhancing the Quality of Asset Information in Engineering Asset Management Information Systems. In: *Business Information Systems -BIS*, pp. 1–15.

Basson, W. (2016). *Risk Management Solutions Flow to Implement Quantitative Methods as Part of ISO 55000 for Physical Asset Management*. Ph.D. thesis.

Basu, R. and Wright, J.N. (2011). Lean and agile supply chain. In: *Total Supply Chain Management*, pp. 199–228. Taylor & Francis.

Beebe, R.S. (2001). *Condition monitoring and its part in maintenance*. MCM Consultants.

Beecham, S., Hall, T., Britton, C., Cottee, M. and Rainer, A. (2005). Using an expert panel to validate a requirements process improvement model. *Journal of Systems and Software*, vol. 76, no. 3, pp. 251–275.

Bekefi, T., Epstein, M.J. and Yuthas, K. (2008). Managing Opportunity and Risks. Available at: `www.cimaglobal.com`

Belekoukias, I., Garza Reyes, J.S. and Kumar, V. (2014). The impact of lean methods and tools on the operational performance of manufacutring organisations. *International Journal of Production Research*, vol. 52, no. 18, pp. 5346–5366.

Bergsjo, P. (1999). Qualitative and quantitative research - Is ther a gap, or only a verbal disagreement? *Acta Obstet Scand*, vol. 78, pp. 559–562.

Bicheno, J. (2004). *The New Lean Toolbox*.

Borenstein, D. (1998). Towards a practical method to validate decision support systems. *Decision Support Systems*, vol. 23, no. 1998, pp. 227–239.

Bornstein, R.F. (2011). Face Validity.

British Standard Institute (2008). PAS 55 asset management Part 1: Specification for the optimized management of physical assets.

Bryman, A. and Bell, E. (2014). *Research Methodology: Business and Management Contexts*. Oxford University Press Southern Africa.

Campbell, J.D., Jardine, A.K. and McGlynn, J. (2010). Asset Classes and the World of Life-Cycle Asset Management. In: *Asset Management Excellence,*, pp. 11–21. CRC Press,.

Chiarini, A. (2009). Integrating lean thinking into ISO 9001 : a first guideline. *International Journal of Lean Six Sigma*, vol. 2, no. 2.

Clow, K.E. and James, K.E. (2014). Questionnaire Design.

Cresswell, J. (2014). *Research design: qualitative, quantitative, and mixed methods approaches*. 4th edn. Sage Publications, United States of America.

Creswell, J. (2003). *Research Design: Qualitative, Quantitative and Mixed Methods Approach*. Sage Publications.

Creswell, J. (2009). *Research design: Qualitative, quantitative and mixed methods approaches*. Sage Publications.

Davis, F. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly*, vol. 13, no. 3, pp. 319–340.

DiCicco-Bloom, B. and Crabtree, B.F. (2006). The qualitative research interview. *Medical Education*, vol. 40, no. 4, pp. 314–321.

Drost, E.A. (2011). Validity and Reliability in Social Science Research. *Education Research and Perspectives*, vol. 38, no. 1, pp. 105–123.

eAsset Management, Guassian Engineering and Asset Care Research Group (2015). Shaping and Charting Priorities.

Eator, M. (2013). *The Lean Practitioner's Handbook*. Kogan Page Ltd, London.

Fink, A. (2003). Keep Questions Closed or Open Them Up? In: *How to Ask Survey Questions*, pp. 35–38. SAGE Publications, Inc.

Flynn, J.R. (2016). *A Business Process Reengineering Framework Using the Analytic Hierarchy Process to Select a Traceability Technology for Spare Parts Management in Capital-Intensive Industries*. Ph.D. thesis.

Flynn, J.R. and Vlok, P. (2016). Lean Approaches in Asset Management Within the Mining Industry. In: *9th WCEAM Research Papers*, pp. 101–118.

Fogel, G., Stander, J. and Griffin, D. (2017). Creating an Effective Asset Management Delivery Model. Available at: `https://docs.wixstatic.com/ugd/f23fff_60ddf679ef6c4230a1bd99138fda7dd7.pdf`

Ford, H. (2002). *Today and Tomorrow: Commemorative Edition of Ford's 1926 Classic.* Taylor & Francis.

Frey, J.H. (2004). Open-Ended Question.

Friedman, T. (2010). Findings From Primary Research Study: Data Quality Issues Create Significant Cost, Yet Ofted Go Unmeasured.
Available at: `https://www.gartner.com/doc/1455915/findings-primary-research-study-data`

Gale, N.K., Heath, G., Cameron, E., Rashid, S. and Redwood, S. (2013). Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Med Res Methodol*, vol. 13, no. 2013.

Gumbley, H. (1998). Knowledge Management. *Work Study*, vol. 47, no. 5, pp. 175–177.

Hafeez, K., Malak, N. and Zhang, Y. (2007). Outsourcing not-core assets and competences of a firm using analytic hierarchy process. *Computers and Operations Research*, vol. 34, no. 3007, pp. 3592–3608.

Haffejee, M. and Brent, A.C. (2008). Evaluation of an integrated asset life-cycle management (ALCM) model and assessment of practices in the water utility sector. *WATER SA*, vol. 34, no. 2, pp. 285–290.

Hamza, S.E.A. (2009). Capturing Tacit Knowledge from Transient Workers. *International Journal of Knowledge Management*, vol. 5, no. 2, pp. 87–102. ISSN 1548-0666.

Hanna, P. (2012). Using internet technologies (such as Skype) as a research medium: a research note. *Qualitative Research*, vol. 12, no. 2, pp. 239–242.

Hardesty, D.M. and Bearden, W.O. (2004). The use of expert judges in scale development. Implications for improving face validity of measures of unobservable constructs. *Journal of Business Research*, vol. 57, no. 2, pp. 98–107.

Hastings, N.A. (2010). *Physical Asset Management.* Springer-Verlag London Limited.

Hawkins, B. and Smith, R. (2004). Common Ground. In: *Lean Maintenance*, pp. 1–19. Elsevier Butterworth Heinemann, Amsterdam, Boston.

Hicks, B. (2007). Lean information management: Understanding and eliminating waste. *International Journal of Information Management*, vol. 27, no. 2007, pp. 233–249.

Hodges, N.W. (1996). *The Economic Management of Physical Assets.* Great Britain.

Hodkiewicz, M. (2014). The Development of ISO 55000 Series Standards. In: *Engineering Asset Management-Systems, Professional Practices and Certification*, pp. 427–438.

Hodkiewicz, M. and Ho, M.-W. (2016). Cleaning historical maintenance work order data for reliability analysis. *Cleaning historical maintenance work order data for reliability analysis*, vol. 22, no. 2, pp. 146–163.

Holweg, M. (2007). The geneaolgy of lean production. *Journal of Operation Management*, vol. 25, pp. 420–437.

Hubbard, D. (2009). *The failure of risk management: Why it's broken and how to fix it.* John Wiley & Sons.

Huh, Y.U., Keller, F.R., Redman, T.C. and Watkins, A.R. (1990). Data QUality. *Information and software technology*, vol. 32, no. 8, pp. 559–565.

ISO 31000 (2009). ISO 31000: Risk management- Principles and guidelines. Standard, International Organization for Standardization.

ISO 55000 (2014). ISO 55000: Asset management - Overview, principles and terminology. Standard, International Organization for Standardization. *BSI Standards Publication*.

ISO 55001 (2014). BS ISO 55001:2014. *BSI Standards Publication*.

ISO 55002 (2014). BS ISO 55002:2014. *Asset management*.

Jardine, A.K. and Tsang, A.H. (2006*a*). *Maintenance, Replacement and Reliability.* Taylor & Francis.

Jardine, A.K. and Tsang, A.H. (2006*b*). *Maintenance, Replacement and Reliability*.

Jenkins, S. (2014). Asset Management's Next Act The newly released ISO 55000 standard represents a framework for maximizing company value from equipment and other assets. *Chemical Engineering*, vol. 2, no. 2014, p. 17.

Jolayemi, J.K. (2008). Total Quality Management & Business Excellence. *Total Quality Management & Business Excellence*, vol. 19, no. 9, pp. 295–320.

Jooste, J.L. (2014). *A critical success factor model for asset management services.* Ph.D. thesis.

Kececioglu, D. (2002). *Reliability Engineering Handbook*. 1st edn. DEStech Publications.

Kelly, A. (2006). Total productive maintenance: its uses and limitations. In: *Maintenance Systems and Documentation*, 2nd edn, pp. 247–265. Butterworth/Heinemann.

Khan, F. and Haddara, M. (2004). Risk based maintenance of ethylene oxide production facilities. *Journal of Hazardous Materials*, vol. 108, no. 2004, pp. 147–159.

Khan, F.I., Haddara, M. and Krishnasamy, L. (2008). A New Methodology for Risk-Based Availability Analysis. *IEEE Transactions on Reliability*, vol. 57, no. 1, pp. 103–112.

Kitchenham, B., Pfleeger, F. and Pickard, L. (2002). Preliminary guidelines for empirical research in software engineering. *IEEE Transactions on Software Engineering*, vol. 8, no. 8, pp. 721 – 734.

Knechel, W. (2002). The Role of Independent Accountant Effective Risk Management. *Review of Business and Economics*, vol. XLVII, no. 1, pp. 65–86.

Kriege, L., Jooste, W. and Vlok, P. (2016). a Framework for Establishing a Human Asset Register for the Improved Management of People in Physical Asset Management. *South African Journal of Industrial Engineering*, vol. 27, no. 4, pp. 77–89.

Lacy, P. and Pickard, S. (2008). Managing Risk and Opportunity: The People Imperative. *The Journal of Corporate Citizenship*, vol. 2008, no. 30, pp. 139–145.

Lai, I.K. and Lau, H.C. (2012). A hybrid risk management model: a case study of the textile industry. *Journal of Manufacturing Technology*, vol. 23, no. 5, pp. 665–68.

Lake, P. and Crowther, P. (2013). Data, an Organisational Asset. In: *Concise Guide to Databases*, pp. 3–19.

Lauesen, S. and Vinter, O. (2001). Preventing requirement defects: An experiment in process improvement. *Requirements Engineering*, vol. 6, no. 1, pp. 37–50.

Liker, J.K. (2013). Principle 6: Standardized Tasks Are the Foundation for Continuous Improvement and Employee Empowerment. In: *Toyota way: 14 management principles from the world's greatest manufacturer*. New York : McGraw-Hill.

Liker, J.K. and Womack, J.P. (1998). *Becoming Lean*. Productivity,Inc, Portland, Oregon.

Lin, S., Gao, J. and Koronios, A. (2006). The eed for a Data Quality Framework in Asset Management. In: *Engineering Asset Management*, pp. 473–482.

Lin, S., Gao, J., Koronios, A. and Chanana, V. (2007). Developing a data quality framework for asset management in engineering organisations. *International Journal of Information Quality*, vol. 1, no. 1.

Lyonnet, P. (1991). *Maintenance Planning*. Chapmann & Hall.

Ma, Z. (2014). Analysis of the new Asset Managment standard ISO 55000 and PAS 55.

Marques, A.C., De Leon, P.M., Fernandez, J.G., Marquez, C.P. and Campos, M.L. (2009). The maintenance management framework. *Journal of Quality Maintenance Engineering*, vol. 15, no. 2, pp. 167–178.

Mather, D. (2007). Lean vs. Lean Maintenance. *PlantServices*, vol. 2007, no. 110, pp. 15–55.

Maulana, M.I.I.M., Al-Ashaab, A., Flisiak, J.W., Araci, Z.C., Lasisz, P.W., Shehab, E., Beg, N. and Rehman, A. (2017). The Set-based Concurrent Engineering Application: A Process of Identifying the Potential Benefits in the Surface Jet Pump Case Study. *Procedia CIRP*, vol. 60, pp. 350–355. ISSN 22128271.

McCarthy, D. and Rich, D.N. (2004). Lean TPM. In: *Lean TPM - A Blueprint for Change*, pp. 28–48. Butterworth/Heinemann.

Minnaar, J., Basson, W. and Vlok, P. (2013). Quantitative methods required for implementing PAS 55 or the ISO 55000 series of Asset Management. vol. 24, no. November, pp. 98–111.

Mitchell, J.S. (2002). *Physical Asset Management Handbook*. 3rd edn. Clarion Technical Publishers.

Mitchell, J.S. (2007). *Physical Asset Management Handbook*. 4th edn. Clarion Technical Publishers, Houston, Texas.

Mobley, R. (2002). *A Introduction to Predictive Maintenance*. 2nd edn. Butterworth/Heinemann.

Mohamed, M. and Lim, C. (1999). Criteria of project success: an exploratory re-examination. *International Journal of Project Management*, vol. 17, no. 4, pp. 243–248.

Morad, A.M., Pourgol-Mohammad, M. and Sattarvand, J. (2014). Application of reliability-centered maintenance for productivity improvement of open pit mining equipment: Case study of Sungun Copper Mine. *Journal of Central South University: Science & Technology of Mining and Metallurgy*, vol. 21, no. 6, pp. 2372–2382.

Mostafa, S., Dumrak, J. and Soltan, H. (2015*a*). Lean Maintenance Roadmap. *Procedia Manufacturing*, vol. 2, no. 2015, pp. 434–444.

Mostafa, S., Lee, S.-H., Dumrak, J., Chileshe, N. and Soltan, H. (2015*b*). Lean thinking for a maintenance process. *Production & Manufacturing Research*, vol. 3, no. 1, pp. 236–272. ISSN 2169-3277.

Mostert, M.P. (2004). Face Validity of Meta-Analyses in Emotional or Behavioral Disorders. *Behavioral Disorders*, vol. 28, no. 2, pp. 89–118.

Moubray, R.-C.M. (1994). *Reliability-Centred Maintenance.* Butterworth/Heinemann.

Myerson, P. (2012). *Lean Supply Chain and Logistics Management.* McGraw-Hill Education: New York, Chicago, San Francisco, Lisbon, London, Madrid, Mexico City, Milan, New Delhi, San Juan, Seoul, Singapore, Sydney, Toronto.

Netland, T. and Ferdows, K. (2016). The S-Curve Effect of Lean Implementation. *Production and Operations Management*, vol. 25, no. 6, pp. 1106–1120.

Ohno, T. (1988). *Toyota Production Systems.* Productivity Press, Massachusetts.

Onwuegbuzie, A.J. and Leech, N.L. (2007). Sampling Designs in Qualitative Research: Making the Sampling Process More Public. *The Qualitative Report*, vol. 12, no. 2.

Paterson, J.C. (2015). A Brief History of Lean, Notable Principles and the Approach Taken by this Book. In: *Lean Auditing: Driving Added Value and Efficiency in Internal Audit*, 1st edn. John Wiley & Sons, Ltd.

Patton, J.D. (1983). *Preventive Maintenance.* Instrument Society of America.

Peterson, R.A. (2000). Rating Scales. In: *Constructing Effective Questionnaires*, chap. 5, pp. 61–82. SAGE Publications, Inc, Thousand Oaks.

Pham, H. and Wang, H. (1996). Imperfect maintenance. *European Journal of OPerational Research*, vol. 94, no. 1996, pp. 425–438.

Prajapati, A., Bechtel, J. and Ganesan, S. (2012). Condition based maintenance: a survey. *Journal of Quality in Maintenance Engineering*, vol. 18, no. 4, p. 3840400.

Robinson, S. (1997). Simulation Model Verification and Validation: Increasing the User's Confidence. In: *Proceedings of the 1997 Winter Simulation Conference*, pp. 1–7.

Rubenstein-Montano, B., Liebowitz, J., Buchwalter, J., McCaw, D., Newman, B. and Rebeck, K. (2001). A system thinking framework for knowledge management. *Decision Support Systems*, vol. 31, no. 2001, pp. 5–16.

Rubin, M., Hiroyuki, H. and The Productivity Press Development Team (1996). *5S for operators: 5 pillars of the visual workplace.* Portland, Or. : Productivity Press.

Sahu, P.K. (2013). *Research Methodology: A Guide for Researchers In Agricultural Science and Other Related Fields.* Springer India.

Samman, T.A.S.A. (2014). Modelling Lean, Agile, Leagile Manufacturing Strategies: An fuzzy analytical hierarchy process approach for ready made ware(clothing) industry in Mosul,Iraq. *International Journal of Advances in Engineering & Technology*, vol. 7, no. 3, pp. 1091–1108.

Sargent, R. (2013). Verification and validation of simulation models. *Journal of Simulation*, vol. 7, no. 1, pp. 12–24.

Sarkar, S.A. and Mukhopadhyay, A.R. (2013). Root cause analysis, Lean Six Sigma and test of hypothesis. *The TQM Journal*, vol. 25, no. 2, pp. 170–185.

Schoeman, J. and Vlok, P. (2014). The possible influence of risk management, forecasting, and personnel training in physical asset management. *South African Journal of Industrial Engineering*, vol. 25, no. 2, pp. 96–104.

Shah, R. and Ward, P.T. (2003). Lean manufacturing: context, practice bundles, and performance. *Journal of Operations Management*, vol. 21, no. 2003, pp. 129–149.

Smith, A. and Hinchcliffe, G. (2004). *RCM: Gateway to world class maintenance.* Butterworth/Heinemann.

Smith, G.C., Poteat-Godwin, A.B., Harrison, L.M.M. and Greg D. MD, R. (2012). Applying Lean Principles and Kaizen Rapid Improvement Events in Public Health Practice. *Journal of Public Health Management and Practices*, vol. 18, no. 1, pp. 52–54.

Spires, C. (1996). Asset and maintenance management - becoming a boardroom issue. *Managing Service Quality: An International Journal*, vol. 6, no. 3, pp. 13–15.

Srinivasan, M.M., Bowers, M.R. and Gilbert, K.C. (2014). *Lean maintenance repair and overhaul changin the way you do business.* New York : McGraw-Hill.

Starr, A. and Rao, B. (2001). Condition Monitoring and Diagnostic Engineering Management. In: *24th International Conference on Condition Monitoring and Diagnostic Engineering.*

Sturges, J.E. and Hanrahan, K.J. (2004). Comparing Telephone and Face-to-Face Qualitative Interviewing: a Research Note. *Qualitative Research*, vol. 4, no. 1, pp. 107–118.

Sutton, I. (1995). Integrated Management System Improvement plant Reliability. *Journal of Hydrocarbon Processing*, vol. 74, no. 1, pp. 63–66.

Tang, C.S. (2006). Perspectives in supply chain risk management. *International Journal of Production Economics*, vol. 103, no. 2006, pp. 451–488.

Tapping, D., Luyster, T. and Shuker, T. (2002). *Value Stream Management.* Productivity Press, New York.

Teddlie, C. and Tashakkori, A. (2010). *Sage handbook of mixed methods in social & behavioral research.* Sage,Thousand Oaks.

The Business Dictionary Online (2017). Framework.
Available at: `http://www.businessdictionary.com/definition/framework.html`

The Cambridge Dictionary Online (2017). Framework.
Available at: `http://dictionary.cambridge.org/dictionary/english/framework`

The English Oxford Living Dictionaries Online (2017). Framework.
Available at: `https://en.oxforddictionaries.com/definition/framework`

The Global Forum on Maintenance and Asset Management (2011). The Asset Management Landscape. , no. November.

The Guardian (2013 July). Piper Alpha disaster: how 167 rig oil workers died. Available at: `www.theguardian.com/business/2013/jul/04/piper-alpha-disaster-oil-rig`

Tsang and Albert, H.C. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, vol. 8, no. 1, pp. 7–39.

Vagenas, N., Runciman, N. and Clement, S. (1997). A methodology for maintenance analysis of mining equipment. *International Journal of Surface Mining, Reclamation and Environment*, vol. 11, pp. 33–40.

van den Honert, A., Schoeman, J. and Vlok, P. (2013). Correlating the Content and Context of PAS 55 with the ISO 55000 Series. *South African Journal of Industrial Engineering*, vol. 24, no. 2, pp. 24–32.

Visser, J. and Botha, T. (2015). EVALUATION OF THE IMPORTANCE OF THE 39 SUBJECTS DEFINED BY THE GLOBAL FORUM FOR MAINTENANCE AND ASSET MANAGEMENT. *South African Journal of Industrial Engineering*, vol. 26, no. May, pp. 44–58.

Walker, E. (2015). *Motivating human assets in the field of Physical Asset Management.* Ph.D. thesis. Available at: `https://scholar.sun.ac.za/handle/10019.1/97952`

Warnecke, H. and Huser, M. (1995). Lean Production. *International Journal of Production Economics*, vol. 41, no. 1-3, pp. 37–43.

Weller, S.C. and Romney, A.K. (1988). Rating Scales. In: *Systematic Data Collection*, pp. 39–43. SAGE Publications, Inc, Newbury Park.

Wheeler, P. (2007). Reliability-Centered Maintenance. Available at: `www.buildings.com/article-details/articleid/5377/title/reliability-centered-maintenance`

Willmott, P. and McCarthy, D. (2001*a*). Putting TPM into perspective from total productive maintenance to total productive manufacturing. In: *Total Productivity Maintenance*, 2nd edn, pp. 1–16. Butterworth/Heinemann.

Willmott, P. and McCarthy, D. (2001*b*). Techniques to deliver the TPM principles. In: *Total Productivity Maintenance*, 2nd edn, pp. 62–76. Butterworth/Heinemann.

Womack, J.P. and Jones, D.T. (1996). *Lean Thinking.*

Womack, J.P. and Jones, D.T. (2003). *Lean Thinking.* Simon and Schuster, London.

Zhang, Y. and Wildemuth, B. (2016). Qualitative Analysis of Content. In: *Applications of Social Research Methods to Questions in Information and Library Science*, 2nd edn, pp. 319–329.