Decision-Making Framework for Inventory Management of Spare Parts in Capital-Intensive Industries

by

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

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Declaration

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Abstract

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Effective management of spare parts inventory is essential to companies because it influences inventory costs and asset utilization. The vast and diverse portfolio of spare parts, intermittent demand patterns and contradicting objectives between departments are examples of some of the factors that complicate Spare Parts Management (SPM). Managers of spare parts are faced with trade-off decisions between risk and cost on a daily basis. These decisions include, amongst many, determining appropriate stock levels and order frequencies. Despite the importance of SPM, decisions are however often made intuitively in practice with little factual support, and the decision-making process is commonly constrained within departmental silos. Even though there is a large body of academic knowledge on this topic, practical applications of spare parts inventory solutions lag behind theoretical studies.

The majority of studies in literature focus on single components of SPM, such as demand forecasting and parts classification, whereas fewer studies consider the decision-making process itself. This study proposes a decision-making framework for spare parts inventory management. The framework is based on a wide-ranging literature review that focuses on capturing the essence of Spare Parts Management (SPM), but also acknowledges the interconnectedness of the problem. Therefore, core inventory management principles, as well as closely related topics such as Supply Chain Management (SCM) and Physical Asset

Management (PAM), are studied in the context of spare parts. The broad scope of the literature study leads to a holistic approach to the problem and prevents sub-optimization.

The proposed framework condenses principles from various fields of study (SCM, PAM, Classification and Inventory Management) into a stepwise methodology presented as a decision-making framework. The objective of the framework is to provide managers with a structured process, based on factual information, to enable better decision-making in the field. Furthermore, the framework aims to capture the fundamentals of SPM in a simplistic manner to ease the adoption of the framework in practice. A case study is conducted in the South African mining industry to validate the framework. The case study demonstrates that the framework is practical, provides structured guidance, and assists managers to make trade-off decisions in managing spare parts inventory.

Uittreksel

Besluitnemingsraamwerk vir Voorraadbestuur van Onderdele in Kapitaalintensiewe Bedrywe

("Decision-Making Framework for Inventory Management of Spare Parts in Capital-Intensive Industries")

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Effektiewe voorraadbestuur van onderdele is belangrik vir maatskappye omdat dit voorraadkoste en die benutting van bates beïnvloed. Die bestuur van onderdele is 'n komplekse probleem. Ondermeer is die portefeulje van onderdele items breed en divers, die vraagpatrone sporadies en word die voorraadvlakke geaffekteer deur kontrasterende doelwitte tussen verskillende departemente. Bestuurders van onderdele word daagliks gekonfronteer met besluite rakende risiko's en kostes, soos om toepaslike voorraadvlakke te bepaal en om te besluit wanneer om bestellings te plaas. Hierdie besluite word dikwels intuïtief geneem met min feitelike ondersteuning en insette in die besluitnemingsproses word gereeld beperk tot sekere departemente. Ten spyte van die geweldige akademiese belang in die onderwerp, is daar min suksesvolle praktiese toepassings.

Die meerderheid van studies in die literatuur fokus op spesifieke elemente van onderdele bestuur, soos vooruitskatting en klassifisering van parte, terwyl minder op die besluitnemingsproses konsentreer. Hierdie studie stel 'n besluitnemingsraamwerk vir die bestuur van onderdele voorraad voor. Die raamwerk is gegrond op 'n deeglike literatuurstudie wat die essensie van onderdele bestuur

ondersoek, maar ook die interverbondenheid van die probleem in ag neem. Voorraadbestuurbeginsels en verwante onderwerpe soos Voorsieningskettingbestuur en Fisiese Batebestuur word dus bespreek. Die breë omvang van die literatuurstudie lei tot 'n holistiese benadering wat sub-optimering van die probleem voorkom.

Die voorgestelde raamwerk som beginsels uit verskillende relevante studievelde op in 'n stapsgewyse metode wat voorgestel word as 'n besluitnemingsraamwerk. Die doel van die raamwerk is om bestuurders te voorsien met 'n gestruktureerde proses, gebaseer op feitelike inligting, om besluitneming in die veld te verbeter. Verder poog die raamwerk om die fundamentele konsepte in voorraadbestuur vas te vang in 'n eenvoudige manier sodat die raamwerk maklik geïmplementeer kan word in die praktyk. Die voorgestelde raamwerk is gevalideer deur middel van 'n gevallestudie in die Suid-Afrikaanse mynbedryf. Die gevallestudie toon dat die voorgestelde raamwerk prakties is, die besluitnemingsproses op 'n gestruktureerde wyse lei, en bestuurders help om beter, ingeligte besluite te neem.

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The Author December, 2014

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Acronyms and Abbreviations

SPM	Spare Parts Management
WIP	Work in Progress
SC	Supply Chain
SCM	Supply Chain Management
PAM	Physical Asset Management
SKU	Stock Keeping Unit
FNS	Fast, Normal and Slow-moving
VED	Vital, Essential, Desirable
AHP	Analytical Hierarchy Process
ROP	Reorder Point
ROQ	Reorder Quantity
EOQ	Economic Order Quanitity
CRS	Continuous Review Systems
PRS	Periodic Review Systems
ANN	Atificial Neural Networks
BPN	Back-Propagation Network
ADI	Average Demand Interval
CV	Coefficient of Variation
SES	Simple Exponential Smoothing
MAD	Mean Absolute Deviation
EWMA	Exponential Weighted Moving Average
MSE	Mean Squared Error
MAPE	Mean Absolute Percentage Error
MPO	Minimum Probability of Occurrence
TLAM	Total Life-Cycle Asset Management
PAS	Publicly Available Standards
OEM	Original Equipment Manufacturer
RCM	Reliability Centred Maintenance
ACRG	Asset Care Research Group

Nomenclature

Chapter 3: Spare Parts Management

ADI	Average demand interval
n_0	Number of periods with no demand
P	Number of total periods with demand
CV	Square coefficient of variation
d_i	Demand during period i
$\bar{d}$	Average demand during period

Chapter 4: Proposed Solution

R	Reorder point
L	Mean lead time duration
z	z-score for the desired service level
σ_L	Standard deviation of demand during lead time
Q	Economic order quantity
D	Average annual demand
K	Order cost per order
h	Annual holding cost per unit

Chapter 5: Validation

C Inventory carrying cost rate (%)

PV Purchase value

T_{stock} Time item is held in stock

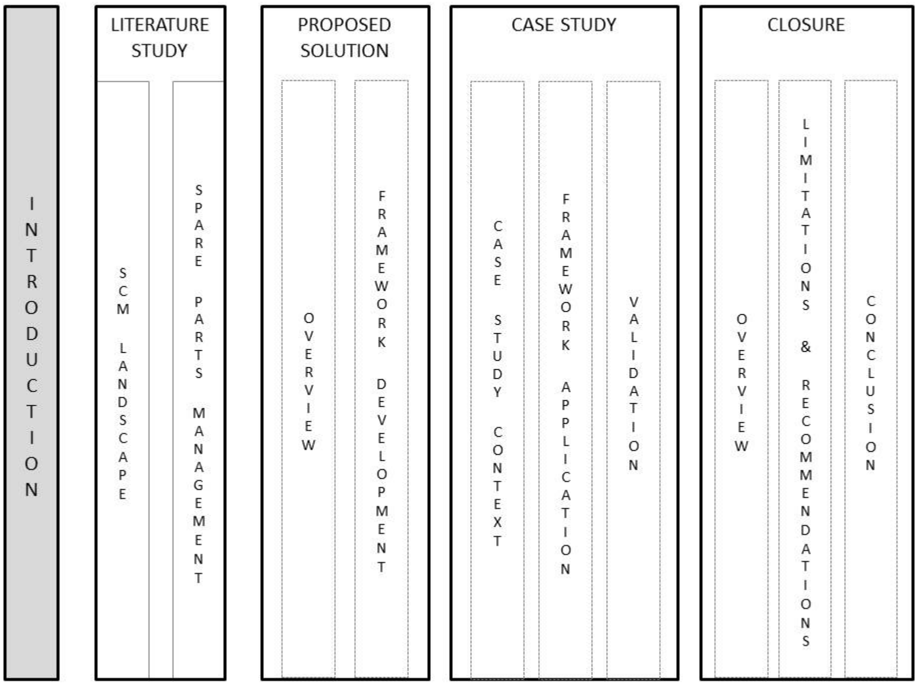
T_{out} Duration of stock-out

Chapter 1

Introduction

This study proposes a decision-making framework for the management of spare parts inventory in capital-intensive industries. This chapter aims to introduce the study by providing context to the research problem and an overview of the research process. It includes background to the research problem, an introduction to fundamental topics and the objectives of the research study. Finally, the chapter concludes with the research design, methodology and thesis outline. Figure 1.1 presents an overview of the structure of the document and acts as a roadmap during the course of this study.

Figure 1.1: Thesis roadmap



1.1 Background

Spare parts play a significant role in organizations. The need for spare parts arises whenever components fail, require replacement or repair. This study is concerned with spare parts in capital-intensive industries. In this regard, a spare part is considered to be a duplicate component used for maintenance purposes or to replace a damaged part of a machine.

Effective management of spare parts inventory is essential in an increasingly competitive business environment. In today's society, operational effectiveness is of high importance and consequently there is an emphasis on reduced operating costs and higher asset utilization. Spare Parts Management (SPM) affects the operating cost of a company, because higher stock levels lead to higher inventory costs. The availability of parts has an effect on asset utilization as it influences the idle time of a machine. Subsequently, Molenaers *et al.* (2012) mention that SPM has acquired great interest from researchers and practitioners over the past decades.

Gajpal *et al.* (1994) state that spare parts constitute a large portion of total inventory in manufacturing companies. The typical inventory system consists of different types of inventory to fulfil various needs. According to Moncrief *et al.* (2006), inventory is often categorized into finished goods, Work In Progress (WIP), raw materials and operating supplies or replacement parts. Spare parts form part of the last-mentioned category and differ from other inventory items mainly in terms of their required function and the inventory policies that govern them (Kennedy *et al.*, 2002). In contrast to other inventory items, the purpose of spare parts inventory is to assist maintenance staff to restore systems to continue to perform their intended function. Furthermore, the inventory control principles that govern spare parts differ from those that govern other inventory items. This is because, unlike other items, spare parts demand is a function of equipment utilization and maintenance.

The key challenge in inventory management is to decide which items to buy, when to buy them and how many items to buy. These decisions are influenced by two contrasting cost objectives. On the one hand, large capital investments are required to keep items in stock. On the other hand, unavailable stock items lead to costly stock-out events influencing the company's service level. Therefore, at the centre of the inventory management challenge there is a trade-off decision between risk and cost. According to Moncrief *et al.* (2006) a well-balanced spare parts inventory system means having in stock exactly what you need when you need it - not too much, nor too little. Huiskonen (2001) agrees and states that the principle objective of inventory control is to achieve a sufficient service level with minimum inventory investment and administration costs.

The management of spare parts is further complicated by a number of factors. Firstly, the spare parts portfolio contains a large number of items with diverse characteristics that leads to a complex inventory system. Secondly, the demand for spare parts is typically slow and intermittent (Wang and Syntetos, 2011; Porras and Dekker, 2008). Intermittent demand patterns are characterized by sequences of zero demand observations, interspersed by occasional non-zero demand occurrences, and are therefore very difficult to forecast. Finally, SPM requires multidisciplinary decision-making. Spare parts demand is influenced by maintenance tactics and stock levels are influenced by Supply Chain (SC) related decisions.

SPM is an interdisciplinary study field. Cavalieri *et al.* (2008) mention that the expertise required for the management of spare parts inventory differ to those required for conventional inventory items. The management of spare parts requires conventional inventory management skills as well as a sound background on maintenance and repair functions. The field consequently includes research in multiple areas such as production, inventory control, logistics, maintenance, reliability and strategic management. The dominant research areas can be consolidated into two major fields of study contributing to the issue of SPM: Supply Chain Management (SCM) and Physical Asset Management (PAM).

The first study field, SCM, is important because the existence of inventory stems from uncertainty in SCs. Inventory can be seen as a buffer against uncertainty and is one of the ways to manage uncertainty in SCs. It is therefore worth investigating the role that SCM plays in the context of SPM and vice versa. The term SC refers to the flow of products or services from source to final customer. SCM includes the management of all activities and components that exist within a SC. It is possible to view the spare parts SC from two different perspectives. The first is to acknowledge the influence of spare parts availability on a company's core SC: higher spare parts availability increases production throughput and prevents unforeseen disruptions in the company's core SC process. The second is to view the spare parts SC as a unique secondary SC that feeds into the company's core SC. In this case, the supplier is the spare parts manufacturer and the customer is the equipment or function in need of a spare part.

The second study field, PAM, also plays a significant role in SPM because it is related to the demand generation process of spare parts and influences service level requirements. Firstly, the demand for spare parts is as a result of part failures and therefore influenced by maintenance tactics. For this reason, Van Horenbeek *et al.* (2013) state that it is clear that maintenance and inventory management are strongly related to the field of SPM and that the two fields should be viewed simultaneously when optimizing a company's operations. Secondly, the availability of spare parts influences asset utilization because the consequence of not having a part in stock when required is extra idle time. In the context of the spare parts SC, asset management is the client of SPM and therefore the service level requirement for spare parts is influenced by PAM-related decisions.

The primary concern of PAM is to ensure the most effective use of assets across their life-cycles. Woodhouse (2006) stresses the importance of interdisciplinary collaboration in asset management and states that organizations have realized that a cross-functional, prioritized approach reaps major benefits. Effective PAM therefore crosses traditional organizational silos. This supports the interdisciplinary view of SPM and emphasizes the need for collaboration between SCM and PAM for an effective solution to the problem.

Capital-intensive industries, in particular, face major challenges in the management of spare parts. Capital-intensive industries require large investments in order to operate. The need to find the balance between inventory costs and risk in SPM is therefore accentuated because the capital cost of equipment and their accompanying parts is expensive and the industry relies on extreme levels of production throughput. Different inventory control policies are used within the industry. In many cases, the problem is that policies are generically applied and intuitive decisions regarding stock levels are taken with little factual and quantitative support.

Decision-making is central to all types of management and therefore also to SPM. According to Al-Tarawneh (2012), many theorists view decision-making as the fundamental managerial function. Consequently, managers devote a substantial amount of time and effort on making the right decisions. Similarly, the choice of inventory control policy is difficult and a time-consuming process as it depends on a variety of different factors.

In summary, the major function of spare parts is to assist maintenance personnel to perform maintenance functions on equipment. SPM is important because of the associated impact on inventory cost and asset utilization. However, it is also a complex issue that contains many different interrelated components. The research domain of this study is presented in Figure 1.2. The figure shows that SPM is an interdisciplinary issue residing in the fields of SCM and PAM. More specifically, SPM is an inventory management problem influenced by maintenance activities. The next section discusses the problem statement and research questions for this study.

1.2 Problem statement

Managers of spare parts are faced with a magnitude of decisions on a daily basis. The common theme amongst these decisions can be summarized in the following questions: which items should be bought, how many should be bought and when should they be bought? Silver *et al.* (1998) state that decision-making in the context of production planning and inventory manage-

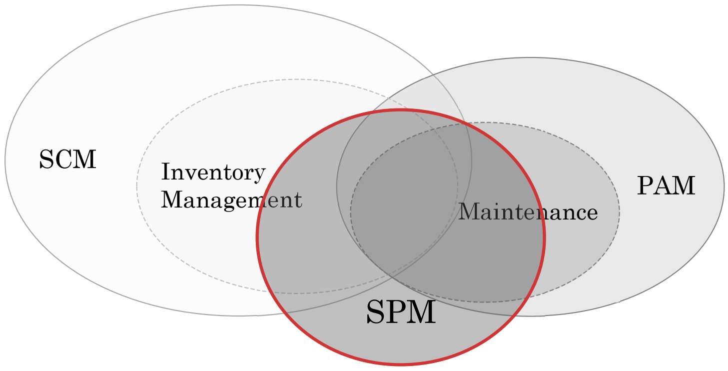


Figure 1.2: Research domain

ment is a problem of coping with large numbers while taking into consideration a diversity of factors. In today's harsh business environment, according to Anderson *et al.* (2011), managers and organizations are looking for structured and logical decision-making processes that depend on evidence rather than relying on mere intuition and personal experience.

The objective of inventory management is to find the optimal stock level to achieve a desired service level at a minimum cost. This results in trade-off decisions between risk and cost. Cavalieri *et al.* (2008) state that in practice few companies adopt structural, factual and quantitative approaches to manage spare parts. Therefore, there is a need for a tool to assist structured decision-making and provide quantitative support for trade-off decisions in SPM.

The spare parts portfolio is diverse and vast. Different industries and companies within industries have different types of spare parts with varying characteristics. Furthermore, even within one company, parts vary in cost, criticality, purpose and demand. Different spare parts therefore require different management approaches and there is no single solution to the spare parts issue. In the pursuit of a potential solution to the general spare parts issue, it is therefore beneficial to focus on the decision-making process itself rather than a single solution to one problem. In this regard, Bacchetti and Saccani (2012) mention that there is a need for practical guidelines to supplement theoretical models in order to increase the adoption of SPM theories in practice. Thus, there is a need for a practical decision-making guideline that takes into consideration the unique attributes of spare parts.

SPM is an interdisciplinary field encompassing principles from SCM as well as PAM. In SPM, the majority of research studies focus on single aspects of the field like the classification of parts (Molenaers *et al.*, 2012; Bacchetti *et al.*, 2010), demand forecasting (Eaves and Kingsman, 2004; Syntetos *et al.*, 2009) and inventory control policies (Porras and Dekker, 2008; Shtub and Simon, 1994). Furthermore, most studies are grounded only in a single study-field. Considering the interdisciplinary nature of SPM, there is a gap in literature and a need for a holistic approach to SPM which takes into consideration aspects of SCM as well as PAM.

In summary, practical applications of SPM lag behind theoretical solutions. Managers require a tool to assist them with the decision-making process in SPM, especially as it relates to trade-off decisions. The tool should act as a guideline and should be flexible and practical, rather than prescriptive. Finally, the tool should take into account the interdisciplinary nature of the issues in SPM and therefore provide a holistic approach.

This study aims to address the above-mentioned needs with the development of a decision-making framework for the management of spare parts in capital-intensive industries. The framework should act as a decision guideline to assist the decision-making process in spare parts inventory management. The framework should provide managers with a structured, factual approach to make informed trade-off decisions and should enable a holistic approach to the problem. The research problems are translated into the following null hypothesis which is central to the research study.

$\boldsymbol{H_0}$

It is possible to improve current practices by developing a decision-making framework to assist the management of spare parts inventory in capital-intensive industries.

This study aims to address the above-mentioned needs. The following section discusses the research objectives of the study.

1.3 Research objectives

The background and problem statement lead to research objectives to guide the execution of the research study. The primary objective of this study is as follows:

Develop a decision-making framework for the management of spare parts inventory in capital-intensive industries.

The research objective aims to address the needs stated in the problem statement. The primary objective can be split into the following manageable sub-objectives:

1. Establish the fundamental principles in relevant fields of study
    a) review the key concepts in SCM
    b) determine the relationship between SCM and SPM
    c) identify the fundamentals of inventory management
    d) define PAM and its relation to SPM
2. Master the field of SPM
    a) identify spare parts characteristics in capital-intensive industries
    b) determine criteria and methods used to classify spare parts
    c) identify techniques used to forecast the demand for spare parts
    d) review appropriate inventory control policies
    e) review existing decision-making frameworks for SPM
3. Develop a decision-making framework for the management of spare parts
    a) determine decision-making criteria for selecting methods to classify inventory, forecast demand and manage inventory
    b) consolidate decision-making criteria into a structured framework
4. Validate the decision-making framework
    a) validate the framework in line with the required framework features
    b) assess proposed inventory control policies

The term framework is used extensively in different contexts. The Oxford dictionary defines a framework as "a basic structure underlying a system, concept, or text". The Business Dictionary defines the term as a "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". Similarly, in the context of this study, the term framework refers to an outline of the decision-making process to assist the management of spare parts. It serves as a guide for the decision-making process by providing the basic structure of the process and establishing the relationship between interlinked concepts. More specifically, following from the background and problem statement, the proposed framework is intended to have the following key features:

1. Practical – It should be possible to apply the framework in practice.
2. Holistic – The framework should provide an integrated, holistic approach to the problem that incorporates multiple disciplines.

3. Structured – The steps in the framework should be logical and guide a structured decision-making process.

This study aims to achieve the above-mentioned objectives. The research process is guided by the objectives and the framework is developed in accordance with the specified framework features. The next section discusses the scope of the research.

1.4 Scope

It is important to establish the boundaries or scope of a research study prior to the execution of the study to focus the study on its intended purpose. The two major boundaries to this study are related to the application field of the framework and the intended function of the framework:

1. The study is concerned with the management of spare parts in capital-intensive industries. Although it is intended as a general framework, it does not take into account specific properties of spare parts that are unique to other industries.
2. The proposed framework acts as a decision-making guideline. It is not prescriptive and does not provide specific solutions to problems, but rather guide the decision-making process.

The above-mentioned delimitations are considered during the execution of the study. The following section discusses the research design and methodology.

1.5 Research design and methodology

The research design is the systematic plan for the intended research process. Creswell (2013) mentions three elements of research design: philosophical world view, research methods and strategy of inquiry. The philosophical worldview refers to the knowledge claims made by the researcher. The research methods are the procedures and methods used to translate the approach to practice. Finally, the strategy of inquiry provides direction for procedures in a research design and is typically described in terms of quantitative, qualitative and mixed methods designs.

This research follows a pragmatic worldview. Pragmatism, as a worldview, arises out of actions, situations and consequences. Rossman and Wilson (1985) state that this worldview does not emphasize specific methods, but rather aims to understand the research problem and find solutions that work by using all possible methods. This study follows a holistic approach to the research problem by investigating the problem from different perspectives. The focus is on obtaining a solution to the SPM problem and not on using certain methods. The approach therefore stems from a pragmatic worldview.

Creswell (2013) describes the pragmatic worldview also as the philosophical underpinning for mixed methods. This study supports this principle and makes use of mixed methods by combining quantitative and qualitative methods to obtain a solution to the research problem. Qualitative methods are used during a comprehensive literature review and both quantitative and qualitative methods are used for the application of the case study. In terms of research methods, the study follows the format of a retrospective case study and data is collected through unstructured interviews and data extraction.

This study comprises of three main sections: the literature analysis, framework development and framework validation. The first section is the literature analysis. Initially, the literature analysis follows a top-down approach. As a result, the discussion starts with the fundamentals of the SCM landscape and then delves deeper into the field of SPM. Later, however, the focus of the literature analysis expands from SPM to the broader field of PAM. This approach is presented in Figure 1.3. The second section is the framework development. The proposed framework is developed by consolidating the appropriate information and decision logic into a structured framework. The final section is the validation of the proposed framework by means of a case study in the South African mining industry. Further elaboration on the outline of the thesis is presented in the next section.

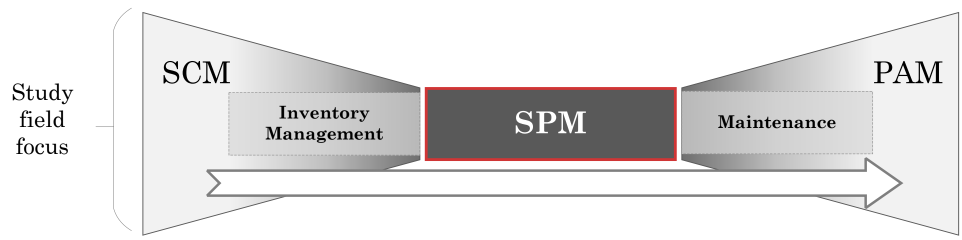


Figure 1.3: Literature review: Direction of focus

1.6 Thesis outline

In accordance to the research design, the thesis is structured in a logical manner to allow continuous flow of key concepts. Each chapter is aimed to address certain research objectives which are shown in Table 1.1. The thesis is structured as follows:

Table 1.1: Thesis outline compared to objectives

Chapter	Objectives
Chapter 2: Supply chain management landscape	1a; 1b; 1c
Chapter 3: Spare parts management	1d; 2a; 2b; 2c; 2d; 2e
Chapter 4: Proposed solution	3a; 3b
Chapter 5: Validation	4a; 4b

Chapter 1: Introduction
Chapter 1 serves as an introduction to the study. First, a background to the study is provided, thereafter the problem statement, scope and research objectives are discussed. Finally, the research design and methodology are explained.

Chapter 2: Supply chain management landscape
Chapter 2 is the first part of the literature analysis. The chapter establishes the fundamentals in SCM and inventory management. A special focus is placed on uncertainty in SCs and the role of inventory to manage uncertainty in SCs. The relationship between SCM and SPM is also elaborated on.

Chapter 3: Spare parts management
Chapter 3 is a continuation of the literature analysis. The chapter focuses on SPM. Topics such as spare parts characteristics, demand forecasting and inventory control policies are discussed in the context of SPM. This chapter also emphasizes the relationship between SPM and PAM and provides an introduction to maintenance and PAM, with the focus on its influence on SPM.

Chapter 4: Proposed Solution
Chapter 4 provides a proposed solution to the problem. The development of the proposed decision-making framework is discussed in detail. Each step in the framework is described in terms of its objectives, input requirements, output, methods and considerations. The framework is developed to comply with the specified framework features as part of the objectives of the study.

Chapter 5: Validation
Chapter 5 is a validation of the proposed framework by means of a case study in the mining industry. The framework is applied to determine appropriate inventory control policies to manage the spare parts of a certain machine. The process of applying the framework is documented and the results are compared to the current practice at the mine. The framework is also assessed against the required framework features.

Chapter 6: Conclusion
The final chapter is a conclusion of the study. The chapter starts with an

overview of the study. Thereafter, the limitations and recommendations are discussed. Finally, the research study is concluded.

The above-mentioned thesis outline is graphically represented in the beginning of this chapter, in Figure 1.1. The figure acts as a roadmap for the remainder of the study and is presented in the beginning of each chapter to guide the reader along the research process.

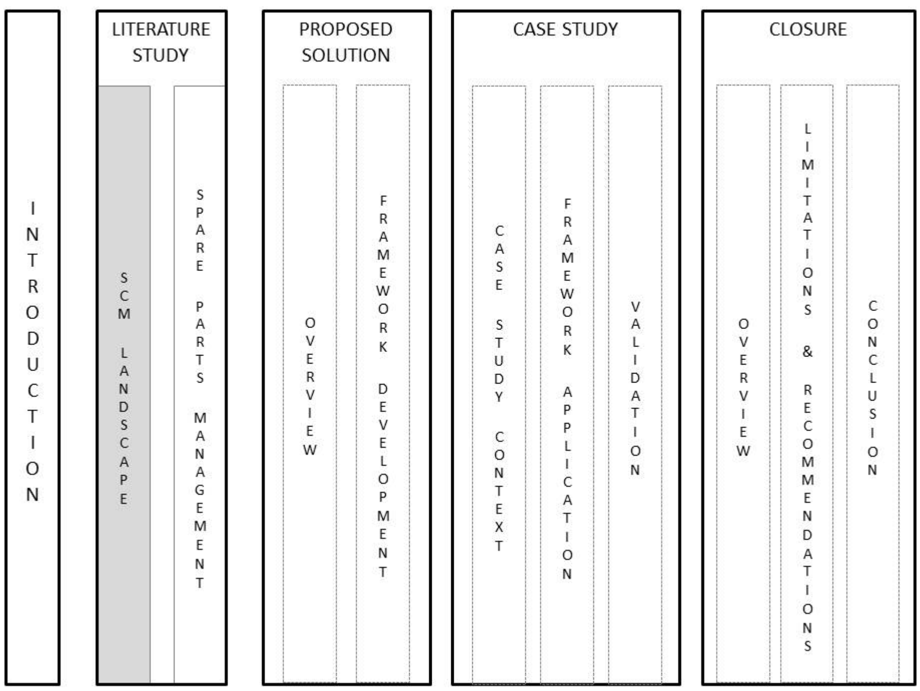
1.7 Chapter summary

This chapter serves as an introduction to the study. First, background to the study is provided. Thereafter, the problem statement is discussed and consolidated into a single null hypothesis. The research objectives and scope of the study are then discussed. The main objective is to develop a decision-making framework for the management of spare parts inventory in capital-intensive industries. This study is demarcated in terms of the application purpose of the framework. Lastly, the research design and thesis outline is discussed. In line with the thesis outline, the next chapter provides the fundamentals in the SCM landscape. SCM, uncertainty in SCs and inventory management are among the topics discussed.

Chapter 2

Supply chain management landscape

This chapter aims to contextualize the study by sketching the Supply Chain Management (SCM) landscape. The fundamental principles of SCM are introduced to provide the appropriate background to the problem statement. This chapter is the first part of the literature review. It consists of an overview of SCM, a brief introduction to the concept of uncertainty in Supply Chains (SCs) and a detailed discussion on inventory management. The second part of the literature review, presented in Chapter 3, makes use of the principles and concepts defined in this chapter to focus on the management of spare parts. The figure below shows the positioning of this chapter relative to the study.



2.1 Supply chain management

The term SC refers to the flow of products or services from source to final customer. SCM includes the management of all activities and components that exist within a SC. When investigating a SC-related problem, it is important to first gain an overview understanding of the terms SC and SCM. Different components within SCs are interconnected and therefore a single component should not be investigated independently from the environment it operates in.

Optimizing an individual item in a SC, without considering the SC as a whole, could lead to sub-optimization. Therefore, it is important to view SPM in the broader context of SCM. The relationship between spare parts and SCM can be understood from two different perspectives. On the one hand, spare parts are viewed as a dominant role player in a company's SC. The main functions of spare parts are to replace broken components and to assist maintenance activities. Spare parts availability therefore impacts the core production process of a company's SC as it affects the downtime of equipment. On the other hand, the service level for the supply of spare parts is a result of the performance of the spare parts SC ranging from the raw materials and manufacturing of parts to the supply of parts. Considering both perspectives, spare parts are often bought in advance and kept in stock to account for uncertainty in the SC, both from a demand as well as a supply point of view.

Effective management of SCs is important in today's complex and competitive marketplace (Pereira, 2009). SCM plays a dominant role in companies' strategies to enhance organizational efficiency and profitability. Abuhilal *et al.* (2006) emphasize the importance of SCM and state that the competition in today's marketplace is between SCs and not individual companies.

The topic of SCM encompasses a broad spectrum of activities across different functional boundaries and is therefore a difficult topic to understand. Lummus and Vokurka (1999) state that many fail to recognize the wide-ranging scope of SCM and confine the term to specific topics in the field such as procurement, inventory management or logistics. Mentzer *et al.* (2001) also conclude that numerous definitions of SCM lead to a poorly defined term which adds to the confusion regarding the term. It is therefore important for this study to first define the concepts of SC and SCM to anchor and provide contextualization for the remainder of the study.

Section 2.1.1 and Section 2.1.2 provide an overview of the topics of SC and SCM. The different interconnected components or functions of SCs are explored in Section 2.1.3. SC decisions are discussed in Section 2.1.4 and finally an overview of SC models is presented in Section 2.1.5.

2.1.1 The concept of supply chain

SCM is the collective term used for the management of different activities related to the SC of a company or SCs ranging between different companies. Wisner (2011) mentions that a comprehension of the concept of SC is helpful for the understanding of SCM. This section provides a brief explanation of the term SC to equip the reader with the necessary knowledge for the rest of the discussion.

Numerous definitions, varying in length, amount of detail and scope, exist for the term SC. Webster (2008) defines a SC as "two or more parties linked by a flow of resources" and states that the resources typically refer to material, money and information. Fiala (2005) and Sukati *et al.* (2012)'s definition for the term focuses on the participants within the SC; namely, suppliers, manufacturers, distributors, retailers and customers. Many authors define a SC as "the network of organizations that are involved through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer" (Erturgut and Soysekerci, 2011). Scukanec *et al.* (2007) prefer a short and broad definition: "Supply chains connect all the elements between the producer and the consumer." For the purpose of this study, a SC includes all activities associated with the flow of products and services from source to final customer.

A popular method used to explain the concept of SC is through a graphical representation. Refer to Figure 2.1 for a graphical illustration of a SC in general. The figure illustrates the different participants in the SC (suppliers, manufacturers, transporters, distributors and retailers) and shows the interacting flow between different activities. It also indicates the general direction of the product and information flow. The illustration clearly shows that SCs range from raw material suppliers to retailers selling the final products to customers.

SCs have different lengths, sizes and levels of complexity. Some companies, involved in one type of product or service, have short SCs including for instance only one supplier and retailer. Other companies have complex, extended SCs reaching from suppliers' suppliers to customers' customers. The size and complexity of the SC typically depends on the raw materials and services used to manufacture and distribute products. Therefore, companies involved in many different types of products are likely to also relate to multiple SCs (Wisner, 2011).

One company could consist of, or take part in, many different SCs. On the one hand, different products or rather product families sold by a company could potentially all have different SCs. On the other hand, there are also SCs that support the core SC of a business. One example could be an apple packing factory. Apples are regarded as the core product and subsequently, the core

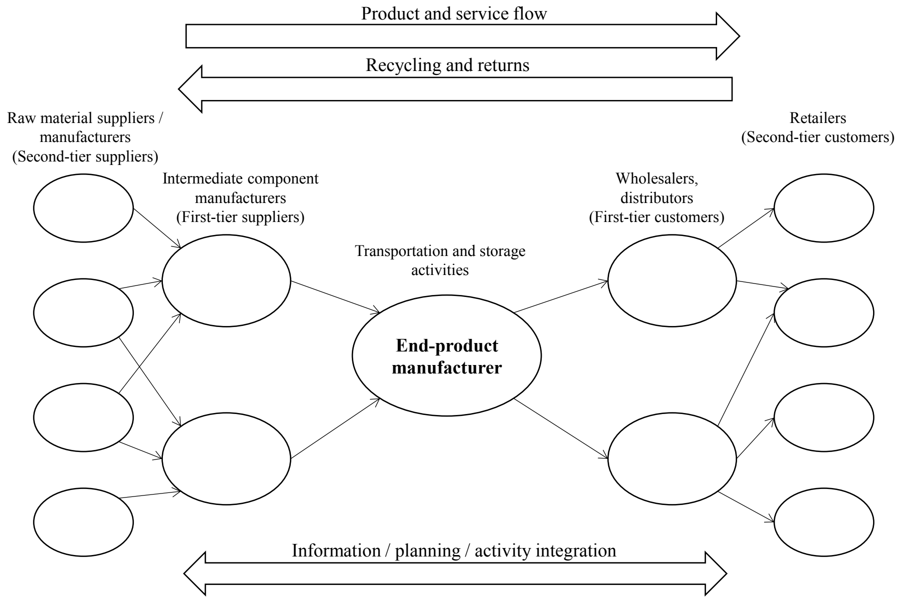


Figure 2.1: Graphical representation of a generic supply chain. Adapted from Wisner (2011).

SC range from the orchard to the customers buying the apples. But there are a number of SCs supporting the core SC such as the SC for packing material and packing equipment. This example illustrates the interconnectedness, not only between the components within a SC, but also between SCs and companies. This could mean that a certain company is a producer in one SC as well as a customer in another SC. The next section provides an overview of SCM.

2.1.2 Supply chain management overview

SCM encompasses numerous different interrelated elements. This section provides only a brief overview of the topic to enable an overview understanding of the term for the remainder of the study. The term SCM, similar to SC, has been defined extensively in literature. Wisner (2011) points out that the majority of the definitions focus on the coordination and integration of participants involved in SC activities related to products or services.

Simchi-Levi *et al.* (1999) define SCM in detail as “a set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, and stores, so that merchandise is produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system-wide costs while satisfying service level requirements”. Webster (2008) states that SCM is concerned with the management of all activities surrounding the flow from raw materials to finished products and back. This study defines SCM, in general, as the approaches and methods used to manage the SC.

The interest in SCM has progressively increased since the 1980's when organizations began to realize the advantages of integration and alignment with other participants in the SC. Lummus and Vokurka (1999) state that big corporations like Walmart, Procter and Gamble, Hewlett-Packard and Whirlpool have focused on SC initiatives as early as in the 1990's. The initial advancement in SCM is owed to the need for individual companies to become more efficient and profitable and therefore SCM initiatives were primarily concerned with individual elements in the SCM (Miles and Snow, 2007). However, recently a number of other factors such as globalization, extensive availability of information, advances in information technology, growth in outsourcing and complexity in the marketplace have also contributed to the growth in SCM (Webster, 2008).

The scope of SCM has consequently been expanded to include not only the efficiency within a single company's SC, but also the overall profitability of the extended SC, ranging from suppliers' suppliers and customers' customers. Today's competitive marketplace is represented by an interacting web of organizations, rather than independent companies. As a result, companies need to work together towards a collective goal to realize true value from their operations (Zhang and Reimann, 2013). These days, it is not satisfactory any more for companies to compete independently or in isolation.

The objective of SCM is to improve efficiencies, quality and customer service through collaboration. According to Fiala (2005) and Lummus and Vokurka (1999), there are numerous benefits from effective integration between different elements within SCM: improved value to customers, lower inventory costs, improved cash flow, higher employee productivity and finally improved competitiveness.

SCM contains many different components like procurement, logistics, material handling, inventory management, manufacturing and distribution. According to Stock *et al.* (2010), more than three quarters of SCM definitions are concerned with the different components that exist within SCM. The next section provides a discussion on the different aspects of and components within SCM.

2.1.3 Supply chain components

In order to explain the concept of SCM, it is helpful to divide the concept into different components and explain it accordingly. Du Toit and Vlok (2014) developed a framework of understanding for SCM (illustrated in Figure 2.2) which acts as a useful tool to aid the explanation of SC components. The framework is a graphical representation of SCM, presenting the components within SCM and the relationship between them. The different components are illustrated by the objects in the framework. The positioning of the objects

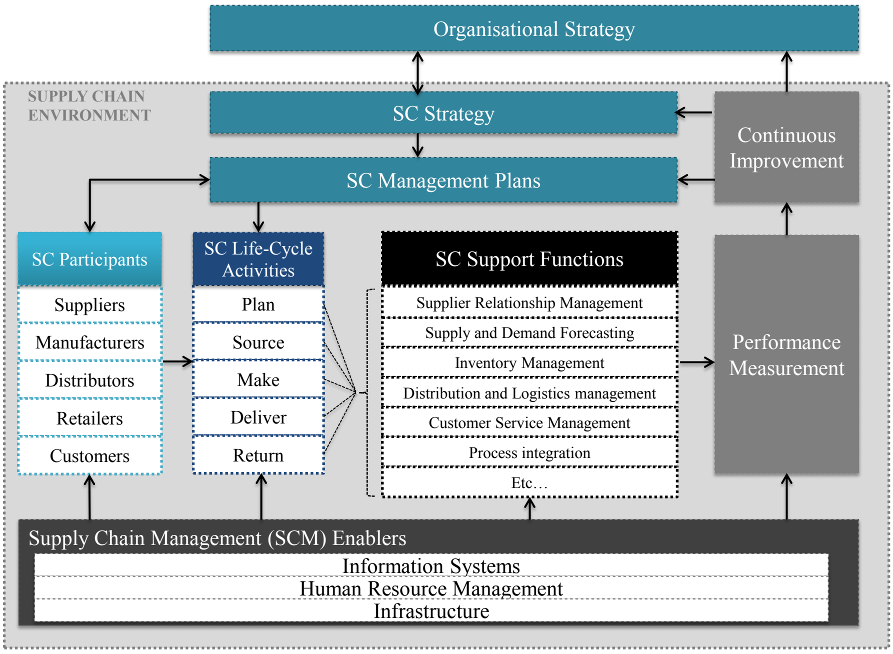


Figure 2.2: Supply Chain Management: Framework of Understanding. Adapted from Du Toit and Vlok (2014)

relative to one another and the flow between them are used to explain the relationships between components.

Strategies provide the overall direction for companies and their associated SCs, therefore the Organizational Strategy and SC Strategy are presented at the top of the framework (Figure 2.2). The next object is SCM, because strategies are implemented through management plans. SCM further encompasses three main components: SC Participants, SC Life-Cycle Activities and SC Support Functions. Performance measurement acts as a feedback loop into Continuous Improvement which affects SC Strategy and Management. The different components within SCM are all affected by SC Enablers which act across functions, activities and participants. The explanation in the remainder of this section is guided by the main components presented in this framework of understanding.

Strategy and Supply Chain

Strategy is an important part of SCM because it provides the overarching direction for management activities. The Oxford dictionary defines strategy as “a plan of action designed to achieve a long-term or overall aim”. The SC strategy is part of the corporate strategy but specifically applies to SC-related activities. Ketchen Jr and Giunipero (2004) point out that better integration between SCM and strategic management improves organizations’ ability to meet their goals. Christopher and Ryals (1999) also found that SC strategy plays a dominant role in generating shareholder value and therefore it is crucial to align SCM activities to the SC strategy.

Supply Chain Management

SCM refers to a set of approaches used to manage the SC and includes the coordination and integration between SC partners (Refer to Section 2.1.2 for an overview of SCM). SCM is situated in the centre of the framework (Figure 2.2) because it is the link between SC strategy and the components of SC such as participants, life-cycle activities and support functions. SCM acts also as the vehicle by which continuous improvement initiatives are implemented.

Participants

Numerous participants play a role in the SC. In general, participants can be clustered into the following groups: suppliers, manufacturers, distributors, retailers and customers. Participants are classified into different types (e.g. supplier or manufacturer) according to the function they perform relative to a particular SC. This implies that one company can be a supplier in one SC and a manufacturer in another SC.

Activities

According to Webster (2008), SCM "involves the management of activities surrounding the flow of raw materials to the finished product". Similarly, numerous other definitions also focus on the activities within the SC domain (Mentzer *et al.*, 2001; Lummus and Vokurka, 1999). In literature, there seems to be consensus that SC activities are all activities involved in the life-cycle of a product from source (raw materials) to customer (final product). The most popular classification of life-cycle activities is according to the SCOR [1] model (Version 9): Plan, Source, Make, Deliver and Return. It is possible for one activity to be split between different departments, and also between companies, depending on the company's involvement in the SC (Li *et al.*, 2011).

Support Functions

The term Support Functions, in this context, refers to the SC management functions that control and support the life-cycle activities. Examples of support functions include warehousing, inventory management, order management, logistics, transport, customer service and information system management. There is a many-to-many relationship between Life-Cycle Activities and Support Functions. An example of a Support Function that clearly illustrates this concept is inventory management. Inventory is positioned at different

[1] The SCOR model was developed by the Supply Chain Council as a standard diagnostic tool for supply chain management

parts of the SC (raw materials, work in progress, finished products). As a result, inventory management is critical to the 'make' and 'deliver' processes, but inventory is also planned during the 'plan' process. The 'make' process however contains many other support functions in addition to inventory management, such as scheduling. Therefore, there is a many-to-many relationship between the 'make' process and inventory management.

Performance Measurement and Continuous Improvement

The constantly changing and competitive business environment requires SCs to continuously adapt and improve current practices. Continuous improvement is consequently a critical issue in the context of dynamic SCs (Cai *et al.*, 2009). Performance measurement is vital in order to know how well the SC is performing and also to measure the effect of continuous improvement initiatives. The performance of SCs can be measured by using numerous metrics and models. Many approaches such as Lean, Total Quality Management and Six Sigma have also been developed to continuously improve the performance of SCs (Andersson *et al.*, 2006).

Supply Chain Enablers

A number of functions can be viewed as enablers for the efficient functioning of the SC system. Enablers are functions that do not necessarily reside within one of the other components in SCM, but rather stretch across multiple activities and participants to enable a SC to perform optimally. Examples of SC enablers are human resource management and infrastructure. SC enablers, in this context, are similar to the support functions in Porter's Value Chain Model. Porter (2008) refers to procurement, technology management, human resource management and infrastructure as support activities in an organization's value chain.

The framework in Figure 2.2 assists the explanation of the different components in SCM and the interaction between them. The principles of the framework can also be applied to the management of spare parts. The spare parts management strategy feeds from the organizational and SC strategy. There are numerous participants playing different roles in the spare parts SC. For instance, suppliers are the producers of spare parts and in most cases external to the organization and customers are equipment in need of spare parts. All the life-cycle activities are involved in the management of spare parts. The main support function is inventory management which relates to other functions such as demand forecasting and customer service. Supplier relationship management is also very important especially in the case of intertwined responsibilities. Lastly, performance is measured to ensure high service levels at low costs and continuous improvement is strived.

As mentioned in the beginning of this section, there are two different perspectives from which the spare parts SC can be understood. On the one hand, the spare parts SC can be viewed as a primary SC or entity on its own producing and delivering spare parts to a customer. On the other hand, the spare parts SC can be viewed as a secondary SC feeding into the core SC of the company. In this sense, the spare parts SC is an enabler to the core SC of the company. This concept is illustrated in Figure 2.3.

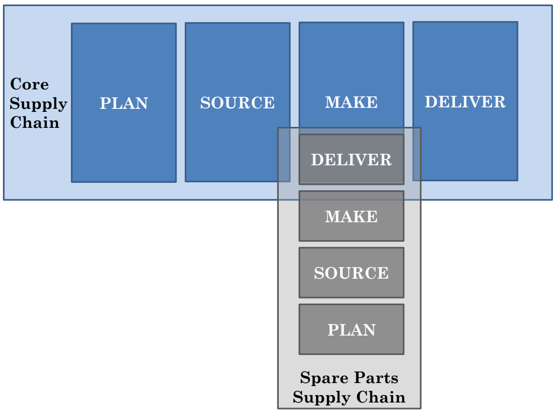


Figure 2.3: Spare parts supply chain integration

SCM involves many decisions on different levels. These decisions affect the above-mentioned components and are discussed in the next section.

2.1.4 Supply chain decisions

Decision-making is central to SCM. According to Sabri and Beamon (2000), SC decisions are broadly grouped into strategic and operational decisions. Strategic decisions are decisions that involve a long time frame. Melo *et al.* (2009) state that this category includes decisions with a long-lasting effect, high investment cost and decisions of which the consequences are expensive to change. Operational decisions are short term and affect the day-to-day operations of the SC. Besides operational and strategic type of decisions, SC decisions can also be grouped according to decision areas into the following four groups as stated by Ganeshan and Harrison (1995): location decisions, transportation decisions, production decisions and inventory decisions.

Location decisions are typically strategic decisions with a major impact on the operations of a business. It includes decisions regarding the placement of production facilities, stock holding points and sourcing points. Production decisions can be both strategic and operational. At a strategic level, production decisions involve the choice of products to produce, where to produce them and the capacity of the production facility. On an operational level, it involves tasks that affect the day-to-day operations of the company, such as the construction of detailed master production schedules and scheduling maintenance activities.

Inventory decisions are both strategic and operational. At a strategic level, managers have to decide on inventory policies which refer to the location and levels of stock-holding in the business. Most research studies have however focused on the operational inventory decisions like deployment and control strategies. These decisions are critical as they are the major contributor to customer service levels.

Transportation decisions involve the strategic mode choice of transport as well as the operational logistics-related choices. Transportation decisions typically flow from inventory decisions and location decisions. For instance, it flows from inventory decisions because of the trade-off between the cost of using a certain mode of transport versus the indirect cost of keeping extra inventory.

There are a number of strategic as well as operational decisions related to the management of spare parts. In a strategic sense, decisions need to be made regarding supplier relationships, the division of responsibility of stock-holding and the risk appetite of the company. Operationally, spare parts inventory need to be managed on a day-to-day basis and decisions need to be made to determine when and how many spare parts to buy.

SC decisions have led to the development of many different types of SC models to assist managers to make decisions. The next section provides a brief overview of the different types of SC models and modelling techniques in the field of SCM.

2.1.5 Supply chain models

Research on SC modelling has steadily increased over the past decade (Badole *et al.*, 2013). There are many different types of models and tools that can be used to model SC behaviour and solve SC-related issues. This section explores different modelling types and tools with the aim to identify appropriate modelling techniques to assist decision-making in SPM.

As expected, the choice of modelling approach is dependent on the type of decisions that the model needs to answer. Modelling approaches for strategic decisions differ from modelling approaches used to model operational decisions. Strategic decisions typically require large amounts of information from different perspectives which is typically difficult to obtain. These models are therefore not as exact as operational models. Operational decisions require a smaller scope of information, but more detailed information. These models have the potential to provide more exact answers (Ganeshan and Harrison, 1995).

In general, SC models can be split into three types: deterministic models, stochastic models and hybrid models. Deterministic models assume all model parameters are known and fixed, and that no randomness is involved. These types of models also assume that its output is certain if the input is fixed and will therefore repetitively produce the same results for a given input. Stochastic models allow for uncertainty in the model's parameters and therefore acknowledge that parameters are susceptible to a changing environment. Beamon (1998) mentions that at least one variable is unknown in stochastic models and is assumed to follow a particular probability distribution. Hybrid models, as expected, take into account mixed characteristics and therefore contain both deterministic and stochastic properties.

Badole *et al.* (2013) analyzed articles on SC modelling in order to provide a comprehensive review of the vast array of literature available on the topic. Out of the 220 models analyzed, 63% were stochastic models, 30% were deterministic models and the remainder were hybrid models. Stochastic models, taking into account demand uncertainty are by far the most popular type of SC modelling and the number of research articles in this area is rapidly expanding.

Ganeshan and Harrison (1995) use a different viewpoint, and categorize modelling approaches into network design, rough cut and simulation approaches. Network design methods are generally used during the inception of a SC to determine the optimal network in terms of locations of production facilities, stock-holding points and supplier points of contact. These models are therefore also mostly strategic in nature, require a large amount of data and would typically provide a general recommendation instead of an exact answer. Rough cut models provide guiding policies for operational decisions. These models form the bulk of SC literature and predominantly involve the tactical and operational decisions faced by SC managers. Inventory management approaches are the most common among these, because inventory management plays a central role in the management of SCs. Simulation models have been used to take into account the stochastic nature of SCs and allow for what-if analysis.

Various modelling tools, techniques and methods have been used to model SCs. According to Badole *et al.* (2013)'s research, optimization technology such as linear and mixed integer programming, followed by simulation are the most popular modelling tools used by researchers to optimize SCs. Buckley and An (2005) mention that linear and mixed integer programming methods perform well in solving well-defined mathematical problems such as inventory optimization and supply network modelling. The disadvantage is however that they are also rigidly structured and confine the problem to the mathematical formulation of the problem. These types of models are often subject to simplified assumptions to make the problem fit into a mathematical equation.

Simulation is a modelling technique commonly used to solve SC-related problems. Computer simulation is the "imitation of the operation of a system and its internal processes, over time, and in appropriate detail to draw conclusions about the system's behaviour" (Kelton *et al.*, 2011). Simulation can be used to predict the effect of changes to existing systems and also to predict the performance of new systems. It is frequently used in the design, operation and emulation of systems. There are different types of SC simulation models. Models can be static or dynamic; deterministic or stochastic and discrete or continuous (Winston and Goldberg, 2004). The major advantage of simulation in SC modelling is its ability to account for uncertainty in the SC with the use of stochastic variables. Caroline Thierry and Bel (2008) argue that simulation is the only method appropriate to capture the complexity of SCM. Min and Zhou (2002) state that simulation models are well-suited to evaluate 'what-if' scenarios and have therefore been applied to model SC dynamics. The drawback of simulation is that the optimization process with simulation is a slow process.

In the context of SPM, it is therefore worth focusing on stochastic models and simulation for modelling the behaviour of a spare parts inventory system. To conclude, this section provided an overview of key concepts in SCM. It includes discussions on the definitions of SC and SCM, the components and decisions in SCM, and SC models. The next section discusses the sources of uncertainty in SCs and also methods to reduce, manage or cope with uncertainty.

2.2 Uncertainty in supply chains

There is an inherent degree of uncertainty in all SCs. Sabri and Beamon (2000) acknowledge uncertainty as one of the most important, but challenging issues in SCM. Simangunsong *et al.* (2012) agree and mention that it is an issue with which most managers in the field struggles. It is therefore nearly impossible to solve SCM problems without taking into consideration the effects of uncertainty.

It is important to clarify the definition of uncertainty in the context of SCs before elaborating on the sources and methods to reduce uncertainty. Van der Vorst and Beulens (2002) define SC uncertainty as decision-making situations in the SC in which the decision-maker does not definitely know what decision to take. This could be because of unclear objectives, a lack of information, or inability to predict the outcome of the decision. For the context of this study, SC uncertainty is defined as any element within the SC not known for certain, containing some form of unpredictability or instability (including risk). The terms risk and uncertainty are sometimes used interchangeably. Risks are however only associated with uncertainty which leads to negative effects, whereas general uncertainty could lead to positive or negative results.

It is known that uncertainty in SCs impact both operational and financial performance. SC processes need stability and predictability for effective coordination, because in an operating context, high levels of uncertainty create a less controlled situation (Germain *et al.*, 2008). High variability in SC processes is expensive because it results (amongst many) in overtime, unused capacity, excess or insufficient inventory, costly changeovers, premium freight charges, variability in quality, and dissatisfied customers.

This section starts with a discussion on the sources of uncertainty and thereafter the methods to reduce and manage uncertainty are explained.

2.2.1 Sources of uncertainty

From the above-mentioned background, it is clear that SC uncertainty is a reality and has a negative financial impact. It is therefore necessary to develop management strategies to deal with uncertainty. This study agrees with Simangunsong *et al.* (2012) who argue that a full list of sources of SC uncertainty is a precursor to developing managing strategies and therefore this section discusses various sources of uncertainty.

Different methods and models have been used to identify sources of SC uncertainty. Davis (1993) developed one of the earlier models and called it the Uncertainty Cycle. This model categorizes sources of uncertainty into four groups: uncertainty in internal manufacturing processes, uncertainty in the supply process, uncertainty in customer deliveries and uncertainty in customer demand. Mason-Jones and Towill (1998) added another category of uncertainty, namely, Control Uncertainty, in their development of the Uncertainty Circle. The model can be used to evaluate the level of SC integration and suggests that costs can be reduced by reducing uncertainties. The Supply Chain Complexity Triangle developed by Wilding (1998) also provides some valuable insights into the generation of uncertainty in SCs.

In general, uncertainty can be categorized according to uncertainty in the manufacturing process, supply process or demand process. Germain *et al.* (2008) identified three main sources of process variability: upstream sources such as supplier performance, internal sources related to manufacturing and downstream sources related to customers. Process variability refers to the level of inconsistency in the flow of goods throughout the firm. More recently, Simangunsong *et al.* (2012) completed a comprehensive review of numerous papers and identified the key sources of uncertainty as summarized in Table 2.1. The next section discusses methods to manage and reduce uncertainty in the SC.

2.2.2 Reducing and managing uncertainty

Uncertainty, in a broad sense, can be dealt with in two ways: reduce uncertainty or manage uncertainty. Some authors refer to managing uncertainty as coping with uncertainty, adapting or cushioning against uncertainty. In today's business world, there are also many common terms in the field of SCM

Table 2.1: Sources of uncertainty

Sources of uncertainty: factors and variables
Product characteristics
Process and manufacturing
Control and response uncertainty
Decision complexity
Organizational structure and human behaviour
Information technology and system complexity
End customer demand
Demand amplification
Supplier characteristics
Parallel interaction
Lead time
Supply chain configuration
Environmental impacts
Natural disruptions

which are associated with dealing with uncertainty. Buzz words like responsiveness, agility and stability are all used with the aim to describe a SC that is robust and able to cope with or manage uncertainty.

Gupta and Maranas (2003) state that an enterprize can adopt two strategic postures when faced with uncertainty. It can either position itself as a shaper (reduce uncertainty) or an adapter (manage uncertainty). Many SC improvement initiatives are aimed at countering the effect of uncertainty. In this regard, Fang *et al.* (2013) classify initiatives into three groups: reducing demand variability, reducing supply variability and reducing demand and supply variability simultaneously.

There are many methods to manage or reduce uncertainty in the SC. Simangunsong *et al.* (2012) present a state of the art literature review on uncertainty and identify ten methods to reduce uncertainty and eleven strategies for coping with uncertainty. Methods to reduce uncertainty include lean operations, product design, collaboration, decision policy and procedure, pricing strategy and redesign of chain configuration. Methods to cope with uncertainty include process, customer and delivery flexibility, multiple suppliers, strategic stock, lead-time management, risk management and also collaboration.

It is important to take the effect of uncertainty into account when developing SC models. Uncertainty in SCs support the argument for the use of stochastic models presented in the previous section (Section 2.1.5). Gupta and Maranas (2003) state that there are essentially two ways to model uncertainty, the one is scenario-based and the other is distribution-based. The scenario-based approach can be used when all possible scenarios are known as discrete events. The distribution-based approach can be used when single discrete events are not known but rather a continuous range of possible outcomes.

It is evident that all SCs contain some form of uncertainty. Most, if not all, SC managers deploy strategies to combat the negative effects of uncertainty within a SC. This is either done by reducing uncertainty or by managing the uncertainty. Melo *et al.* (2009) state that the most well-known form of risk in SCs relates to the uncertainty in customer demand and costs. Demand uncertainty is one of the reasons why inventory exists within a SC. Similarly, uncertainty in the demand for spare parts impacts spare parts inventory. In the context of spare parts inventory management, an understanding of uncertainty in the spare parts SC can therefore contribute to a better solution to the problem. The next section focuses specifically on inventory management.

2.3 Inventory management

Section 2.1 provides an overview of SCM and Section 2.2 discusses uncertainty in the SC context. Inventory is one method to manage uncertainty and buy down risk. This section provides an overview of inventory management principles.

Inventory management is one of the cornerstones of SCM. The link between inventory management and SCM is not a new concept. In fact, according to Ganeshan and Harrison (1995) the term 'Supply Chain' first appeared in literature as an inventory management approach. Schroeder *et al.* (2013) state that inventory is one of the most visible signs of SCM.

In today's competitive marketplace, where change is the only constant, managing uncertainty is very important. Davis (1993) compares inventory to insurance against uncertainty. If all variables in a SC were known for certain, there would not be a need for inventory management. Inventory is relevant in business because of its direct link to service level which affects revenue. Abuhilal *et al.* (2006) state that inventory is one of the key cost-contributors in any SC. This statement is supported by Ganeshan and Harrison (1995) who mention that inventory cost can be between 20 - 40 % of revenue and Heizer *et al.* (2004) who state that inventory is one of the most expensive assets of many companies and can represent as much as 50 % of total invested capital.

Gajpal *et al.* (1994) state that spare parts constitute a large portion of total inventory in manufacturing companies. There is a large amount of uncertainty in the management of spare parts ranging from unpredictability of demand to varying supplier lead times. For this reason, inventory management plays a prominent role in SPM and is a field worth investigating. This section starts by providing an overview of inventory management. Thereafter, the principle concepts within inventory management are explained: classification of inventory, demand forecasting and inventory models. The aim of this section is to provide an overview of the theory on inventory management to aid as a sound background for the rest of the study.

2.3.1 Overview of inventory management

In order to provide an overview of inventory management, it is necessary to first clarify some of the key terms in the field. Inventory, as defined by Chase (2010), is the "stock of any item or resource used in any organization". Following on this definition, an inventory system is the set of policies and controls used to ensure adequate levels of inventory. Inventory management is concerned with setting appropriate stock levels, determining order frequencies and specifying optimal order sizes. Schroeder *et al.* (2013) define the term 'supply' as the rate at which inventory is replenished and the term 'demand' as the rate at which inventory is depleted. Inventory therefore acts as the buffer between the supply and the demand rate.

Chase (2010) states that the purpose of inventory is to maintain independence of operations, to satisfy demand, to allow flexibility in production scheduling, to provide a safeguard for variability in supplier lead-times and to take advantage of economic order sizes. The link between the purpose of inventory and managing uncertainty is very clear. This study agrees with Ganeshan and Harrison (1995) that the purpose of inventory, can be summarized as to act as a buffer against uncertainty. The more uncertain a SC, the more stock is needed. Inventory is held throughout a SC in the form of raw materials, work in progress (WIP), finished goods and replacement parts or operating supplies. In a SC there could be multiple points of stock-holding and also multiple types of stock held at stock-holding points. Figure 2.4 shows a generic view of a SC with specific reference to the inventory points (indicated by triangles).

Huang *et al.* (2010) state that the trade-off in inventory management is logical and clear: on the one hand, the risk associated with unavailable stock items is high; while on the other hand, high stock levels ties up large amounts of capital. The first point regarding stock-outs could result in poor service and costly emergency actions. Heizer *et al.* (2004) state that the objective of inventory management is to "strike a balance between inventory investment and customer service." The basic purpose of inventory management is to answer the following questions (Kennedy *et al.*, 2002; Chase, 2010):

1. When should an order be placed?
2. How many units should be ordered when an order is placed?
3. What is the objective of the inventory policy? Is the objective to reduce costs or to increase availability or service level?

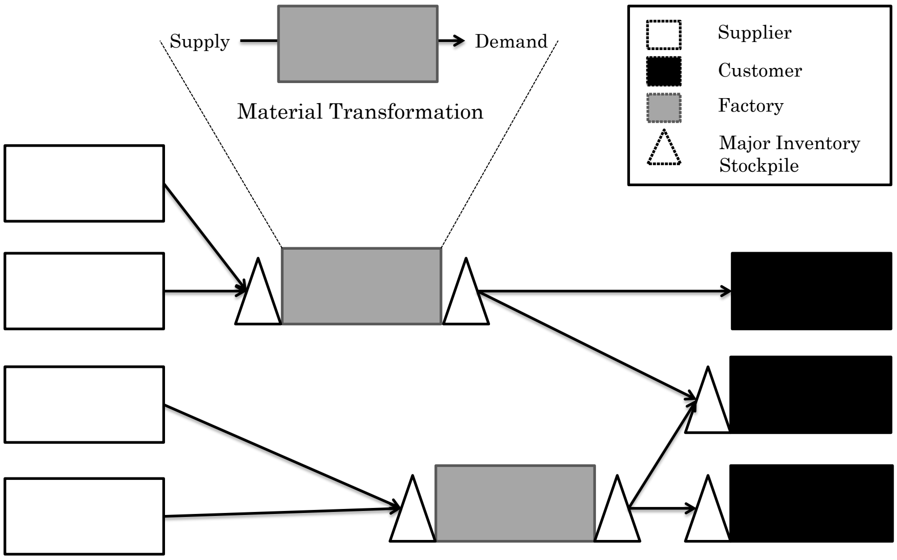


Figure 2.4: Inventory in supply chains. Adapted from Davis (1993)

Inventory classification, demand forecasting and inventory models and costs are intricate components of inventory management which assist managers to manage inventory systems. These components are discussed in the remainder of this section.

2.3.2 Classification of inventory

Inventory classification is necessary to effectively manage inventory. According to Silver *et al.* (1998), some large manufacturing companies have more than 500,000 distinct items in stock and typical medium-sized companies stock approximately 10,000 types of raw materials, parts and finished goods. It is therefore clear that it is necessary to divide the inventory portfolio into manageable subgroups. Van Kampen *et al.* (2012) state that two questions need to be answered to classify SKUs: how should the boundaries between classes be determined and how many classes should be used. Inventory items are generally classified on a Stock Keeping Unit (SKU) level. A SKU refers to a unit that is completely specified according to function, size, colour or any other unique characteristic (Silver *et al.*, 1998). This section highlights the common approaches used to classify inventory items.

Van Kampen *et al.* (2012) studied numerous literature papers on the classification of inventory and divide classification approaches into statistical and judgemental based methods. Statistical approaches include, amongst many, the ABC approach and the Fast, Normal and Slow-Moving technique (FNS). Judgemental approaches include techniques such as the Vital, Essential and Desirable approach (VED) and the Analytical Hierarchy Process (AHP).

Ramanathan (2006) mention that the most common approach to classify inventory items is the ABC approach which is based on the Pareto principle. The Pareto principle refers to the logic that is often used based on the principle that few items have large importance and that many items have little importance (Chase, 2010). The principle is also referred to the 80:20 principle in which 80% of products are seen to contribute 20% of revenue and 20% of products contribute to 80% of revenue. The FNS approach is related to the ABC approach. In the FNS approach, SKUs are classified according to their demand volume into 'fast', 'normal' and 'slow-moving' categories. Molenaers *et al.* (2012) argue that despite the fact that the ABC classification scheme is easy to use, it is very limited. The ABC-method is only successful when the assortment differs mainly in terms of a single criteria. In practice, there is often however a need to classify inventory items according to more than one criteria. For example: items are classified not only according to value but also other factors such as lead time, inventory cost, demand distribution, criticality, stock-out penalty cost, substitutability, order size requirement, scarcity and durability. Nevertheless, the ABC approach is widely adopted. Silver *et al.* (1998) state that one of the benefits of the ABC approach is the identification of the large group of C items. These items typically consume a large amount of data input and managerial time without contributing significant value and therefore have to be managed accordingly.

The VED method is a popular judgemental classification approach and especially used to classify items according to criticality. The approach is based on managers' judgements to divide SKUs into 'vital', 'essential' and 'desirable' categories. It is easy to implement but is based on subjectivity. Another judgemental classification technique, AHP, can be used to rank different items according to different characteristics using pairwise comparisons (Gajpal *et al.*, 1994). Other, more complicated methods have subsequently been developed to accommodate for the shortcomings in traditional classification approaches. Authors have proposed multiple-criteria decision-making tools, cluster analysis and heuristic approaches based on artificial intelligence.

The choice of classification criteria is very important and is dependent on the situation and part characteristics. Amongst the many criteria used; items can be classified according to revenue, volume, criticality and cost. According to Ramanathan (2006), items are predominantly classified according to their annual use value which is the product of the annual demand and the average unit price. Van Kampen *et al.* (2012) state that volume, product, customer and timing are amongst the most common criteria used.

Most inventory management literature papers start with the classification of inventory and it is clear that it is a vital and important task for effective management of inventory. This topic is discussed in further detail as it applies to SPM in a latter part of this study (Section 3.2). The next section discusses demand patterns and forecasting.

2.3.3 Demand patterns and forecasting

Demand forecasting is a key component of inventory management. In this regard, Ghobbar and Friend (2003) point out that demand forecasting is a prominent issue in inventory management because it forms the basis for determining appropriate inventory levels. According to Winklhofer *et al.* (1996), the selection of forecasting technique is dependent on a number of factors such as accuracy, time frame, data availability, ease of use, data pattern and number of items.

The nature of demand can broadly be categorized into derived and independent demand types. Dooley (2005) state that derived demand is dependent on production or the demand of another product. Independent demand is a factor of the demand for an end product. An end product is the state a product is in when it can be used in its final form. Chase (2010) also states that independent demand is highly uncertain.

There are many different types of demand trends: seasonal demand, sporadic demand, intermittent demand, constant demand, etc. The demand trend is dependent on the type of product and the source which initiates the need for the product or the demand generation process. Demand trends are also classified according to industrial demand and domestic demand, autonomous and induced demand, perishable and durable goods demand, new and replacement demands, final and intermittent demand, company and industry demand.

The most common distinction made between forecasting techniques is between qualitative and quantitative techniques. There are a number of different forecasting techniques available in literature. Silver *et al.* (1998) describe Regression Procedures and the Box-Jenkins approach as examples of aggregate medium-range forecasting methods and describe the Moving Averages, Simple Exponential Smoothing and variations of Exponential Smoothing methods as short-term forecasting models. In addition to the above-mentioned methods, numerous other techniques are also available in literature, such as Bootstrapping, the Croston method and Holt-Winters Double Exponential Smoothing. Winklhofer *et al.* (1996) state that the most commonly used quantitative methods are the Moving Average approach and Straight Line Projections and also however observed that, in general, firms are more familiar with judgemental forecasting techniques than quantitative methods. This viewpoint is supported by Sanders and Manrodt (2003) who explored why judgemental forecasting techniques are favoured in practice despite technological and research advancement in new qualitative forecasting techniques.

This section serves as a short introduction to demand forecasting. This topic is further explained in the next chapter, in Section 3.3, when demand forecasting principles, specifically applicable to spare parts, are discussed. The next section discusses different models and policies which can be applied to assist inventory management. An important distinction between demand forecasting methods and inventory models is that the former requires a point estimation of the mean demand whereas the latter requires the entire demand forecast across a certain period.

2.3.4 Inventory models and policies

Inventory control policies are commonly used to assist the management of inventory. They are used to answer two main questions: When to place an order and how much to order. Different philosophies and models can be used to manage inventory. The choice of inventory model is dependent on factors such as demand pattern, lead time, uncertainty and variability in the inventory management process and availability of information. This sections starts by introducing the concept of lead time demand. Thereafter, the difference between a replenishment and a requirements philosophy is briefly discussed. The remainder of the section focuses on the inventory models used under the replenishment philosophy.

It is important to note the difference between point forecast estimators and estimations of the entire lead time demand. Different forecast methods, such as moving averages and exponential smoothing, are introduced in the previous section. These techniques provide a point estimator of demand. Inventory control systems require estimations of the entire lead time demand. In oversimplified terms, this is a summation of point forecasts, but it also need to take into account the effect of uncertainty. This effect is accounted for by means of probabilistic forecasts (i.e. distributions). After obtaining an appropriate point forecast, this implies that a point forecast has to be transformed into a probabilistic forecast by estimating the distribution and its parameters.

For example: the average point estimation of demand is 2 units per month and the lead time is one year. The lead time demand is then 24 units, but there is also a degree of uncertainty in this estimation. The uncertainty is accounted for by describing the distribution of the demand. The demand could for example be normally distributed with an average of 240 units and a standard deviation of 3 units. The resulting probabilistic forecast is shown in Figure 2.5. The x-axis is the lead time demand and the y-axis is the probability of the lead time demand occurring.

Different inventory philosophies are used for independent and dependent or derived demand patterns. Schroeder *et al.* (2013) state that a replenishment philosophy is appropriate for independent demand patterns because stock is replenished as it is used so that the stock on hand satisfies customer demand. On the other hand, a requirements philosophy is used for dependent demand patterns. This is because the amount of stock to be ordered is dependent on the requirements for another product. In contrast to the replenishment philosophy, additional items are not ordered as the products are used. Fixed-quantity

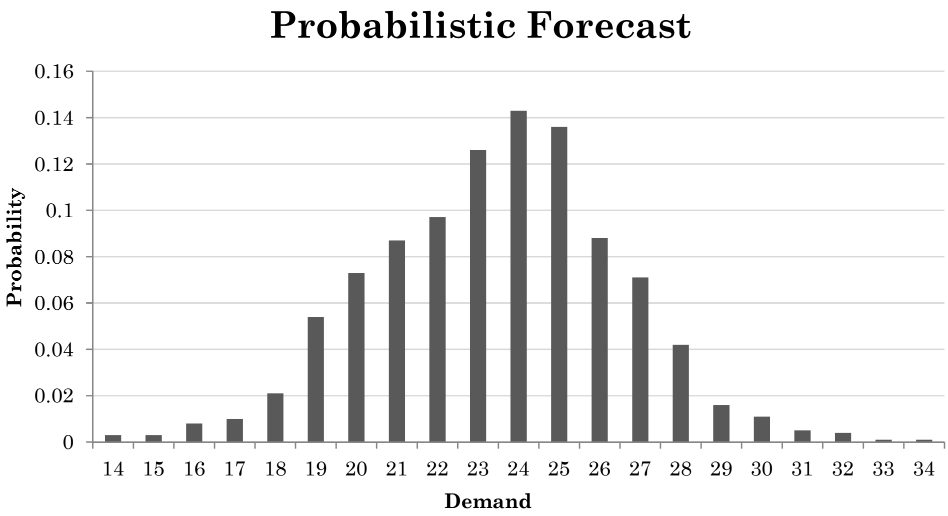


Figure 2.5: Demonstration of probabilistic forecasts

and fixed-period systems are mostly used for replenishment philosophies and materials requirement planning are used for requirements philosophies. Figure 2.6 summarizes the main types of inventory models.

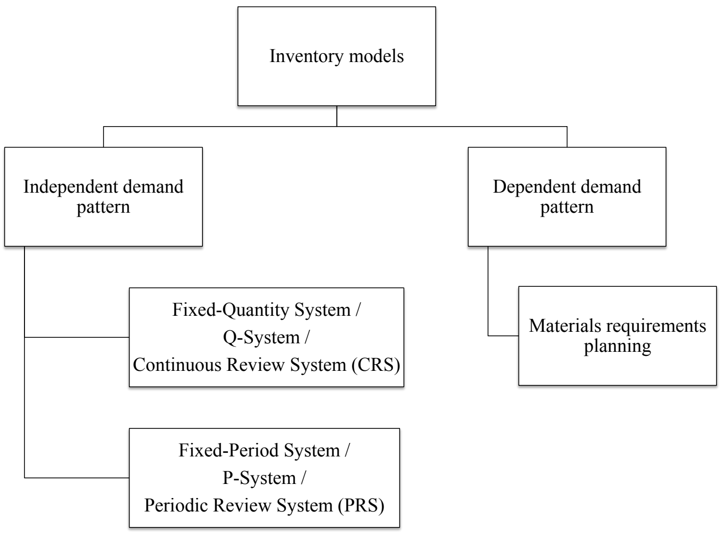


Figure 2.6: Inventory models categorization

This section focuses on models for independent demand patterns categorized under the replenishment philosophy. This is because material requirements planning under the requirements philosophy is predominantly applicable to the inventory of raw materials in a production process and managed with information systems. Also, the demand for spare parts is to a large degree independent as it is determined by part failures. It is influenced by the usage of equipment, but does not depend directly on the demand for a final product, as is the case in typical items with dependent demand patterns.

Models for independent demand patterns are broadly divided into fixed-quantity systems (Q-systems) or fixed-period systems (P-systems). Q-systems are triggered by events. In Q-systems, an order is the same size each time an order is placed. Orders are triggered when the inventory level reaches a certain point called the Reorder Point (ROP) and a fixed quantity called the Reorder Quantity (ROQ) is ordered each time. The following basic models exist for Q-systems: Economic Order Quantity (EOQ) model, Minimizing Cost model and Quantity Discount model (Heizer *et al.*, 2004). P-systems, on the other hand, are triggered by timing. This implies that stock levels are reviewed after a certain time period to determine whether an order is placed. The quantity ordered depends on the difference between the current stock level and the desired stock level.

There are many different terminologies used to differentiate between different inventory models. The distinction between inventory systems is often according to the review period: continuous and periodic review systems. Continuous review systems (CRS) are similar to fixed-quantity systems and periodic review systems (PRS) are similar to fixed-period systems. The CRS is also referred to as a (T, S) system and the PRS as a (R, Q) system. The one big difference between the two systems is that PRS have fixed review periods whereas CRS do not have fixed review periods. On the one hand, this leads to higher average stock-levels in PRS because extra inventory has to be kept to account for the demand during the lead time as well as the review period. On the other hand, CRS is more work because inventory has to be monitored constantly and is therefore not always practically feasible. In PRS, it is also possible to consolidate large orders and take advantage of economies of scale.

One of the main questions that arise in inventory management is how much to order when replenishing stock. This question is frequently answered by the Economic Order Quantity (EOQ) model which was developed by F.W. Harris in 1915. The EOQ model and its variations are widely used in practice and provide valuable insights on managing inventories. According to Stevenson and Hojati (2007), the EOQ model determines an optimal order size by minimizing the sum of certain annual costs.

Inventory usage over time for inventory managed with the EOQ model follows a sawtooth shape as can be seen in Figure 2.7. Inventory is replenished with a quantity, Q, when an order arrives. Inventory decreases at a constant rate equal to the demand (refer to the sloped lines in Figure 2.7). The inventory level therefore ranges between 0 and 100. The average inventory is half of the maximum inventory.

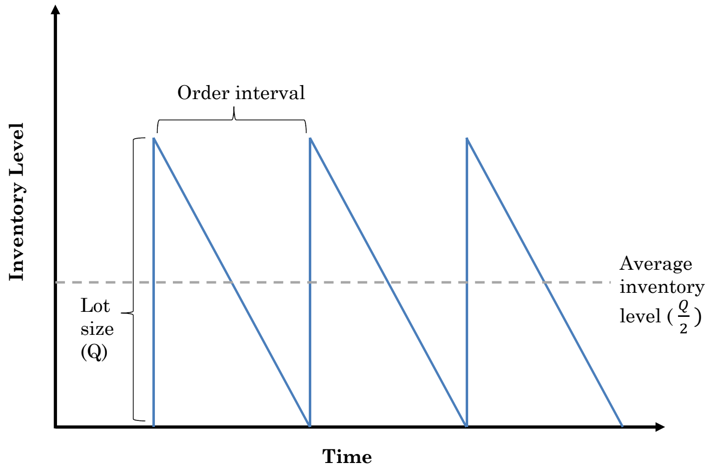


Figure 2.7: EOQ Inventory level over time. Adapted from Heizer *et al.* (2004)

Schroeder *et al.* (2013) and Heizer *et al.* (2004) state that the EOQ model is based on the following assumptions:

1. The demand rate is known, reasonably constant and recurring.
2. Lead time is known and constant. The lead time refers to the time between an order placement and an order delivery.
3. The unit item cost is constant without discounts.
4. Orders arrive in batches and all inventory from an order is received at the same time.
5. Stockouts can be avoided if orders are placed in time.
6. An item is a single item, independent and without interaction to other items.

The above-mentioned assumptions also contribute to the limitations of the EOQ model, because few of the assumptions hold in reality. The basic EOQ model, Economic Production Quantity model and the Quantity Discount model are three different models which are frequently applied in this context. The basic EOQ model is the simplest form of the model and does not consider lot sizes or discounts. The Economic Production Quantity model is applied in production environments where orders are not placed externally but rather produced by the company itself. It is similar to the basic EOQ model but takes into account lot sizes, replenishment is over time and no order costs are applicable. The Quantity Discount model is applicable when price discounts are received for large orders.

Another question that arises in inventory management is when to place an order. ROP models can be used to determine the inventory level which triggers an order. The ROP is a predetermined amount of stock on hand. It should take into consideration expected demand during the lead time as well as a cushion of stock to absorb uncertainty which is referred to as safety stock. Stevenson and Hojati (2007) mention the following determinants of the ROP quantity:

1. Rate of demand
2. Lead time
3. Extent of variability in demand and lead time
4. Service level requirements

The above-mentioned discussion on inventory models acts as an introduction to inventory control policies, there are numerous variations to the mentioned models. Examples of other models used are Single Period models, Base Stock models and inventory models with planned shortages. Detailed models with a specific focus on the application for spare parts are discussed in Section 3.4.

2.3.5 Inventory costs

Inventory management decisions, like most other decisions in business, are ultimately evaluated according to their financial impact. Therefore, it is important to understand the different costs associated with inventory management. According to Chase (2010), inventory costs can be split into the following categories: holding cost, set-up cost, ordering cost and shortage cost.

The holding cost category consists of costs for storage facilities, insurance, breakage, obsolescence, handling and also the opportunity cost for capital. The cost is usually split according to the cost of capital, cost of storage and cost of obsolescence (Schroeder *et al.*, 2013). It is important to mention that an opportunity cost has to be taken into account because of the revenue potential of the capital if it was not used as carrying cost. The opportunity cost is dependent on how the money would be spent if not spent on inventory (Dooley, 2005).

Set-up costs are the costs associated with making different products or changing from the production of one product to another. In most cases, this cost is dependent on the amount of time required to prepare machinery for a new production run or the materials required to perform a change-over operation. Set-up costs are important as it relates to the link between production processes and inventory. A company could decide to increase the length of production runs to produce more of a particular item than is required. This would decrease the total set-up cost, but would increase the holding cost of inventory because the produced items need to be kept in stock until required.

The ordering cost is the cost associated with placing an order. It includes inbound transport and storage costs. The order cost, in most cases, relates to ordering the entire batch of items and is not dependent on the size of the order. Moncrief *et al.* (2006) state that the following factors should be included to determine the cost of ordering inventory: administration cost to create purchase order, receipt and inspection costs, expediting costs, cost to process accounts payable and discounts.

Shortage costs are also referred to as stock-out costs. It is the cost related to the scenario when stock is depleted and orders cannot be fulfilled. This could either result in an order being cancelled or in a backorder. In the case that the order is cancelled, this cost is the lost profit. In the case of a backorder, this cost could include additional charges to deliver the order as well as future potential lost sales because of customer disappointment.

Dooley (2005) mentions the inverse proportionality between service level and logistics costs (which includes inventory costs). It is possible to achieve a higher service level by carrying more inventory, but the trade-off is however that higher inventory levels drives higher costs. According to Dooley (2005), as service level increases, logistics costs increase steadily up to a point and then exponentially with service levels above 90% (Refer to Figure 2.8). The total inventory cost is an important metric for determining appropriate inventory control policies and is therefore a fundamental concept to take into consideration in the proposed solution and validation of this study.

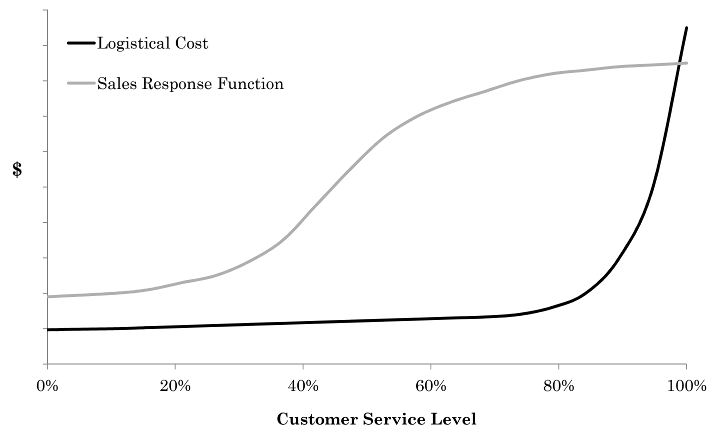


Figure 2.8: Service level versus logistics costs. Adapted from Dooley (2005)

This section, Section 2.3, provides an overview of inventory management and discusses the classification of inventory, demand patterns and forecasting, inventory models and policies, and finally inventory costs. The next section summarizes this chapter.

2.4 Chapter summary

In conclusion, Chapter 2 sketches the SCM landscape. It provides an overview understanding of the topic and discusses the key components, decisions and models in the field. This chapter also deals with the issue of uncertainty in SCM and discusses the fundamentals of inventory management which is one method to manage uncertainty.

This chapter contributes towards achieving the first objective of this research study. Consequently, the following sub-objectives, as stated in Section 1.3, were achieved in this chapter:

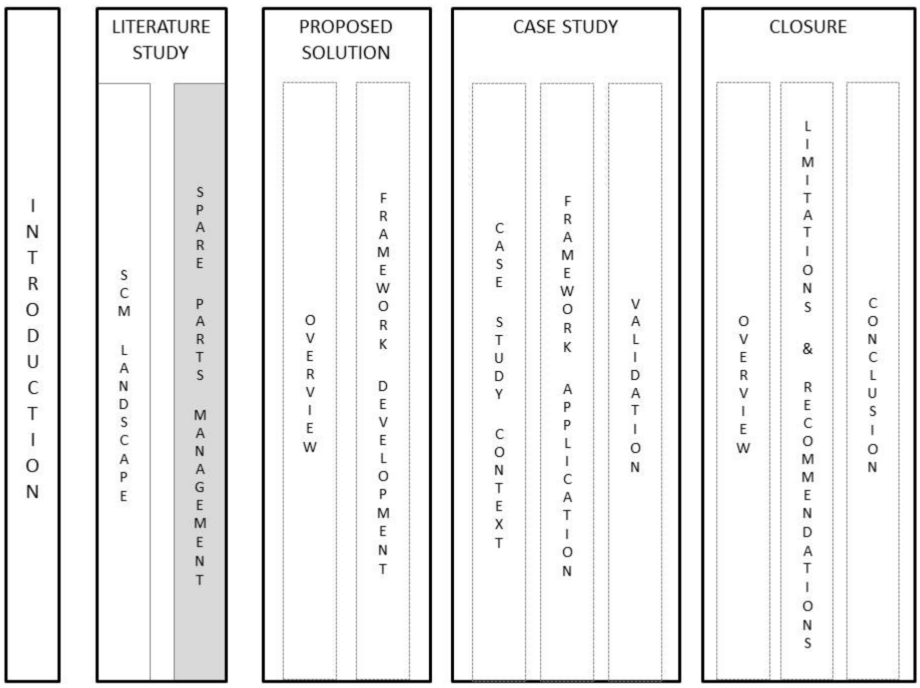
- Review the key concepts in SCM
- Determine the relationship between SCM and SPM
- Identify the fundamentals of inventory management

This chapter aims to anchor and guide the discussion in the second part of the literature review and remainder of the study. The next chapter, Chapter 3, applies the fundamentals established in this chapter to the management of spare parts.

Chapter 3

Spare parts management

This chapter constitutes the second part of the literature study. Chapter 2 provides an overview of key concepts and background to the Supply Chain Management (SCM) field of study. This chapter uses the background and defined concepts as a basis and focus on the specific application of theories in the context of Spare Parts Management (SPM). First, it provides an overview of SPM, summarizes literature in the field and presents a summary of the characteristics which uniquely define spare parts. Thereafter, the chapter discusses the key considerations in spare parts inventory management. Finally, the discussion evolves to include the topics of maintenance and Physical Asset Management (PAM). The aim of this chapter is to provide background on the issue of SPM and to identify relevant practices in literature to be applied in the proposed solution in Chapter 4.



3.1 Spare parts management overview

Spare parts are essential in modern societies. Their need arise whenever components fail, need replacement or repair. For the purpose of this study, a spare part can be considered as a duplicate or replacement component used to replace a damaged part of a machine or for preventative maintenance purposes. The term spare parts are often used interchangeably with service parts, spares, repair parts and replacements parts. In this context, the term spare parts is used as a collective term for all duplicate parts including consumables and repairable parts.

According to Cavalieri *et al.* (2008), the management of maintenance, repair and operating materials is a vital task in capital-intensive companies. Ghodrati and Kumar (2005) state that good SPM enhances productivity in a company, because it reduces idle time and increases resource utilization. The availability of spare parts influences the performance of equipment and the stock levels of spare parts influence inventory costs. In this regard, Moncrief *et al.* (2006) mention that a well-balanced spare parts inventory system means having in stock exactly what you need when you need it - not too much, nor too little. The principle objective is therefore to achieve a sufficient service level with minimum inventory investment and administration costs (Huiskonen, 2001). A sufficient service level requirement is determined by a company's management by considering the trade-off between risk and inventory cost. This trade-off is presented in Figure 3.1. The figure shows that the inventory holding costs increase as the unavailability cost (risk) decrease. The challenge is to find the optimal stock level where there is an acceptable balance between risk and cost.

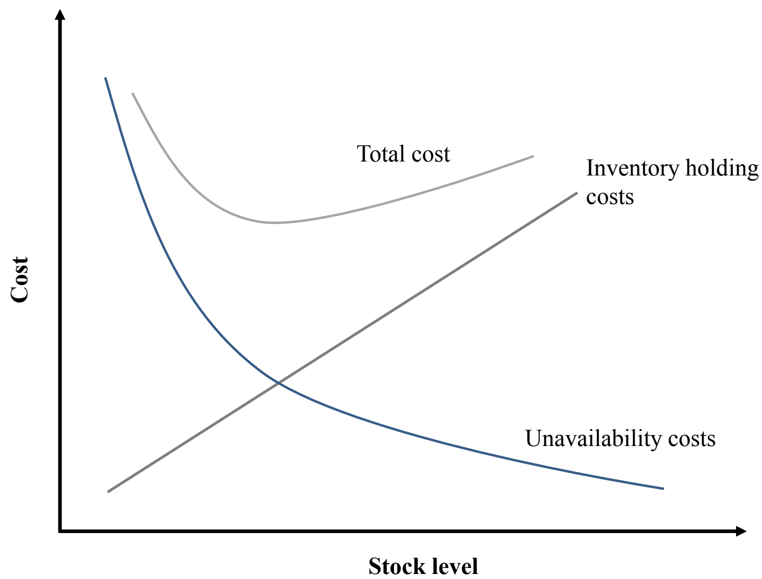


Figure 3.1: Inventory cost trade-off. Adapted from Cavalieri *et al.* (2008)

The aim of this section is to provide an overview of the field of SPM by outlining the literature in the field (Section 3.1.1) and discussing the characteristics of spare parts (Section 3.1.2).

3.1.1 Literature outline

There has been a growing interest in SPM over the past decades (Molenaers *et al.*, 2012). The field includes research areas such as production and inventory control, SCM, maintenance and reliability, asset management and strategic management. The literature related to SPM can roughly be divided into the following categories: review papers, studies on the classification of spare parts, studies related to demand patterns and forecasting of intermittent demand, studies focused on the maintenance aspect of spare parts and studies associated with inventory models and policies.

There are a number of review papers that have summarized significant parts of the literature on SPM. Kennedy *et al.* (2002) reviewed literature on maintenance strategies. The review is focused on typical issues in maintenance inventory management such as age-based replacement and obsolescence. Do Rego and de Mesquita (2011) reviewed literature on spare parts inventory control and discuss demand forecasting techniques and inventory control decisions. The study is concerned only with single location inventory control decisions. Van Horenbeek *et al.* (2013) reviewed joint maintenance and inventory optimization systems. The review is focused on optimization studies that take into account maintenance as well as inventory policies. Moncrief *et al.* (2006)'s book, "Production Spare Parts: Optimizing the MRO Inventory Asset", also provides a comprehensive overview on theories and practices in the field. The book includes numerous relevant case studies.

Literature studies concerning the topic of SPM include both non-technical approaches to problems as well as very technical, detailed and narrow in scope approaches. Examples of non-technical approaches are studies that propose generic guidelines for the management of spare parts (Cavalieri *et al.*, 2008; Huiskonen, 2001; Porras and Dekker, 2008). Technical research, on the other hand, is predominantly performed to improve existing systems and therefore required to design and test parts of models. An example of a technical study is the study performed by Vaughan (2005) which addresses an inventory policy for spare parts considering demand both from a scheduled preventative maintenance perspective as well as random failure perspective. The study proposes a stochastic dynamic programming model to address both sources of demand.

There are numerous studies focused on the classification of spare parts. Molenaers *et al.* (2012) suggest part classification based on item criticality. Bacchetti *et al.* (2010) propose and discuss a hierarchical multi-criteria spare parts classification method and test it by means of a case study at an Italian household appliances manufacturing company. Gajpal *et al.* (1994) discuss the evaluation of the criticality of spares by applying the Analytical Hierarchy Process (AHP). The topic of spare parts classification is further discussed in Section 3.2.

The intermittent demand nature of spare parts makes it difficult to forecast and has been a source of encouragement to many papers in literature. Some studies focus specifically on the demand for spare parts while others focus on forecasting intermittent demand patterns in general. Boylan and Syntetos (2010) reviewed the development of forecasting methods used to forecast the demand for spare parts. Wang and Syntetos (2011) developed a maintenance driven model which relies on the sources of demand generation to forecast the demand of spare parts. The performance of the model is compared to the well-known time-series model. Ghodrati and Kumar (2005) argue that environmental factors need to be taken into consideration when forecasting the demand for spare parts and therefore developed an operating environment-based forecasting model. Strijbosch *et al.* (2000) examined the performance of two inventory models and combined demand forecasting methods to obtain an optimal solution. Spare parts demand forecasting is further discussed in Section 3.3.

Inventory models and policies assist the management of inventory by defining a set of rules to determine when to place orders and what quantity of goods to be ordered. A number of studies have focused specifically on inventory policies best suited for the management of spare parts inventory. Shtub and Simon (1994) determined an appropriate reorder point for spare parts inventory in a two-echelon SC. Porras and Dekker (2008) empirically compared different re-order point methods for spare parts at a refinery. Haneveld and Teunter (1997) determined an optimal provisioning strategy for slow-moving spare parts which have small lead times and Gelders and Van Looy (1978) determined an inventory policy for slow and fast-movers. Inventory control policies applicable to SPM are discussed further in Section 3.4.

This study is similar to studies performed by Cavalieri *et al.* (2008); Bacchetti *et al.* (2010) and Kalchschmidt *et al.* (2003). It is similar in the sense that each of these studies propose a methodology to determine inventory policies for spare parts. It differs in the area of application, the scope and focus of the framework and the outline of the proposed steps. Decision-making frameworks for the management of spare parts are discussed in Section 3.7.

Other issues that have been addressed in literature are age-based replacement, multi-echelon problems, obsolescence and repairable items. Authors also gave recommendations for future research areas. Bacchetti and Saccani (2012) mention the need for integrated approaches to manage spare parts and to supplement theoretical models with practical guidelines in order to narrow the bridge between research and practice. Cavalieri *et al.* (2008) agree with this argument and state that few companies deliberately use proper tools and approaches to assist the management of spare parts despite the vast body of academic literature on the topic.

The next section explores the characteristics which uniquely define spare parts and thereafter the above-mentioned topics are studied in further detail when each of the main components of inventory management are discussed.

3.1.2 Spare parts characteristics

Different types of inventory exist to fulfil various needs. In a manufacturing environment, inventory is often categorized as follows: finished goods, Work In Progress (WIP), raw materials, and operating supplies and replacement parts (Moncrief *et al.*, 2006). Spare parts form part of the last mentioned category.

Cavalieri *et al.* (2008) mention four different types of spare parts: consumables, generic spare parts, specific spare parts and strategic spare parts. Consumables are those parts characterized by a steady and continuous assumption rate and also typically have a large supplier base. Generic spare parts are parts that can be used for more than one type of equipment. Specific spare parts, in contrast to generic parts, are only used for one type of equipment. Strategic spare parts are typically characterized by high cost, long supplier lead times and a sporadic demand. Capital-intensive companies require large initial capital expenditure (typically for equipment and machines) to operate. Capital-intensive industries are highly dependent on the effective use of equipment and machines, and therefore also require all types of spare parts. Spare parts play a prominent role to gain returns on capital expenditure, because parts are required to keep equipment and machines in a good working condition.

Spare parts have unique attributes which differ from finished goods, WIP and raw materials. Kennedy *et al.* (2002) note two main differences between the management of spare parts inventory and other types of inventory. The first difference is in the function of the inventory kept. WIP inventory acts as a buffer to uncertainty in the production process. Final products inventory is held to ensure good customer service levels by taking into account uncertainty and variability in lead times, quality and any other differences between supply and demand. In contrast, the main function for spare parts inventory is to assist maintenance staff to keep all equipment in a good operating condition. The second difference is in the policies that govern spare parts inventories. WIP and other final product inventories are a function of production, scheduling, lead time and demand and can therefore be governed accordingly. Spare parts inventory is a function of the utilization and maintenance of equipment and therefore maintenance policies have a direct impact on spare parts inventories.

Louit *et al.* (2011) agree that maintenance actions have a large effect on the forecast of demand for spare parts and state that the main differentiating factor for spare parts is the fact that the demand rate is dependent on the units in operation and not on an infinite population as is the case with general inventory. In addition, Kennedy *et al.* (2002) identify the following list of conditions which differentiate spare parts from general inventory items:

1. Effect of maintenance policies on demand forecast
2. Dependency of part failures
3. Influence of spare parts on equipment downtime
4. Possibility to cannibalize spare parts
5. Difficulty to determine the cost of 'lost sales' as it relates to equipment downtime
6. Obsolescence of spare parts in the case of discontinuation of related equipment
7. Repairability of parts

The quantification of the cost of unavailability (lost sales or tardiness) is another attribute of the management of spare parts which distinguishes it from the management of other types of inventory. The 'lost sales' in the case of unavailable spare parts directly influence the downtime of equipment. The total repair time of equipment consists of the active repair time as well as the administration delay and logistics delay. The availability of spare parts influences the administration and logistics delay.

The management of spare parts is a complex topic which has been studied by numerous authors. There are a number of factors that contribute to the complexity of managing spare parts inventory. Firstly, spare parts management is affected by many factors typically not taken into account in general inventory management problems, such as maintenance and repairs. Secondly, spare parts typically have intermittent or lumpy demand patterns which are difficult to forecast. Thirdly, the decision regarding optimal stock levels is influenced by conflicting objectives between different departments. For example: an item that is considered important from a maintenance perspective is not necessarily viewed worth keeping in stock from a logistics perspective (Molenaers *et al.*, 2012). Finally, the spare parts portfolio contains a wide range of products with diverse characteristics. This complicates the management of stock items and customized inventory control policies are therefore needed to manage the different items.

It is important to take into account all these factors in SPM and impossible to view the problem in isolation. This section provided an overview of SPM and the characteristics of spare parts. It sets a good basis for a detailed discussion on the different components within the study field of SPM. The next section discusses the classification of spare parts which is the first component of SPM to be presented.

3.2 Classification of spare parts

Inventory classification is a common method applied for effective inventory management. Even as the use of advanced computerized systems to manage inventory is increasing, it is still necessary to classify inventory in sensible groups for better controlled management. Refer to Section 2.3.2 for an overview of inventory classification methods in general. This section focuses on methods and criteria specifically appropriate to classify spare parts.

The spare parts assortment often varies highly in size of demand, costs, service requirements and demand patterns. It is therefore common amongst researchers, as well as practitioners, to classify spare parts in different categories in order to control the wide and highly varied assortment. Bacchetti and Saccani (2012) state that the classification of parts assists managers to make forecasting and stock control decisions as well as to determine service level requirements for different classes. Jouni *et al.* (2011) agree and state that spare parts categorization is necessary in order to create manageable control groups to focus management efforts effectively. Cavalieri *et al.* (2008) point out that the classification of spare parts assists financial departments to determine which items require capital investment and which are considered as consumables, assists logistics departments to determine stock levels and assists maintenance departments to ensure consistency between maintenance policies and the availability of spare parts.

In this section, classification methods are discussed first (Section 3.2.1) and thereafter the criteria for classification are discussed (Section 3.2.2). Demand patterns are one of the core criteria influencing forecasting methods. There are certain methods for the categorization of demand patterns which do not pertain to other criteria. The categorization of demand patterns is therefore discussed separately in Section 3.2.3.

3.2.1 Classification methods

The methods used to classify spare parts are in principle similar to the general classification methods discussed in Section 2.3.2. Most literature papers on the topic of spare parts classification however propose general methods which are tailored to the specific needs of spare parts. Both quantitative and qualitative methods can be used to classify spare parts. In quantitative methods, a numerical value is appointed to drivers. In qualitative methods, subjective judgements are made to determine the magnitude of drivers.

Most researchers focus on quantitative methods for classifying spare parts. The traditional Pareto-based or ABC approach is the most common method (Bacchetti *et al.*, 2010). According to Syntetos *et al.* (2009), a Pareto report lists all stock keeping units (SKUs) in a descending order according to a certain criteria and divide the SKUs into relevant categories. The categories are typically called A, B and C. A indicates the items with the highest value for the specified criteria and C the lowest value. The advantage of this method is that it is easy to use and implement. Usually, this approach is however concerned with measuring a single criterion (eg. demand volume) which limits the extent of use of the method to items which are homogeneous in nature.

Molenaers *et al.* (2012) argue that the assortment of spare part is too heterogeneous to be classified using the ABC approach based on a single parameter. Other authors, such as Ramanathan (2006) and Chen (2011), agree and have extended the traditional ABC approach to a multi-criteria ABC analysis by integrating other methods such as Weighted Linear Optimization and Artificial Neural Networks (ANN). Variations of the ABC approach therefore range from mono-driver-based methods to multiple-driver-based methods. Nevertheless, besides its limitations, the ABC approach is still a simple method, widely adopted in practice to classify spare parts.

The most popular qualitative method used to classify spare parts is the VED (vital, essential, desirable) approach (Gajpal *et al.*, 1994). This approach uses expert judgement to categorize spare parts into 'vital', 'essential' and 'desirable' groups. The advantage of this method is that it takes qualitative judgements into account and is easy to understand and implement. The disadvantage is that the rating of criteria can be considered subjective. There are numerous variations of the VED approach available in literature. Cavalieri *et al.* (2008) mention for example a method which is called the BRIC method. This method classifies spare parts based on the following equipment criteria: B, Breakdown effect; R, Running (defined according to production shifts); I, Importance in production process and C, Condition of ageing. According to Do Rego and de Mesquita (2011), spare parts for industrial maintenance are commonly classified with the VED approach and consumer goods classified with the ABC approach.

The Analytical Hierarchy Process (AHP) is another common approach for classification. Molenaers *et al.* (2012) state that the AHP is "based on expert judgements and pair-wise comparisons, assigning relative weights to different attributes." The difference of importance is based on a ratio scale in the form of judgement matrices and translated into mathematical matrices. A major advantage of the AHP is the fact that qualitative as well as quantitative criteria can be combined and weighted according to importance. A possible limitation of the method is the fact that pair-wise comparisons could be viewed as subjective. A case study by Botter and Fortuin (2000) showed that the AHP approach was the best solution to a spare parts classification problem dealing with electronic devices for industrial applications. An interesting observation is however that this approach was deemed to theoretical by managers and was therefore reduced to the VED approach.

Other, more advanced methods have also been proposed to classify spare parts. Braglia *et al.* (2004) propose a multi-attribute decision-making classification model as a tool for spare parts inventory management. The operative scheme is based on the application of a standard maintenance classification scheme combined with the AHP. Huang *et al.* (2010) applied the Back-Propagation Network (BPN) method to evaluate the criticality class of spare parts. BPN is an Artificial Neural Networks technique. The study confirmed that the application of the BPN technique results in lower holding cost, because target service level settings are modified appropriately according to criticality classes of parts.

This study prefers the practical classification approaches suggested by Molenaers *et al.* (2012), Braglia *et al.* (2004), Botter and Fortuin (2000) and Syntetos *et al.* (2009) to classify spare parts. The proposed solution in Chapter 4 aims to integrate the ABC approach with the VED approach to classify items. The ABC approach is used as an initial filter to categorize items into broad categories. Thereafter, experts' judgements are incorporated to divide items into smaller subgroups through VED analysis. The choice of the proposed classification methods is influenced by Botter and Fortuin (2000)'s observation that management prefer practical approaches to theoretical approaches despite the potential of improved accuracy by using theoretical approaches. In Botter and Fortuin (2000)'s case, the VED approach was preferred over the AHP approach even though the AHP approach delivered better results.

3.2.2 Criteria for classification

Classification methods use criteria to classify inventory items. Numerous criteria can be used to classify spare parts. The choice of criteria is dependent on the inventory situation and stems from different perspectives. From an inventory perspective, spare parts are typically classified based on attributes like demand pattern, purchasing price and inventory costs. Some authors have also extended the classification to a maintenance perspective. In which case, other criteria such as lead times, machine failure, supplier reliability, and item criticality are also taken into consideration.

In literature papers, different criteria are used to classify spare parts. A summary, adapted from Bacchetti *et al.* (2010), of criteria used in papers since the year 2000 is presented in Figure 3.2. The summary confirms Huiskonen (2001)'s observation that multi-criteria classification criteria are most commonly used and furthermore it shows that the use of criteria is spread almost evenly between part criticality, part value, supply characteristics and demand patterns (including demand variability and demand value).

Author(s)	Year	Mono Criteria	Multi Criteria	Criterion					
				Part Cost / Value	Part Criticality	Supply Characteristics	Demand Volume / Value	Demand Variability	Others
Huiskonen	2001		x	x	x			x	x
Sharaf and Helmy	2001		x	x	x	x	x		
Partovi and Anandarajan	2002		x	x		x	x		
Braglia et al.	2004		x	x	x	x	x		
Eaves and Kingsman	2004		x			x		x	
Syntetos et al.	2005		x					x	
Ramanthan	2006		x	x	x	x	x		
Zhou and Fan	2006		x	x	x	x	x		
Boylan et al.	2008		x					x	
Cavalieri et al.	2008		x	x	x	x		x	x
Chen et al.	2008		x		x	x	x		
Chu et al.	2008		x	x	x				
Porras and Dekker	2008		x	x	x	x	x		
Persson and Saccani	2009		x	x	x	x	x		x
Syntetos et al.	2009	x					x		
Bacchetti	2010		x	x	x	x	x	x	x
Molenaers et al.	2012		x		x	x			

Figure 3.2: Literature summary: Classification of spare parts. Adapted from Bacchetti *et al.* (2010)

Bacchetti and Saccani (2012) identified that part criticality and part cost are amongst the most commonly proposed criteria for the classification of spare parts. Part criticality, in particular, is a popular criteria used for spare parts classification. Huang *et al.* (2010) agree and emphasize the importance of the evaluation of criticality in SPM. Molenaers *et al.* (2012) proposed a spare parts classification method based on the criticality level of an item. The method starts with a multi-criteria analysis to convert criteria impacting criticality into a single score called the criticality-level. The criticality-level is then used to rationalize the efficiency of the spare parts inventory policy. Gajpal *et al.* (1994) also elaborate on the criticality of spare parts and use the AHP as a classification method.

The distinction of repairable and non-repairable parts is another important criterion as it affects the SC processes and the lead time of parts. A repairable part is a part that is removed from the system after failure, sent to a repair facility and returned to operation after some time. A non-repairable part is a part that, once removed from operation, is discarded and not returned. This categorization is important as it affects inventory control decisions. In the context of repairable items, the repair time is similar to the conventional lead time of a part and therefore it is important to take into consideration the repair time to determine whether extra spare parts need to be held in stock.

In summary, criteria for the classification of spare parts can roughly be divided into the following three groups: demand-, supply- and cost-related criteria. Demand-related criteria include the demand pattern, demand volume and machine failures. Supply-related criteria include the lead time, supplier availability and supplier reliability. Lastly, cost-related criteria include part cost, inventory cost, administration cost and risk cost.

Part criticality, part cost, supplier lead time and demand patterns are considered to be primary criteria in this study. This choice is supported by the number of occurrences of each of these criteria in literature papers. These factors, of which part criticality are assumed most important, are taken into account explicitly in the proposed framework in Chapter 4. The other factors are also taken into consideration implicitly when using expert judgements to determine the criticality of parts. The criteria can be divided into two groups according to their objective. The first three criteria (part criticality, part cost and supplier lead time) influence the required service level of parts and feed into the stock control policy. The fourth criteria (demand patterns) influences primarily the forecasting method. These two types of criteria should therefore be applied separately to accommodate the necessary outcome. Traditional methods discussed in Section 3.2.1 can be applied to the first group of criteria. The next section discusses the methods used to classify items according to the second group of criteria (demand patterns).

3.2.3 Demand pattern categorization

Demand pattern classification relate directly to forecasting and stock control decision-making. Numerous methods and criteria have been used to classify demand patterns. Bacchetti *et al.* (2010) state that the average inter-demand interval and variability of demand size have shown to be particularly important.

Williams (1984) proposed a method to categorize demand patterns into 'smooth', 'slow-moving' and 'sporadic' groups by partitioning the variance of demand during a lead time into causal parts. A matrix indicating the categorization criteria can be seen in Figure 3.3 where symbol L is the mean lead time duration, λ is the mean demand arrival rate and CV is the coefficient of variation of demand sizes. The vertical axis indicates the intermittence of demand and the horizontal axis indicates the lumpiness of demand. Lumpy demand patterns are both intermittent and vary in demand size. Category D2 items are sporadic, category B items are slow-moving items and category A, C and D1 items are smooth with a continuous demand.

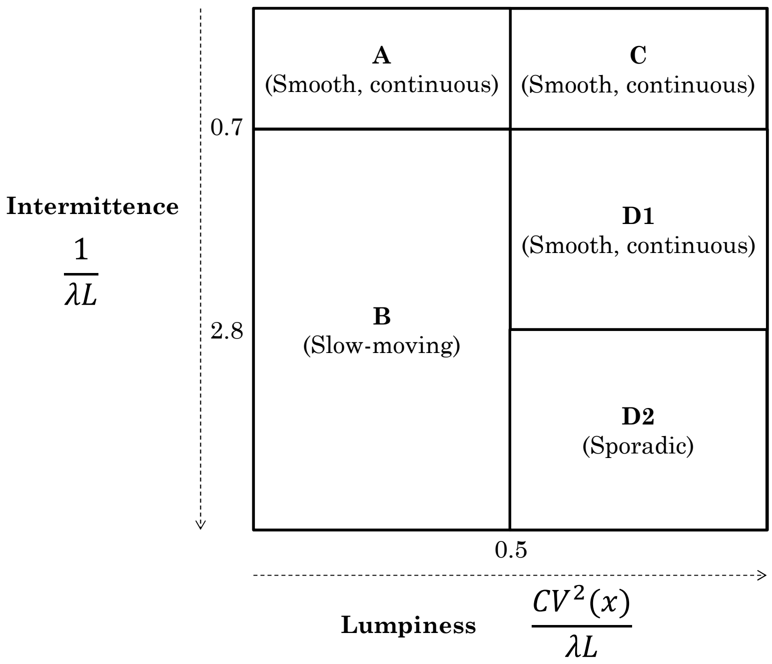


Figure 3.3: Demand pattern categorization. Adapted from Williams (1984)

Eaves and Kingsman (2004) state that the above-mentioned classification scheme did not adequately represent the Royal Air Force observed demand structure. This led to the development of a revised classification scheme based on transaction variability, demand size variability and lead time variability which subdivides demand patterns into 'smooth', 'irregular', 'slow-moving', 'erratic' and 'highly erratic' groups. Both classification schemes make use of arbitrary chosen cut-off values which are only appropriate for a particular empirical situation.

Ghobbar and Friend (2003) also modified Williams' criteria and use the Average Demand Interval (ADI) and Coefficient of Variation (CV) to classify parts according to the following conditions:

- $ADI \leq x, CV^2 \leq y$ – Condition test for fast-moving, smooth demand patterns
- $ADI > x, CV^2 \leq y$ – Condition test for slow-moving or intermittent demand with little variability when it occurs
- $ADI > x, CV^2 > y$ – Condition test for lumpy demand items which are typically intermittent and erratic
- $ADI \leq x, CV^2 > y$ – Condition test for fast-moving, erratic demand patterns

In the above-mentioned conditions, a cut-off value of 1.32 was used for ADI and 0.49 for CV^2. The cut-off values determine the number of items categorized in each of the groupings. The following equations are given to calculate ADI and CV (Cavalieri *et al.*, 2008):

$$ADI = \frac{n_0}{P} \tag{3.2.1}$$

$$CV = \frac{\sqrt{\sum_{i \in \hat{P}} (d_i - \bar{d})^2 / \text{card}(\hat{P})}}{\bar{d}} \tag{3.2.2}$$

In Equation 3.2.1, n_0 refers to the number of periods with no demand and P is the set containing all the periods with demand. In Equation 3.2.2, d_i refers to the demand during period i, $\bar{d}$ refers to the average demand. In simple terms, the coefficient of variation equals the standard deviation divided by the mean. Take note, in this case, the periods with no demand is excluded from the CV calculation, because ADI already takes the absence or presence of demand into account.

A number of similar methods and criteria are incorporated in SPM-related studies. Bacchetti *et al.* (2010) classify items into 12 classes based on their demand patterns as well as other factors such as part criticality, part cost and response lead time to customers. Moncrief *et al.* (2006) divide spare parts into 'active' and 'rarely-used' groups. 'Active' parts are items which are used frequently enough (more than once per month) so that future demand can be predicted with reasonable accuracy. The priority objectives for active parts are to improve service level, reduce item cost and minimize transaction cost. 'Rarely used' parts are used infrequently and their future demand is difficult to predict. Moncrief *et al.* (2006) also observe that the majority of items fall into the 'rarely-used' category and account for the majority of the value. This phenomenon is depicted in Figure 3.4 which shows the typical production inventory portfolio. Rarely-used items account for 88% of items, 90% of the value of items, but only 55% of usage value and 25% of the number of transaction. This distribution of items across the inventory portfolio is important when considering inventory control policies.

Some studies concentrate on the link between the categorization of demand and forecasting methods, with the aim to match demand patterns to the best suited forecasting methods, as well as inventory policies. Kalchschmidt *et al.* (2003) filter demand patterns into 'stable' and 'irregular' demand patterns according to the variation in demand. Forecasting methods based on the Simple Exponential Smoothing (SES) method is proposed for the stable demand and the Croston method is proposed for irregular demand. Bacchetti *et al.* (2010) propose a multi-criteria classification scheme that suggests how to forecast demand and control inventories for each of the resulting categories. Forecasting

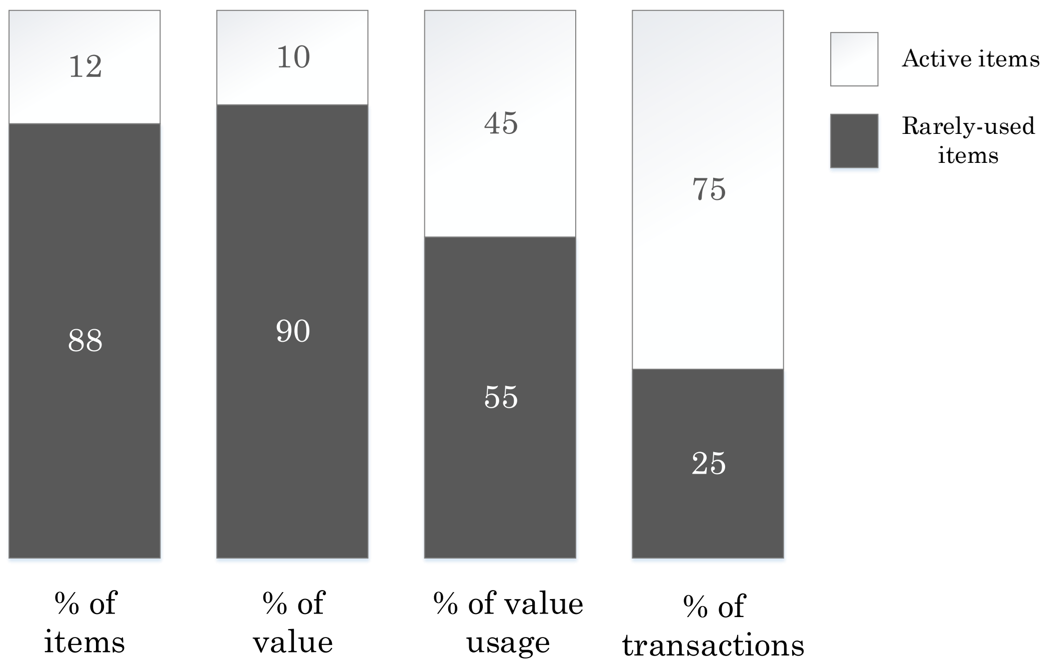


Figure 3.4: Typical inventory portfolio. Adapted from Moncrief *et al.* (2006)

methods are chosen based on theoretical background and viable policies are tested with a simulation study.

Syntetos *et al.* (2009) classified spare part items according to the Pareto principle with the demand value as criteria into A, B and C categories. In addition, D,E and F categories were also used for new products, problematic products and phase-out products respectively. Judgemental forecasting methods are proposed for A classified items. System based forecasting methods, where the estimator and parameters are based on the minimization of the mean absolute deviation (MAD), for B items and a method based on the moving average principle for C items. The summary of the outcome of the study is shown in Table 3.1. The table refers also to control methods and processes. Further detail regarding this topic is provided in Section 3.4.

Table 3.1: Forecasting and stock control policies proposed by Syntetos *et al.* (2009)

Category	Review Period	Forecasting	Control Method	Control Process
A	Week	Judgmental	Re-order point	Manual
B	Two weeks	System	Re-order point	Automatic
C	Month	Manually set	Re-order point	Automatic

Demand pattern categorization is highly dependent on the availability of data and information. The life-cycle of the asset, to a large degree, influences the availability of data and should therefore be taken into consideration before categorizing demand. Persson and Saccani (2009) added the life-cycle phase of equipment as an additional criterion for classification and found that it added significant value to the outcome of the study, specifically contributing to the safety stock requirement for each of the classes of items. Do Rego and de Mesquita (2011) also classified assets according to their life-cycles with the aim to determine appropriate stock control policies.

Demand intervals and variability are the two most common measures used to categorize demand. The demand interval is calculated by calculating the ADI and the demand variability is calculated by calculating the squared coefficient of variation. For the purpose of this study, a categorization scheme similar to Ghobbar and Friend (2003) and Cavalieri *et al.* (2008) is preferred which categorizes demand into 'fast-movers' and 'slow-movers' according to their demand interval, and 'smooth' and 'erratic' according to their demand variability. The next section discusses spare parts demand forecasting.

3.3 Spare parts demand forecasting

Demand forecasting is an important part of inventory management. There are numerous forecasting methods available to forecast demand patterns. This section builds onto Section 2.3.3 and discusses forecasting methods specifically applied to spare parts. It also seeks to find the common criteria of application for the use of different models.

Forecasting the demand for spare parts is a challenging task as the demand is intermittent and lumpy (Boylan and Syntetos, 2010). Intermittent demand is characterized by sequences of zero demand observations interspersed by occasional non-zero demands. Sometimes the demand observations also highly vary in size and are therefore seen as erratic. If demand is both intermittent and erratic it is termed as lumpy demand. The difference between slow-moving and lumpy demand patterns can be seen in Figure 3.5.

Research in the area of forecasting for intermittent demand has developed rapidly in recent years. Wang and Syntetos (2011) mention that the insights gained in research is useful for the development of inventory policies and some of the results are implemented in inventory management software, but practical implementation of policies however still lack somewhat behind.

This section starts by discussing the various demand forecasting techniques and thereafter more detailed information is provided on hypothesized demand distributions. Lastly, the link between demand patterns and forecasting methods is discussed.

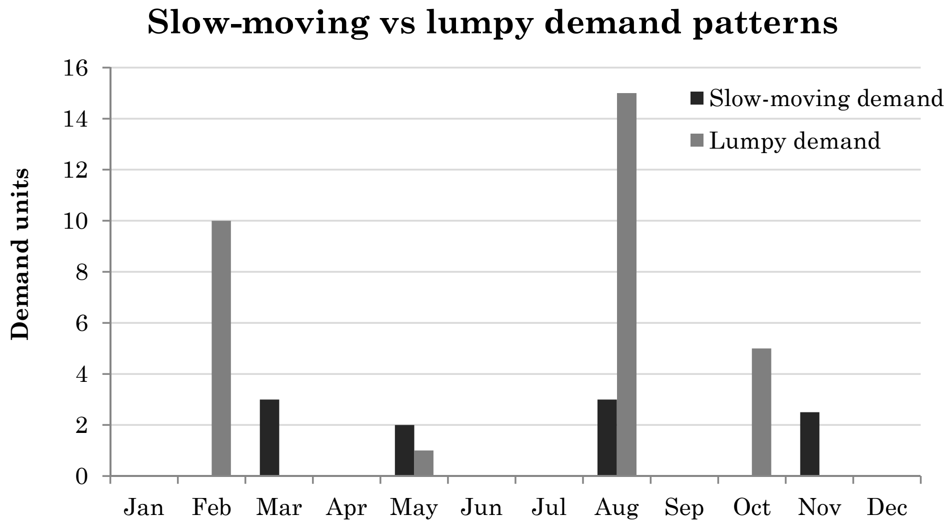


Figure 3.5: Slow-moving versus lumpy demand patterns

3.3.1 Demand forecasting techniques

There are two main classes of forecasting techniques for spare parts: reliability based forecasting and time-series based forecasting. Data availability is a critical determinant influencing the choice of forecasting technique. Reliability based forecasting techniques can only be used when condition monitoring information is available. Wang and Syntetos (2011) and Cavalieri *et al.* (2008) state that time-series analysis is more commonly used in practice to forecast the demand for spare parts unless historical data on explanatory variables are available.

Nevertheless, numerous studies have been based on reliability based forecasting techniques and proved significant benefits (Kennedy *et al.*, 2002; Wang and Syntetos, 2011; Van der Westhuizen and Van der Westhuizen, 2009). Kalchschmidt *et al.* (2003) state that models which are based on extensive information related to the process of demand generation (eg. maintenance information) cope better than traditional time-series models as demand uncertainty increases.

Farnum and Stanton (1989) defines a time-series as a "sequence of measurements of some numerical quantity made at or during successive periods of time". The following time-series based methods and approaches are commonly used to forecast the demand for spare parts: Croston method, SES and Moving Averages. Croston (1972) developed the Croston method, a forecasting method which combines both the interval of demand as well as the size of demand. In particular, the method is used by forecasting both the interval of demand and demand size using the SES method and then combining the output to get a forecast. Moving Averages and SES are simple and typical time-series approaches. Exponential Smoothing assigns different weights to past observations whereas the basic Moving Average method assigns equal weight to past observations.

Ghobbar and Friend (2003) compared 13 forecast methods and revealed that the Weighted Moving Average, Holt Winters and Croston method showed superior results in forecasting intermittent demand patterns. The Additive Winter, Seasonal Regression, Weighted Regression Demand Forecaster and Double Exponential Smoothing Method were amongst the 13 forecast methods studied.

The Bootstrapping approach has also received considerable attention in terms of a non-parametric approach used to forecast the demand for spare parts. According to Boylan and Syntetos (2010), classical bootstrapping involves "consecutive sampling, with replacement, from an available dataset, to construct an empirical distribution of the data under concern". The main assumption in Bootstrapping is that the past behaviour of data also pertains in the future.

Willemain *et al.* (2004) developed a patented Bootstrapping approach to simulate an entire distribution for lead-time demand rather than a single forecast. The relative accuracy of the approach was compared to the Exponential Smoothing and Croston method on a dataset consisting of over 28,000 items. The study concludes that the Bootstrapping method outperformed the Exponential Smoothing and Croston methods in terms of forecast accuracy, especially for short lead times. Willemain *et al.* (2004) also mention other advantages of the Bootstrapping method: the method is easily understood by practitioners and the skewness of the bootstrap distribution is more realistic than the normal distribution. The two main drawbacks of Bootstrapping is that potential autocorrelation of the data is not taken into account and values generated in the reconstructed distribution could be the same as past values.

Besides the above-mentioned methods used to forecast intermittent demand, a number of other methods have also been developed and used. Eaves and Kingsman (2004) mention that the approximation method, which is a modification of the Croston method, has been observed to provide significant reductions in the value of stock to attain certain service levels. Romeijnders *et al.* (2012) propose a two stepped approach to forecast intermittent demand which combines repair information into the demand forecast. There are also other factors that play a role in demand forecasting. Do Rego and de Mesquita (2011) mention the choice of time bucket to categorize demand - the shorter the time bucket, the more demand seems intermittent. Boylan and Syntetos (2010) also discuss the benefits of information sharing and role of the forecast system in the recent review on forecast techniques for spare parts.

This study is particularly interested in forecasting methods which are commonly used in practice. Ghobbar and Friend (2003) and Cavalieri *et al.* (2008)

state that the SES method is the most popular in practice. Bacchetti and Saccani (2012) agree and state that authors tend to acknowledge that traditional methods (SES and Moving Averages) are favoured in practice and that the application of specific, more complicated, methods seem to lag behind. The next section presents more information on hypothesized demand distributions and thereafter the link between demand patterns and forecasting techniques is discussed.

3.3.2 Hypothesized demand distributions

There is a measure of inherent uncertainty in determining the demand for spare parts in the future. As mentioned in Section 2.2, demand uncertainty is one of the most common sources of uncertainty which managers face. The term uncertainty insinuates that the future demand cannot be known with 100% certainty and that there is an unavoidable risk involved in forecasting. Safety stock is used to combat this risk and probability theory is used to assist the understanding of demand patterns and the likelihood of demand realizing.

Moncrief *et al.* (2006) state that many algorithms in the field of SPM rely on statistical distributions to replicate part failure rates and use the outcome to determine an appropriate stock level. Literature has devoted major attention to evaluate which statistical distributions better approximate the demand patterns of spare parts. In simple terms, a distribution is a display of all the possible values along with the probability of achieving those values for a certain variable. According to Moncrief *et al.* (2006), risk-based inventory solutions relying on distribution assumptions for future demand patterns are especially useful for slow-moving, rarely used stock items.

The Poisson distribution is the most obvious and most commonly used distribution to model very low demand patterns (Louit *et al.*, 2011; Kalchschmidt *et al.*, 2003). According to Silver *et al.* (1998), the Poisson distribution is only appropriate to use when the standard deviation of the lead time demand is less than 10% of the square root of the mean lead time demand.

Syntetos *et al.* (2009) state that the Normal distribution provides a good empirical fit in the case of small coefficients of variation in demand. The advantage of the Normal distribution is that it is convenient to use from an analytical point of view and widely tabulated and therefore it is often used for stock control purposes. According to Boylan and Syntetos (2010) and Silver *et al.* (1998), the Normal distribution is generally not however advised for modelling the demand of slow-moving and intermittent demand because the lead time demand is often skewed to the right. Nevertheless, evidence has shown that the normality assumption may be more appropriate for cases with long lead times that permit central limit theorem effects.

Kalchschmidt *et al.* (2003) analyzed demand data to evaluate which distribution fits better the demand for spare parts. The study concludes that the demand of some of the items is best represented by the Poisson distribution whereas others are best represented by the Normal distribution. This leads to a theory that the Poisson distribution performs best when the process of demand peak generation is memoryless as is the case when demand results from a number of different customers.

Syntetos *et al.* (2009) mention also other, more complex, compound distributions proposed in literature. These distributions explicitly take into account the demand arrivals and the demand size by modelling them separately. In terms of compound distributions that include both the demand arrivals and demand size. If the demand arrivals are Poisson distributed and the demand size is arbitrary distributed, the total demand over fixed lead time is Compound Poisson. Similarly, if the inter-arrival times follow a Geometric distribution and the demand size is arbitrary, it results in the Compound Binomial distribution. The Stuttering Poisson distribution can also be used to model the total demand over lead time. This is the case when demand occurs according to the Poisson distribution and the demand size according to the Geometric distribution.

In addition, the Negative Binomial, Chi-Squared (χ^2) and Gamma distribution have also been used to model the demand of spare parts. Eaves and Kingsman (2004) provide empirical evidence in support of the Negative Binomial distribution. Strijbosch *et al.* (2000) propose the Gamma distribution and tested it together with an inventory control policy with the application of a case study. Moncrief *et al.* (2006) state that the χ^2 distribution is also commonly used by using past failure history to predict the future.

Hypothesized demand distributions form an important part of stock control as it influences the amount of safety stock to be carried and assists to understand the service level impacts of stock holding. Demand distributions are preferred above conventional forecasting methods for slow-moving items with limited data. The next section focuses on linking demand patterns to forecasting techniques.

3.3.3 Demand patterns versus forecasting techniques

Some forecasting techniques forecast certain demand patterns better than others. It is therefore worth investigating which forecasting techniques are more appropriate for which demand patterns. A number of authors have investigated this phenomenon in the context of spare parts.

In general, traditional time-series based forecasting models (i.e. SES and derivatives) are more appropriate for fast-movers than slow-movers. Cavalieri *et al.* (2008) state that these models are more suitable for fast-moving, smooth and erratic demand patterns whereas customized models are better equipped for intermittent and lumpy demand patterns. Hypothesized demand distributions are appropriate to forecast the demand for slow-moving and new items because of the limited data available for these items. Boylan and Syntetos (2010) state that Exponential Smoothing methods are also favoured for fast-moving inventory in software packages.

Moncrief *et al.* (2006) similarly recommend using the Moving Average, Linear Regression or Least Squares Method for fast-moving items and the χ^2 statistic for slow-moving items. The χ^2 statistic is a hypothesized demand distribution method that uses the χ^2 distribution to predict the future demand. The procedure involves the following steps:

1. Determine the observed failure rate during the years of data.
2. Use the χ^2 statistic to determine a failure rate for the future.
3. Set the confidence level and degrees of freedom for the χ^2 statistic. The confidence level should be set high enough to anticipate a future failure rate $20 - 30\%$ higher than the current rate.

Johnston and Boylan (1996) compared the Exponentially Weighted Moving Average (EWMA) method to the Croston method and found that the Croston method performs better than the EWMA method if the inter-order interval is greater than 1.25 the review period. The gains which the Croston method generate increase as the inter-order interval and lead time increases. Kalchschmidt *et al.* (2003), on the other hand, propose forecasting methods according to demand variability and propose the SES method for stable demand and Croston method for irregular demand patterns.

Forecasting methods can be tested by using historic data to generate a forecast for a period of which the actual values are already known. The forecast can then be compared to the actual data observed during that period. For example, if actual demand for January until April is known, the data from January until March can be used to forecast the demand for April. The actual demand for April can then be compared to the forecast. Common measures used to evaluate forecasts are the Mean Absolute Deviation (MAD), the Mean Squared Error (MSE) and the Mean Absolute Percentage Error (MAPE).

In summary, the Moving Average and SES methods are the most common methods used for fast-moving and smooth demand. The Croston and Bootstrap method, as well as hypothesized demand distributions, are predominantly appropriate for slow-moving, intermittent demand patterns. It is clear that that demand patterns and forecasting techniques form an important part of spare parts inventory control. The next section discusses the use of inventory control policies.

3.4 Spare parts inventory control policies

This section discusses inventory control policies appropriate for the management of spare parts inventory. Section 2.3.4 provides an overview on inventory control policies. The classification of inventory items, demand forecasting and service level requirements feed into the determination of inventory control policies. This section builds onto the previously defined concepts and focus on the application of inventory control policies for spare parts. First, inventory control policies are discussed and thereafter specific elements such as the Reorder Point (ROP) and Reorder Quantity (ROQ) are discussed.

The demand for spare parts is independent in the sense that it does not depend on the demand for other items. Stevenson and Hojati (2007) state that dependent demand is certain and independent demand is uncertain. In a production process, the demand for parts required to produce a final product is dependent on the demand for the final product. Spare parts are constituents of a machine or piece of equipment, but the demand for spare parts is not dependent on the demand for another item and hence, the demand for spare parts is independent. This section therefore focuses on the replenishment philosophy because of its appropriateness for the management of spare parts.

It is useful to subdivide the inventory control problem according to the life-cycles of equipment into four categories. The first is the decision to stock an item or not, the second is initial orders, the third is inventory control during the continuous operating period and the fourth is final orders and obsolescence (Do Rego and de Mesquita, 2011). It is important to note that the choice of inventory model varies according to the asset life-cycle of equipment. Different models are therefore appropriate during the different life-cycle stages.

The first question of whether to stock an item or not is an important initial consideration for managing inventory. It is rarely the case of not keeping any stock but it is important to critically evaluate whether it is worth bearing the cost of stocking even one item versus ordering upon demand. During new product launches, it is difficult to decide how much stock need to be kept because there is no demand history. Similarly, in the field of spare parts, it is difficult to determine how many spares parts need to be bought and held in stock when new equipment is bought. Initial stock levels are difficult to determine without any historical data and therefore product manufacturers are often consulted to assist with reasonable demand forecasts (Do Rego and de Mesquita, 2011).

In the case of new equipment, spare part managers have three choices: they can decide to stock initial inventory, they can wait until demand occurs until orders are triggered or they can order an item when the risk of a part failure is above a certain threshold. The issue of initial ordering has been analyzed and the results summarized in numerous literature papers (Silver *et al.*, 1998;

Botter and Fortuin, 2000). Haneveld and Teunter (1997) developed a storage strategy for the provisioning of spare parts across their lifetime by taking into account the concept of remaining lifetime. Syntetos *et al.* (2009) dealt with the issue of initial orders in the classification of spare parts by adding an additional category (D) to their ABC classification so that parts belonging to the category D can be managed separately.

The bulk of the literature on spare parts inventory management focus on the inventory control policies which are applicable during the normal or repetitive phase of the spare parts life-cycle. In other words, the phase between the initial orders and final orders before the end of the lifetime of the equipment. In this context, both continuous review and periodic review systems have been used to manage spare parts inventory.

Van Horenbeek *et al.* (2013) state that the most common continuous review systems used for spare parts are the (s, S) and (s, Q) systems. In a (s, S) system, stock-items are ordered when the stock-level is below s to reach the S stock-level. Orders therefore vary in size dependent on the difference between s and S. In a (s, Q) system, a quantity Q items are ordered when the stock-level is below s. In addition, Do Rego and de Mesquita (2011) mention a variation of the (s, S) model, called the Base Stock model. In this model an order is placed at each withdrawal from inventory to fill the inventory up to a predetermined baseline amount (Webster, 2008). The amount ordered is therefore equal to the amount of the last withdrawal. In the case where the average demand is 1 unit, the model is also referred to as a $(S-1, S)$ model, a variation of the continuous review $(s,\ S)$ model with $s = S-1$ and $Q = 1$. In a periodic review policy (R, S), an order is placed in the beginning of the review period R. The current stock-level and demand forecast is evaluated against the required stock level. The order size is equal to the difference between the forecast for the stock level and the required stock level S.

During the phase-out phase of equipment, it is important to closely monitor spare parts inventory to prevent obsolete stock. The phase-out phase is dependent on manual intervention and there is very little scope for mathematical models to predict inventory behaviour. This is because future trends do not follow on past trends. Subsequently, very little research has been done on this topic. Persson and Saccani (2009) propose a make-to-order policy, with a ROP of 0, for parts during the phase-out phase.

Different variations of inventory policies have been developed and discussed in numerous instances in literature. Shtub and Simon (1994) consider a two-echelon inventory system composed of a central warehouse and maintenance facilities and assume a periodic review policy for the central warehouse and a continuous review policy for the maintenance facilities. Porras and Dekker (2008) evaluated different demand modelling techniques and inventory policies using real data and used a $(s,\ nQ)$ inventory policy. This policy is similar to the (s, Q) policy with the only difference being that Q refers to a lot size determined by the EOQ method and n refers to an integer value. Order sizes are therefore constrained to lot sizes.

Cavalieri *et al.* (2008) state that few companies in practice apply complex and specific models, primarily due to their mathematical complexity. This statement is confirmed with the observations of Bacchetti and Saccani (2012) when they analyzed the adoption of SPM practices in ten case studies. The study shows that policies adopted were simple and generic, not customize for spare parts. A periodic review policy (R, S) was adopted by four companies and continuous review policies by the rest. Three companies adopted a (s, S) policy with an order up to level and the other three a (s,Q) policy with fixed reorder quantity.

In SPM, the periodic review system is preferred, especially for fast-moving items, because of the convenience of regular order intervals and optimized delivery schedules (Cavalieri *et al.*, 2008). Sani and Kingsman (1997) compared 10 different inventory control policies and confirm that the (s, S) policy is better for slow-moving demand or intermittent demand patterns. The Base Stock Model (also referred to as the ($S-1$, S) policy) is a variation of the continuous review (s, S) policy which is advised for low demand items which are replenished with single units upon use (Do Rego and de Mesquita, 2011). Kalchschmidt *et al.* (2003) propose two categorizations of demand patterns: stable and irregular. Simple techniques such as an order-up-to policy is proposed for the stable demand and a more complex method is proposed for the irregular demand patterns which binds the emission of an order to the minimum probability of occurrence (MPO).

The Economic Order Quantity (EOQ) is predominantly applicable for fast-moving spare parts. Moncrief *et al.* (2006) state that the EOQ for slow-moving items is 1 unit approximately 80% of the time and defines slow-moving items as rarely-used items with an average demand of less than or equal to 1 unit per period. This leads to the thinking that the (s,Q) continuous review model is more appropriate for fast-moving items than slow-moving items. Moncrief *et al.* (2006) propose that generic approaches such as using the EOQ to calculate the minimum and maximum stock levels are used for the fast-moving items and a risk-based approach is used for slow-moving items.

In both, continuous and periodic review inventory policies there are references to a ROP and in some cases also a ROQ. Different methods can be used to determine a theoretical reorder point. According to Slater (2010), the most common approaches in the field of spare parts inventory are the Gaussian or Normal model and the Poisson model which is based on the probability / impact decision. The Gaussian model assumes normally distributed demand and incorporates a service level factor in the safety stock calculation. The Poisson model assumes that demand follows the Poisson distribution. The Poisson function calculates the probability of achieving a certain level of demand which directly relates to the service level requirements. The ROQ can be calculated by using the classic EOQ model as described in Section 2.3.4.

This study is concerned with the development of a decision-making framework which should be practically applicable to managers and therefore acknowledges the complex control policies, but focuses on the simple, implementable control policies. Table 3.2 summarizes the different policies which are considered in each of the life-cycle phases of the equipment for the purpose of this study.

Table 3.2: Inventory control policies during life-cycle phases

Life-Cycle Phase	Policy 1	Policy 2	Policy 3	Policy 4
Launch	Initial Ordering	Risk-Based Ordering	Order on Demand	
In-Use	Continuous Review (s, S)	Continuous Review (s, Q)	Base Stock Model	Periodic Review (R, S)
Phase-Out	Continuous Review (s, S)	Order on Demand		

During the launch phase of equipment, decisions need to be made whether or not to stock spare parts and how many spare parts to buy. These decisions are dependent on the demand characteristics of the parts, the cost and criticality of parts. During the launch phase, the following three control policies are considered: initial ordering, risk-based ordering and order on demand. Initial ordering refers to the case when orders for the initial provisioning of spare parts are placed simultaneously with the order for new equipment. This policy applies to parts with high demand, high criticality and long lead times. Risk-based ordering refers to the case when orders are placed for spare parts when the risk of requiring the part reaches past a specified level. Moncrief *et al.* (2006) propose that risk-based approaches are used for slow-moving items, expensive items. The last policy, order on demand, refers to the case when orders are only placed ons demand occurs and applies to items with short lead times and low criticality.

Traditional continuous and periodic review systems are proposed during the repetitive or in-use phase (phase between launch and phase-out) of equipment to provision for spare parts. In the proposed framework, the continuous review (s, S) and (s, Q) policies are proposed, the Base Stock Model and the periodic review (T, R) policy.

During the phase-out or final phase of equipment's lifetime, it is difficult to provision for spare parts. Typical questions arise such as whether spares should be kept in stock, how long the equipment will remain in use and whether to dispose of obsolescence stock items. During this phase, a continuous review policy (s, S) is advised to closely monitor stock levels or alternatively orders can be placed upon demand.

It is clear from the above-mentioned discussion that there is no single inventory policy available that outperforms all other models for all scenarios. It is crucial to realize the interdependency between inventory classification, demand forecasting and inventory control policy. The choice of an optimal inventory control policy depends on the extended SC environment and the characteristics of the spare parts.

Spare parts inventory management is an important part of SPM. The literature analysis on the classification of spare parts, demand patterns and forecasting and inventory models discussed in this section is used in Chapter 4 to propose a methodology for the management of spare parts inventory. The discussions on demand forecasting however continuously allude to the effect of maintenance on part failures. It is therefore important to explore the field of maintenance and also the broader field of PAM to provide a holistic solution to the SPM problem. The next section provides a brief overview of maintenance principles and aims to address the effect of maintenance on SPM and vice versa.

3.5 Maintenance and spare parts management

The expertise required to determine the optimal stock control policy is not only based on a logistics and financial background, but a sound understanding of maintenance strategies and technical skills is also required (Cavalieri *et al.*, 2008). There are many different components of maintenance and at a detailed level the study field is vast and complex. For the context of this study, the concept will however only be briefly introduced with a focus on the influence of maintenance policies on the demand for spare parts.

According to Pintelon and Gelders (1992), the objective of maintenance is to "maximize equipment availability in an operating condition permitting the desired output quantity and quality". Van Horenbeek *et al.* (2013) state that the link between maintenance and inventory control is logical and clear. On the one hand, the demand for spare parts is as a result of part failures which are influenced by maintenance tactics. On the other hand, the maintenance function relies on the availability of spare parts in order to complete maintenance activities and reduce down-time.

There are numerous definitions for the term maintenance. Jardine and Tsang (2013) state that the role of maintenance according to the classic view is to fix broken items. This view clearly confines the term to include only reactive tasks. Maintenance has however since evolved to encompass a broader scope of functions which include a future outlook into the life-cycle of the asset. It includes not only reactive tasks but also proactive tasks such as preventative maintenance, routine servicing and periodic inspection. Gulati (2009) defines maintenance in a general sense as the action to keep a system in its designed state or an acceptable condition. In short, maintenance can be summarized as an act to continue through repair. This broader scope of maintenance can be seen from Dhillon (2002)'s definition of maintenance as

> "all actions appropriate for retaining an item/part/equipment in, or restoring it to, a given condition"

There are different types of maintenance categories and each category is associated with different tactics and maintenance types. Following on the evolution of the definition of maintenance, the most common categorization of maintenance is the differentiation between preventative and corrective maintenance. In this categorization, preventative maintenance includes what some authors refer to as predictive maintenance and also includes maintenance types such as periodic service, component replacement, inspection, condition monitoring and time or condition-based maintenance.

Preventative and corrective maintenance have different impacts on demand. On the one hand, Wang and Syntetos (2011) mention that demand arising from preventative maintenance is deterministic in terms of the demand arrivals, but stochastic in terms of the size of the demand. This decreases the dependency on a stock pile and parts could hypothetically be ordered just in time (Kennedy *et al.*, 2002). On the other hand, demand arising from corrective maintenance is usually deterministic with regards to the demand size (often the quantity is one) and stochastic with regards to the arrival time. The consequence of corrective maintenance could include lost production with large costs and therefore safety stock is necessary. In addition to preventative and corrective maintenance, there are also other types of categorization of maintenance strategies. Van Horenbeek *et al.* (2013) investigated joint maintenance and inventory optimization systems. The study categorizes articles into the following maintenance categories: block-based, age-based and condition-based maintenance policies.

The two major forecasting approaches for the demand of spare parts are time-series based forecasting and reliability-based forecasting. Time-series based forecasting rely on historical demand data, in terms of occurrences over time, to forecast future trends. Reliability-based forecasting is based on the underlying reliability characteristics of parts and therefore maintenance tactics should be incorporated (Ghodrati, 2005). Maintenance tactics not only influence the future demand, but can also be used to predict future failures with the use of condition monitoring. Cavalieri *et al.* (2008) state that reliability-based forecasting can be performed by using information from data banks to obtain an average failure rate. The average failure rate can then be adjusted with factors indicating the condition of use, required performance and duty cycle. Cavalieri *et al.* (2008) also however mention that a more precise solution is to apply Weibull analysis (using data from the parts in the installed base) to obtain an actual failure rate. Obtaining adequate and accurate data is a major challenge in reliability-based forecasting. Therefore, the final choice between time-series and reliability-based forecasting in practice often depends on the availability of data.

A number of previous studies have been performed to incorporate maintenance tactics in demand forecasting. Wang and Syntetos (2011) compared a maintenance driven forecasting approach to a conventional time-series approach and concludes that an approach based on the demand generation process itself (maintenance driven) delivers better results than the time-series approach. Vaughan (2005) developed a stochastic dynamic programming model to characterize an ordering policy which addresses demand as a result of preventative and corrective maintenance in a unified manner. Kabir and Al-Olayan (1994) combined age-based replacement and a continuous review spare parts policy and reported significant savings in the total cost of the system as a result of joint optimization.

It is clear that combined solutions, incorporating maintenance and inventory control policies, have great potential to optimize SPM systems. According to Silver *et al.* (1998), operationalizing such approaches is however difficult. Besides the mathematical complexity, maintaining the correct data and sharing the data between departments is challenging. Furthermore, accurately estimating the service life distribution is difficult.

According to Jardine and Tsang (2013), if the strategic decisions are taken into account in the maintenance function, it should also cover decisions related to the future maintenance requirements of the organization. This leads the literature analysis to include the field of PAM which not only includes maintenance but also other key functions to optimize the use of the asset throughout its life-cycle. The next section discusses the key elements in PAM and how it relates to SPM.

3.6 Physical asset management

The term asset is used extensively. An asset can be seen as anything that has the potential to or adds value to an organization. Assets are used to make products or provide services, and therefore form a core component of any business. PAM is concerned specifically with physical assets. Examples of other types of assets are financial, human, information and intangible assets. This section provides a brief overview of PAM. Similar to the previous section, it does not provide a comprehensive discussion on PAM, but introduces the topic with the aim to find intersecting points between PAM and SPM.

The British Standards Institute published the Public Available Specification 55 (PAS 55) as a guiding framework incorporating international consensus on PAM (PAS, 2008). In PAS 55 physical assets are referred to as "plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organisation" and PAM is defined as follow:

> "the 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."

The terms PAM and Maintenance are often confused. Lutchman (2006) state that few companies understand the difference between maintenance and asset management. Maintenance is an important component of PAM, but has a narrower scope to that of PAM. PAS 55 divides PAM into three levels: manage asset portfolio, manage asset systems and manage assets. Maintenance is one of the functions in the manage asset level. It is therefore clear that the scope of PAM extends further than the scope of maintenance and has to be treated as such in the context of SPM.

According to Frolov *et al.* (2010), assets are the foundation for success and future growth in many companies and as such effective asset management is a crucial element of overall success. In line with this statement, Lutchman (2006) mentions numerous benefits of PAM including; lower overall costs, improved organization effectiveness, lower risks and improved safety. In addition, Gulati (2009) states that it is important to use assets to their full capacity and therefore assets should be kept in a good working condition at all times. This statement relates directly to maintenance activities but also to the management of spare parts. Hastings (2009) lists SPM as one of the activities within PAM. This is because spare parts affects the down-time of equipment and consequently also asset utilization.

PAM, in the past, was mostly focused on maintenance management, but has since evolved to the management of the life-cycle of all major assets and components from inception to disposal (Woodhouse, 2006). The term Total Life-Cycle Asset Management (TLAM) is the practice of taking an expanded view of how assets are planned for, used, maintained and disposed of (Campbell *et al.*, 2010). This is with the aim to improve uptime of equipment and create a competitive edge against competition. TLAM is an integrated approach, optimizing assets across their life-cycles. This implies that decisions related to assets are taken to achieve an overarching goal towards a collective strategy. As such, functions conventionally viewed as separate and independent, need to work together. According to PAS (2008), typical activities of an asset's life-cycle include the creation, acquisition, enhancement, utilization, maintenance, decommissioning and disposal of assets.

The scope of PAM has evolved and broadened to include different disciplines. According to Frolov *et al.* (2010), an interdisciplinary approach is widely acknowledged as a key contributor towards effective asset management. Such an approach should include synergies between traditional departments such as logistics, finance, engineering and information system technology. Woodhouse (2006) also state that organizations realized that working through functional silos limits opportunities for optimization. The holistic approach to asset management emphasizes the important link of PAM to other areas in the business so that asset management is settled as a unique cross-functional component in an organization's structure.

Campbell *et al.* (2010) state that the TLAM approach compliments an asset-centric SC because decisions related to strategy, procurement, product-life cycle, logistics and operations are directly influenced by the utilization and reliability of a company's assets. The acknowledgement of the importance of managing assets across their life-cycle is similarly applied in the inventory management of spare parts. Different inventory management policies are appropriate for the different stages of the equipment's lifetime.

The issue of Spare Parts Management is situated at a key linkage point between SCM and PAM. On the one hand, the issue can be viewed as a SCM-related problem because inventory management clearly resides in the field of SCM. On the other hand, Spare Parts Management forms a part of Asset Care Plans and is therefore also part of PAM. Campbell *et al.* (2010) state that a recent survey of 150 companies suggests that companies lacking significantly behind the industry's averages should take a more holistic approach to asset management which specifically includes tools, spare parts and maintenance materials.

There are a number of overlapping areas between PAM and SCM. Both terms emphasize a holistic, interdisciplinary approach and life-cycle view. There is also a clear link between the perception of excellence in PAM and SCM. According to Campbell *et al.* (2010), excellence in PAM is "the balance of performance, risk and cost to achieve an optimal solution". This relates clearly to a similar aim in SCM to balance costs with performance. The only difference is in the measurement of performance. SC performance is measured in terms of customer service level where as PAM is measured in utilization and throughput of equipment.

The relationship between PAM and SCM is intertwined. On the one hand, PAM can be viewed as an enabler to the 'Make' process in a typical SC. This is because it ensures utilization and operational efficiency of assets used to make products. On the other hand, in the field of Spare Parts Management, SCM can be viewed as an enabler to PAM. This is because spare parts are necessary to ensure optimal asset care and spare parts are delivered via a spare parts SC. For this reason, PAM plays a crucial in determining an appropriate inventory control policy because it influences the service level requirements of parts. It is clear that PAM needs to be incorporated in the decision-making process for determining an optimal inventory control policy. The next section discusses existing decision-making frameworks in the field of SPM.

3.7 Decision-making frameworks

Decision-making is central to SPM. Managers are faced with decisions regarding stock-levels and inventory requirements on a daily basis. According to Anderson *et al.* (2011), in today's harsh business environment, managers and organizations are looking for structured and logical decision-making processes that depend on evidence rather than relying on mere intuition and personal experience. Subsequently, a handful of decision-making frameworks and methodologies have been proposed in literature to assist in the management of spare parts.

Before providing details on existing frameworks, it is however important to define what is meant by the term 'decision-making framework' in a SPM environment. The term 'framework' is extensively used in different contexts. A framework, as defined by the Oxford dictionary, is a "basic structure underlying a system". The Business Dictionary's definition of the term also refers to a broad overview of interlinked terms to support a practical approach. A decision-making framework, in this context, provides a structured format for the thought process involved in making decisions.

Cavalieri *et al.* (2008) developed a stepwise decision-making path consisting of five sequential steps: part coding, classification, demand forecasting, stock management policy and validation. The objective of the proposed decision-making path is to "orientate an industrial manager on how to pragmatically handle the management of spare parts". The study includes a case study in a multi-echelon SC in the process industry and policies were tested with discrete-event simulation.

Bacchetti *et al.* (2010) developed an hierarchical multi-criteria spare parts classification scheme for inventory management and tested the proposed framework with a case study in the household appliances industry. The company involved in the case study delivers white goods and spare parts. The business unit performs after-sales service and is involved in the distribution of parts. The study consists of three phases: framework development, simulation and analysis of performance. The framework development phase includes the identification of a multi-criteria classification model and the specification of forecasting methods - inventory policy combinations. In the simulation phase, the best suited policy for each classification is selected.

Kalchschmidt *et al.* (2003) propose and discuss an integrated system for managing inventories in a multi-echelon spare parts SC. This study takes a broader SC view by first analyzing the SC. Thereafter, it provides four alternative approaches to inventory management and test the alternatives with simulation analysis. The study refers to the alternatives as algorithmic solutions.

The first alternative is a basic approach consisting of two steps, forecasting and inventory management. In this approach all parts are treated the same. The second approach includes filtering of demand into a stable and irregular series. This approach uses the Exponential Smoothing forecasting method for the stable series and a variation of the Croston method to forecast the irregular series. All parts are however still treated according to the same inventory management policy. The third approach expands on the second approach and in addition to different forecasting methods also uses different inventory management policies for the stable and irregular series of demand. The three different approaches are presented in Figure 3.6. The fourth approach includes information sharing of demand. The service level and average inventory levels for the four different alternatives were compared with the use of a simulation study. The outcome shows that the second approach reduces inventory investment by 49% when compared to the first approach and the third approach further reduces inventory costs by 50.6% when compared to the second approach. The results also show that the fourth alternative, where information is shared, performs better than the third alternative.

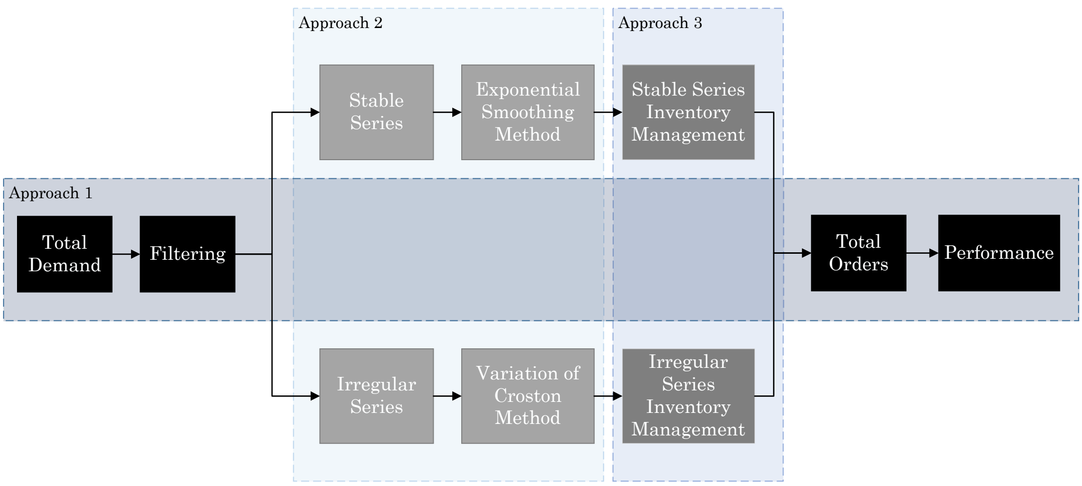


Figure 3.6: Inventory management alternatives. Adapted from Kalchschmidt *et al.* (2003).

Considering the above-mentioned decision-making frameworks, there is still however a gap in the literature concerning the interdisciplinary nature of SPM. Existing frameworks seem to focus on spare parts inventory without explicitly taking into account the context and environment of the equipment to which the spare parts are constituents. Inventory control policies are also dependent on the life-cycle phase of equipment (as mentioned in Section 3.4) which the existing frameworks do not account for. Furthermore, this study challenges the idea of sequential steps towards a single solution. In practice, decision-making is, more often than not, an iterative process and can be viewed as an interconnected web of activities.

This study aims to build on existing frameworks and address the above-mentioned needs in developing a decision-making framework for the management of spare parts inventory. The main factor differentiating this study to others is the holistic approach towards a solution for SPM which incorporates principles from SCM and PAM. PAM especially plays a vital role in SPM which is not emphasized sufficiently in existing methodologies. This study also differs in the area of application and the acknowledgement of the asset's life-cycle. Furthermore, similar to Bacchetti *et al.* (2010)'s study, this study proposes forecasting methods and inventory control policies based on the classification of parts. The proposed framework in this study is however not prescriptive and provides multiple options of methods and policies per classification group for consideration. This is based on the argument that spare part portfolios are unique and no one-shot solution is possible for parts, even if they are classified in the same group.

3.8 Chapter summary

This chapter built onto the concepts defined and discussed in Chapter 2 to analyze the specific application of theories to spare parts. This chapter establishes the fundamental concepts in SPM. First, an overview is provided which includes a summary of available literature on SPM and spare parts characteristics. This is followed by a detailed discussion on the centroid study-field of this paper, spare parts inventory management. Lastly, an overview is provided on maintenance tactics and PAM to complete a comprehensive view of the problem.

The literature analysis (including both chapters) followed an explorative nature and evolved through different study areas in an attempt to provide a holistic, comprehensive view of the problem introduced in Chapter 1. The thought path of the literature review through the research domain is presented in Figure 3.7. The study started at a high level in the field of SCM, it then focused on general inventory management principles. Thereafter, a specific application of inventory management, SPM was discussed. This discussion raised the need to also include the effect of maintenance on the forecasting of demand patterns which also led to the field of PAM, of which maintenance forms part of. SPM is a unique study field where there is a clear overlap between the fields of SCM and PAM which is not commonly acknowledged.

The overall objective of this chapter, as defined in Section 1.6, was to master the field of SPM. The following sub-objectives (refer to Section 1.3) were achieved in this chapter:

- Define PAM and its relation to SPM
- Identify spare parts characteristics in capital-intensive industries
- Determine criteria and methods used to classify spare parts
- Identify techniques used to forecast the demand for spare parts
- Review appropriate inventory control policies
- Review existing decision-making frameworks for SPM

The next chapter uses the literature analysis as a foundation to propose a solution to the problem.

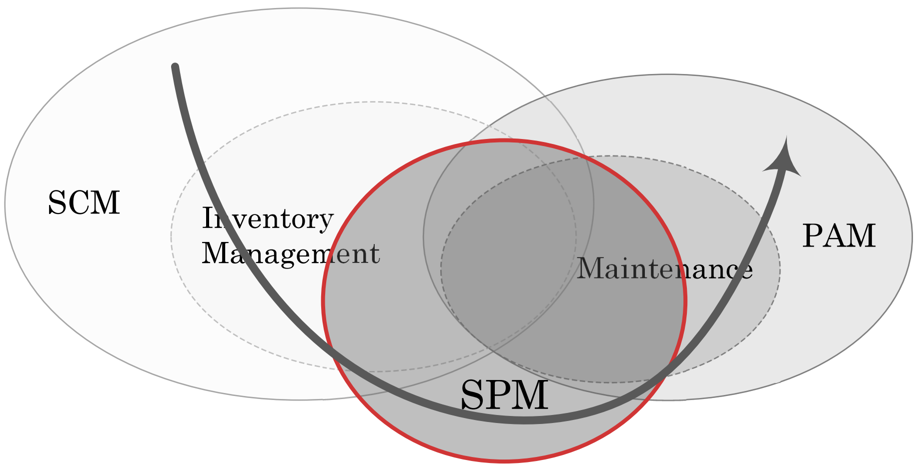
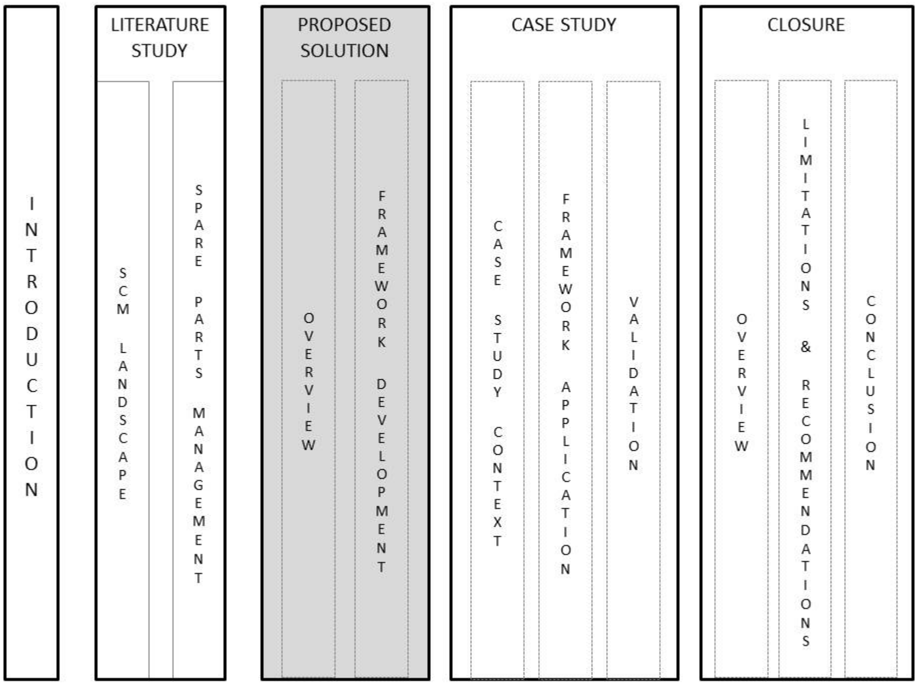


Figure 3.7: Literature review exploration path

Chapter 4

Proposed Solution

The literature analysis consists of Chapter 2, discussing the Supply Chain Management (SCM) landscape, and Chapter 3, exploring the topic of Spare Parts Management (SPM). Chapter 3 concludes, with the discussion on the literature exploration path, that SPM is situated at an intersection point between SCM and Physical Asset Management (PAM). This chapter uses the literature analysis as a foundation to propose a decision-making framework for the management of spare parts inventory in capital-intensive industries. First, an overview of the framework development is provided. Thereafter, each component of the framework is discussed in detail.



4.1 Overview

It is clear from the literature analysis that the spare parts inventory arena is vast and diverse. An one-shot solution for all parts within a company is unlikely to be possible. Spare parts managers face a magnitude of decisions in their daily operations. These decisions have large consequences and are often intuitively made without proper factual information. Managers are in need of structured guidance for decision-making. This study therefore focuses on the decision-making process itself instead of providing a specific solution to a given scenario.

The objective of this study is to develop a decision-making framework for the inventory management of spare parts. The decision-making framework should assist managers to determine appropriate inventory control policies. More specifically, it should act as a guide and reference for managers in the field. The framework consists of structured steps leading to the determination of appropriate inventory control policies for spare parts. The framework is specifically developed for application in capital-intensive industries.

The framework is based on the thorough and broad literature base presented in Chapters 2 and 3. In particular, Section 3.7 summarizes existing frameworks in the field of SPM and provides a good starting point for the development of the framework. Existing frameworks are adjusted with the best-practices in literature (presented in the rest of the literature review) so that the framework is practical, provides a structured guideline and gives a holistic approach to the problem.

This section provides an overview of the development of the framework. First, a recital of the research objectives is provided. Thereafter, the framework development and framework features are discussed. This section provides the foundation for the detailed discussion on the proposed framework in Sections 4.2, 4.3, 4.4 and 4.5.

4.1.1 Recital of research objectives

The research objectives of this study is presented in Section 1.3. This chapter is specifically concerned with the third research objectives:

- Develop a decision-making framework for the management of spare parts
  - Determine decision-making criteria for selecting methods to classify inventory, forecast demand and manage inventory
  - Consolidate decision-making criteria into a structured framework

The literature review, together with relevant information obtained from practice, provide sufficient information to propose a decision-making framework and to reach the objectives. The next section discusses the framework development.

4.1.2 Framework development

The proposed solution to the problem is a decision-making framework for the management of spare parts. The development of the framework is an iterative process which is influenced by literature in three different study fields: SCM, PAM and Inventory Management. Some could argue that inventory management is a study field within SCM, but because of the extent and importance of inventory management in the context of this study, it is viewed as a separate field of study.

A graphical representation of the proposed decision-making framework is shown in Figure 4.1. There are three different types of components in the framework: work clusters, study fields and steps. Work clusters are presented as horizontal swimlanes, study fields as dashed grey blocks and steps as blue rectangles. Steps indicate activities to be performed; study fields, the type of study area to which the steps belong; and work clusters, the type of work to be done.

The following four work clusters are included in the framework: contextualize, analyze, synthesize and validate. The objectives of steps performed in the 'contextualize' work cluster is to gain a better understanding of the background of the problem enabling a holistic solution. Steps performed in the 'analyze' work cluster are used to perform the detailed analysis related to the problem which leads to an exact solution. The 'synthesize' work cluster contains only one step which is to determine an inventory control policy. This step is very important, because during this step, all previously gathered information and data need to be combined into a single control policy which should be implementable. The final cluster is the 'validate' work cluster where the methodology is evaluated to ensure that it improves current procedures.

Each of the steps are numbered. The function of the numbering scheme is to act as a logical sequential guideline to users when following the framework. It is important however to note that the framework is not bound to a certain sequence and for that reason the steps are not linked to one another in the framework. Some of the steps could be performed concurrently and some steps may be returned to in a later phase in order to obtain additional information.

A distinctive feature of the framework is the 'contextualize' work cluster where there is integration between SCM and PAM principles which feed into the determination of the inventory control policy. One of the primary issues in the management of spare parts is contrasting objectives between departments. This integration therefore eliminates bias decision-making regarding spare part

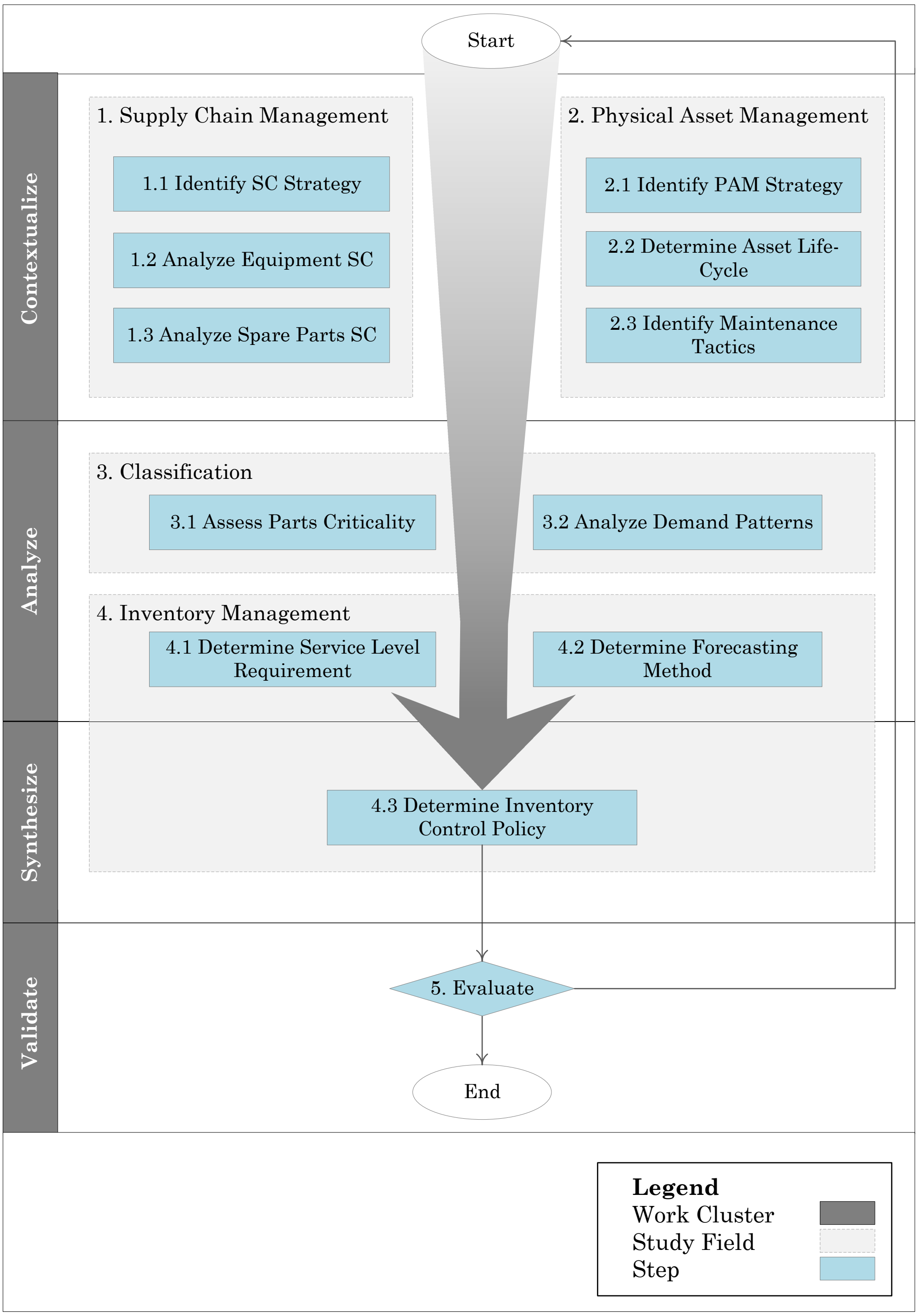


Figure 4.1: Proposed decision-making framework

inventory and sets a foundation for a holistic solution.

The 'analyze' work cluster consists of steps which belong to the classification and inventory management study fields. This work cluster follows a similar structure to existing decision-making frameworks in the field as presented in Section 3.7. It includes part classification service level requirements and demand forecasting.

The different steps in the framework influence each other and work together to develop inventory control policies. Even though the steps are not linked in a sequential manner, it is vital to understand the interaction between the different steps in order to focus on the correct information and principles. It is useful to view the framework as an interconnected web of activities. Figure 4.2 represents the interaction and relationships between the different steps in the 'contextualize', 'analyze' and 'synthesize' work clusters. For example: Step 4.2 uses inputs from Steps 2.3 and 3.2, and feeds into Step 4.3.

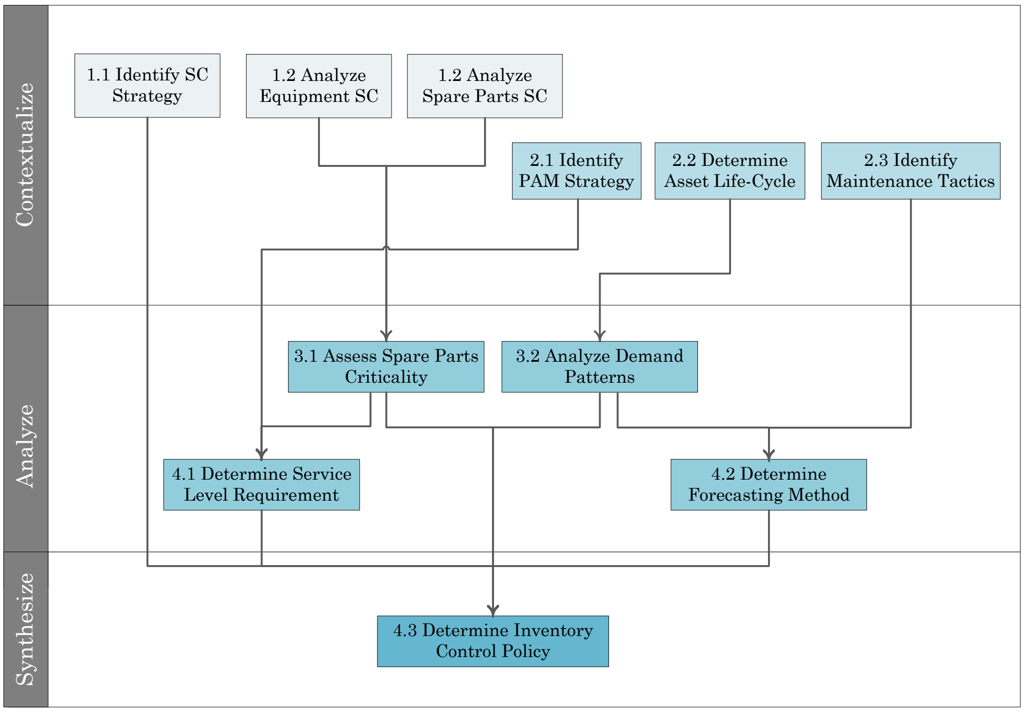


Figure 4.2: Framework interactions between different steps

The methodology is intended to be used for a single piece of equipment for which the spare parts are to be managed. The term 'equipment' refers to that piece of equipment and the term 'spare parts' refers to the equipment's constituent parts. It is important to note that the term 'spare parts', in this context refers, to all parts that could be replaced in the equipment, it includes consumables.

Each of the steps are discussed in detail in the subsequent chapters. The discussion follows the structure of the proposed framework by discussing similar study fields together in one section. The objective, methods, considerations, inputs and outputs for each of the steps are discussed when it is applicable. Steps related to SCM and PAM are discussed first in Sections 4.2 and 4.3. Thereafter, the classification of inventory items is discussed in Section 4.4. The inputs of these steps are used to perform the inventory analysis and develop an inventory control policy which is discussed in Section 4.5. Lastly, the validation of the framework is discussed.

4.1.3 Framework features

The framework is required to have the following features as stipulated in Chapter 1, Section 1.3:

- Practical – It should be possible to apply the framework in practice.
- Holistic – The framework should provide an integrated, holistic approach to the problem that incorporates multiple disciplines.
- Structured – The steps in the framework should be logical and guide a structured decision-making process.

Managers are faced with difficult decision regarding SPM on a daily basis and therefore the framework should provide managers with a structured, pragmatic approach for decision-making. The framework should however be practical and simple to implement. This increases the probability of the framework to be adopted in practice. The SPM problem stretches across multiple disciplines, it is important for the framework to provide a comprehensive view to the problem in order to find the optimal solution.

Furthermore, there are other features which uniquely define the proposed framework. In addition to the structured stepwise framework (Figure 4.1), the proposed solution includes the intricate relationships between different steps (Figure 4.2), which the majority of other frameworks neglect to show. The framework also accommodates different life-cycle phases of equipment by proposing different forecasting and inventory control policies based on the asset's life-cycle. Lastly, the framework provides an end-to-end, top-down view of the problem by incorporating a contextualize phase before the typical inventory management steps.

The remainder of this section discusses each of the study fields and steps in the proposed framework.

4.2 Study field 1: Supply Chain Management

The detailed discussion of the proposed framework in Figure 4.1 starts with the study field of Supply Chain Management. This study field forms part of the 'contextualize' work cluster in the framework because it allows the user to gain the appropriate background information for a holistic solution which does not sub-optimize the problem. The following steps are categorized under the Supply Chain Management study field: identify SC strategy, analyze equipment SC and analyze spare parts SC. Refer to Section 2.1 for an overview of key SCM principles.

4.2.1 Step 1.1 Identify SC strategy

The framework starts with an identification of the company's SC strategy in Step 1.1. This step is important because the strategy determines the overarching direction of the company. Refer to Section 2.1.3 for more information on the SC strategy.

Objective: Identify the SC strategy of the company.

Output: The SC strategy feeds into the development of the inventory management policy presented by Step 4.3.

4.2.2 Step 1.2 Analyze equipment SC

The second step (Step 1.2) in the SCM study field is the analysis of the equipment SC. The equipment SC refers to the SC of which the equipment forms part of and often refers to the core SC of the company. It is important to understand the background of the process in which the equipment plays a role, because the criticality of the equipment also influences the criticality of its constituent parts. For example: trucks (referred to as equipment) are needed to transport goods from point A to point B and form part of the distribution process of the company. When determining how many tyres (referred to as spare parts) to keep in stock, it is important to understand how critical the availability of the trucks are to the company.

Objective: Understand the context in which the equipment operates and determine the criticality level of the equipment.

Methods: Methods such as process mapping and value stream mapping are available to assist users to better understand the context of the equipment SC. The criticality can be determined by identifying bottleneck processes. A bottleneck refers to a phenomenon where the performance of the entire system if constrained by one of its processes.

Considerations:

Consider the following elements of the SC:

1. Process in which the equipment partakes
2. Direct links to and from the process in which the equipment partakes
3. Number of identical pieces of equipment in the SC
4. Criticality of the equipment's availability
5. The equipment's influence on the amount of value added by the company

Output: The analysis and criticality measure of the equipment SC feed into the criticality classification of spare parts which in turn influences the service level requirements of parts.

4.2.3 Step 1.3 Analyze spare parts SC

The third step (Step 1.3) is the analysis of the spare parts SC. The spare parts SC refers to the SC of the constituent parts. In the previous example, this would refer to the SC of the tyres. It is important to understand the SC context of the spare parts because factors, such as the lead time and availability of supply, need to be accounted for in an inventory policy. It is also important to note that this step potentially refers to numerous different SC's as different parts could be sourced from different suppliers.

Objective: Understand the spare parts SC.

Methods: Similar to the analysis of the equipment SC, methods such as process mapping and value stream mapping are available to assist users to analyze the spare parts SC.

Considerations:

In the literature review, in Section 2.1.3, the different components of the SC are discussed which could add as a valuable reference for this step. In summary, the following elements of the SC should be considered:

1. Supplier-related information
    a) Number of suppliers and supplier information
    b) Supplier locations
    c) Supplier lead times

2. Inventory responsibility
    a) Responsibility of stock-holding
    b) Items held in stock by suppliers
3. Distribution information
    a) Responsibility of distribution
    b) Distribution channels
4. Demand information
    a) Typical customers (in this case equipment) of parts
    b) Customer locations
5. Sources of uncertainty
    a) Supply uncertainty
    b) Demand uncertainty

It is important to understand the responsibility of spare parts inventory. Often, in the case of capital-intensive companies, suppliers of equipment have a nearby off-site or on-site warehouse where they keep some of the critical, fast-moving parts. These items can be retrieved with a short lead time and are often shared amongst different customers using the equipment. The company should have visibility of these stock items and should be able to make an informed decision as to whether it is necessary to also keep these items in stock at their own warehouse.

Output: The spare parts analysis feeds into the classification of spare parts.

4.3 Study field 2: Physical Asset Management

In the proposed framework (Figure 4.1), the Physical Asset Management study field is also in the 'contextualize' work cluster similar to Supply Chain Management. It consists of the following steps: identify PAM strategy, determine asset life-cycle and identify maintenance tactics. Literature regarding this topic is discussed in Sections 3.5 and 3.6 in the previous chapter.

4.3.1 Step 2.1 Identify PAM strategy

The first step (Step 2.1) in the PAM study field is the identification of the PAM strategy. It is important to align inventory-related decisions to the overarching PAM strategy as it could influence the service level requirements of spare parts. According to PAS (2008), an asset management strategy is the long term direction for the management of assets. It should be aligned to a company's corporate strategy and should apply the asset management policy. It feeds into the objectives and asset plans of the company and therefore should also be taken into consideration in the management of spare parts.

Because of the unique intersection of SCM and PAM in the spare parts industry, it is equally important to take into consideration the strategy of both study fields in the development of an inventory control policy. This prevents bias decision-making and allows for cross-pollination between different departments.

Objective: Identify the PAM strategy of the company.

Output: The PAM strategy influences the service level requirements and therefore feeds into Step 4.1.

4.3.2 Step 2.2 Determine asset life-cycle phase

The second step (Step 2.1), in the PAM study field, is to categorize the equipment into its life-cycle phase. Physical assets transform through different phases from inception to disposal. It is important to understand the asset's life-cycle as it provides an indication of the availability of data and influences the choice of inventory control policy.

Objective: Determine asset life-cycle phase.

Methods: Assets are divided into three life-cycle phases based certain criteria. The phases and corresponding criteria are summarized in Table 4.1.

Table 4.1: Life-cycle phases criteria

Phase	**Criteria**
Launch	In use for less than two years
In-use	In use for more than two years, no plan to discontinue
Phase out	In use, plan to discontinue within next two years

Output: The life-cycle phase feeds into the analysis of demand patterns as it influences the amount of data and information available to analyze past demand trends.

4.3.3 Step 2.3 Identify maintenance tactics

The third step (Step 2.3), in the PAM study field, is the identification of maintenance tactics. Refer to Section 3.5 for a discussion on the link between SPM and maintenance. Maintenance tactics could provide key information to the demand generation process in the case of predictive and preventative maintenance. Condition monitoring is performed when predictive maintenance tactics are followed. This information is aimed at predicting when parts would fail and could therefore add valuable insight into demand forecasting. Preventative maintenance is usage based. When a preventative maintenance plan is followed, parts are replaced at specified intervals. This information is vital to SPM as the demand for a part is known in advance.

Reliability based information should however be used in conjunction with a time-series based forecast to account for the inherent uncertainty in the demand for parts. Maintenance and inspection are ongoing processes and therefore the information obtained from these activities should regularly feed into the SCM process to enhance the forecast for spare parts and consequently also to optimize the inventory management process.

Objective: Determine maintenance tactics applied to spare parts and the influence thereof.

Output: The maintenance tactics influence the methods which are used to forecast the demand. The methods are determined in Step 4.2.

4.4 Study field 3: Classification

The classification study field is the first study field in the 'analyze' work cluster in the proposed framework (Figure 4.1). The 'analyze' work cluster contains the bulk of the detailed analysis and therefore requires the most effort. Classification allows parts to be clustered in homogeneous classes which ease the management of inventory. The categorization of spare parts is necessary to determine service level requirements for the different classes and to facilitate the allocation of the most appropriate forecasting methods and stock control policies.

Refer to Section 3.2 for a review on classification methods and criteria. Demand characteristics and the criticality of spare parts are amongst the most popular classification criteria. The proposed framework in Figure 4.1 splits the classification of parts into two separate steps: assessment of criticality (Step 3.1) and analysis of demand patterns (Step 3.2). The reason for this separation is because of the impact of each of these classifications: the criticality of a spare part primarily influences the required service level whereas the demand pattern primarily influences the choice of forecasting method.

4.4.1 Step 3.1 Assess spare parts criticality

The criticality assessment of spare parts is the first step (Step 3.1) in the classification study field. Criticality is one of the most common and important criteria used in practice to categorize spare parts. This measurement provides a guideline for the service level requirement. The criticality measure should take into account other factors such as part value and supplier information. The analysis of the spare parts and equipment SCs (Steps 1.2 and 1.3) serves as valuable inputs to this classification.

Objectives: Determine a relative criticality measurement for spare parts.

Inputs: The analysis of the spare parts and equipment SCs provides valuable insights to this step. Data regarding part value and lead times are also necessary.

Methods:

The aim of the proposed framework is to assist managers to make better informed inventory management decisions and one of the required framework features is therefore practicality. Therefore, the 'ease of implementation' is very important in choosing a method to classify items.

There are numerous quantitative and qualitative methods available to classify items. The most popular methods, according to the literature review, are the ABC method, Vital, Essential and Desirable (VED) method and Analytic Hierarchy Process (AHP). Refer to Section 3.2 for a detailed discussion on classification methods and criteria. A summary stating the advantages and disadvantages of each approach is presented in Table 4.2.

Table 4.2: Methods for classification

Method	Type	Advantages	Disadvantages
ABC	Quantitative	Easy to implement	Difficult to combine multiple criteria
VED	Qualitative	Easy to implement	Based on subjective judgement
AHP	Qualitative	Accommodates more than one criteria	Complex, based on subjective judgement

Criticality, part value and supplier lead time are amongst the most popular criteria used to classify spare parts. These criteria have also shown to generate the highest benefit. In the proposed framework, parts are first classified according to the part value, thereafter according to lead time and lastly the results as well as expert judgements lead to a criticality measurement. The proposed decision-tree is presented in Figure 4.3.

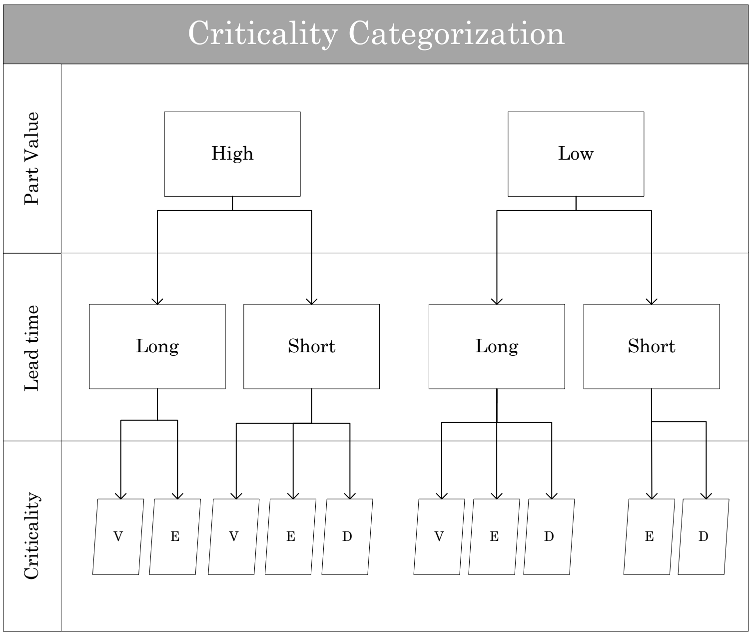


Figure 4.3: Criticality categorization

A simplified variation of the ABC method is proposed for the first two categorizations (part value and lead time). In this method, items are sorted in descending order according to the criteria and the highest and lowest values are grouped together. The cut-off values for the groups are not specified because it depends on the specific scenario. A typical rule is however to group those items contributing to 80% of the value into one group. According to the Pareto principle, the group would consist of approximately 20% of the items. Two classes, 'high' and 'low', are proposed for the part value classification and two classes, 'long' and 'short' are proposed for the lead time classification. In traditional ABC classification three groupings are used. However, in this case, for ease of implementation, the framework proposes splitting parts only into two groups.

The resulting four groups from the first two categorizations are used to narrow the criticality options in the third categorization. In the third categorization, expert judgements are used to divide items into three groups: vital (V), essential (E) and desirable (D). This categorization process is simplified by agreeing definitions for each of the criteria beforehand.

The proposed classification method and criteria aim to contain few enough permutations for ease of implementation without compromising on the quality of classification. The first two steps are quick to implement and filter options for the criticality assessment. This decreases the work load on the subjective criticality categorization which is more time-consuming.

Considerations:

The following factors should be considered in addition to the part value and lead time of the part to determine the final criticality measure:

1. Supplier reliability
2. Supplier availability
3. Inventory cost
4. Administration cost
5. Risk cost of unavailability of item

Output: The output of this step is a criticality measurement for each part (V,E or D). The criticality measurement is important for determining the service level requirement (Step 4.1).

4.4.2 Step 3.2 Analyze demand patterns

The second step in the proposed framework (Figure 4.1) under the classification study field is the analysis of demand patterns (Step 3.2). The demand pattern analysis is aimed to ease the identification of appropriate forecasting methods. This is because logistics requirements are to a large degree dependent on the underlying demand pattern of the spare part. The demand interval and variability are the two most important characteristics to take into consideration when categorizing items according to their demand patterns.

Objectives: Categorize items into logical groups according to their demand patterns.

Inputs: Demand pattern analysis is largely dependent on data concerning the historical demand and therefore data is the primary input for this step. The life-cycle phase of the asset however influences the amount of data available and is therefore considered as another input to this step. The life-cycle phase is determined in Step 2.2 in the proposed framework.

Methods:

The proposed criteria for categorizing demand patterns are the equipment life-cycle phase, demand interval and demand variability. The multi-criteria classification is presented in Figure 4.4. The inputs from Step 2.2 are used to filter the decision steps accordingly.

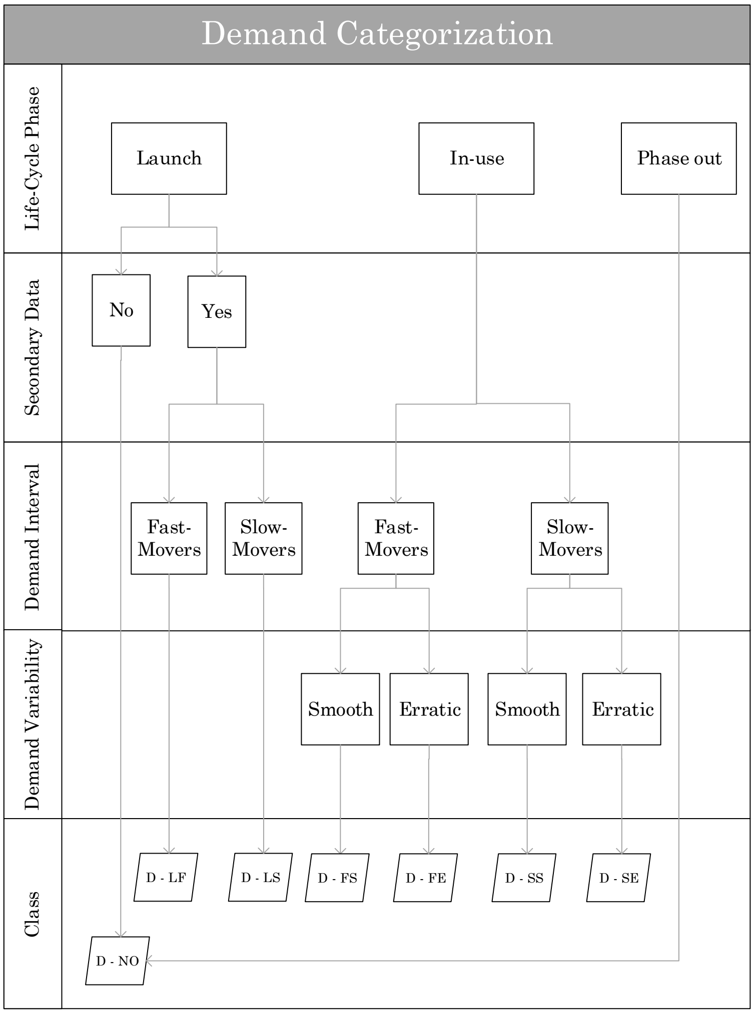


Figure 4.4: Demand categorization

The life-cycle phase of the equipment influences the subsequent categorization according to demand interval and variability. Equipment in the 'launch' phase typically do not have historic data available. In some cases secondary data is available from Original Equipment Manufacturers (OEMs). However, data from OEMs mostly only state the Average Demand Interval (ADI) of the part which is a good starting point to classify the items into fast- and slow-movers. Data regarding the demand variability is not common for parts in the 'launch' phase and therefore parts are only classified according to demand interval and not demand variability.

It is assumed that equipment in the 'in-use' phase have data available and therefore items are grouped according to both demand interval and demand variability. The future demand for equipment in the 'phase-out' phase will not continue to follow the same pattern as the historic demand. Therefore, items are grouped together with those items for which no data is available.

The demand interval is measured by calculating the ADI per item. The ADI is used together with cut-off values to divide parts into 'fast-moving' and 'slow-moving' categories. The choice of cut-off values depends on the specific scenario. Refer to Section 3.2.3 for an explanation of the ADI and the formula (Equation 3.2.1).

Demand variability can be measured by calculating the Squared Coefficient of Variation (CV^2) over the demand history or a predetermined time period. Cut-off values should be determined (per scenario) and should be used to divide items into stable and erratic groups. Section 3.2.3 also provides an explanation of and formula (Equation 3.2.2) for the CV.

Considerations: Determining the cut-off values is a difficult task as it is highly dependent on the type of data and influenced by outlier points. Numerous studies have been performed on the classification of demand patterns and proposed methods for classification but suggest that cut-off values are scenario specific.

Output: The demand categorization feeds into Step 4.2 (Determine forecasting method)

4.5 Study field 4: Inventory Management

Inventory management is the second study field in the 'analyze' work cluster in the proposed framework (Figure 4.1). The inventory management study field consists of 3 steps. The first two steps (determine service level requirement and determine forecast method) are in the 'analyze' work cluster and the third step (determine control policy) is in the 'synthesize' work cluster.

4.5.1 Step 4.1 Determine service level requirements

Determining service level requirements is the first step (Step 4.1) in the inventory management study field in the proposed framework. Service level is one of the most important metrics in SCM. It is used to indicate how well the SC performs to meet the needs of customers. If a company aims to achieve a service level of 90%, it aims to satisfy the needs of their customers 90% of the time.

Higher stock levels increase the availability of stock and therefore also increase the service level. However, logistics costs increase exponentially as service level increases towards 100% as indicated in Figure 2.8 in Section 2.3.5. In inventory management, two main approaches can be followed regarding service level. The first is to determine a required service level and adjust stock levels accordingly regardless of the associated inventory costs. The second is to find an optimal balance between cost and service level (above a certain minimum threshold) where the total cost of the inventory system, including the stock-out cost, is at a minimum. The second approach optimizes the system as a whole, but the first approach is still favoured in some situations when the service level is vitally important.

In inventory management it is therefore important to determine the service level requirements and strategy regarding service level as it influences stock levels. The service level requirement is predominantly included in safety stock calculations which are discussed in Step 4.3.

Objective: Determine service level requirements.

Inputs: The criticality assessment of spare parts in Step 3.1 forms a key guideline for determining service level requirements. Furthermore, the PAM strategy also plays a role in the service level decision-making. The PAM strategy provides the general direction of service level requirements from an asset performance perspective.

Considerations: In spare parts inventory management, there is an important trade-off between service level and cost. This step should highlight a preliminary service level, but it is advised that a final decision is only made once the estimated cost to achieve the service level is also known. This step helps managers to get consensus on spare parts objectives. In general, from a PAM perspective service levels should be as high as possible and from a SCM perspective, an adequate service level should be attained at a minimum cost. Discussing service level requirements before determining an inventory control policy therefore highlights discrepancies in objectives and provides clear direction for the remainder of the steps.

Output: The service level requirements feed into the inventory policy which is determined in Step 4.3.

4.5.2 Step 4.2 Determine forecasting method

The determination of an appropriate forecasting method is the second step (Step 4.2) in the inventory management study field in the proposed framework (Figure 4.1). Forecasting methods are used to forecast the demand for parts which serves as a vital input into inventory control policy calculations. There is an intricate relationship between the forecasting method and the stock control policy.

Refer to Section 3.3 for a review on spare parts forecasting methods and approaches. This step aims to propose appropriate forecasting methods for different demand patterns by matching demand patterns to possible forecasting methods. The proposed methods are combined with possible control policies in Step 4.3 to determine appropriate inventory control policies.

Objective: Determine appropriate forecasting methods per inventory class.

Inputs: The inputs to this step is the demand patterns categorization and maintenance tactics.

Methods:

Two types of forecasting methods are used to forecast the demand for spare parts: reliability-based forecasting and time-series based forecasting. A hybrid approach between the two methods is proposed in this framework.

Reliability-based forecasting has proven to provide superior forecasting accuracy compared to time-series based forecasting for the demand of spare parts. This is because reliability-based forecasting considers the demand generation process itself, whereas pure time-series based forecasting is reliant on the output of the demand generation process. Reliability-based forecasting is however dependent on condition monitoring data and good co-ordination between the maintenance and SCM department. This type of coordination and data is not always available. A hybrid approach between the two methods is therefore proposed. The time-series based forecast, despite its shortfalls, provides a realistic base forecast which is often more practical to obtain. It is therefore proposed that a time-series forecast is used to provide a base forecast, but is then enhanced with reliability-based information. The forecast should be updated at periodic intervals with a standard process between the different departments.

In terms of a time-series based forecast, the proposed links between demand patterns and forecasting methods are presented in Figure 4.5. The manual forecasting technique is dependent on expert judgements and most appropriate in the case where there is little to no data available. The 'D-LF' and 'D-LS' demand classes are for parts of equipment that is in the 'launch' phase, but for which some data is available from secondary sources. This data is not historic data and usually in the form of average demand intervals. It is therefore unrealistic to propose forecasting methods relying on historic data for these demand classes. The hypothesized demand distribution method is proposed for these items. This is because it takes into consideration the average demand and demand pattern and accommodates for the uncertainty in new parts in the form of probability theory.

Equipment in the 'in-use' life-cycle phase has been in operation for a certain time period which usually mean that some historic information is available and therefore more technical forecasting methods can be proposed. The Exponential Smoothing and Moving Averages methods have shown good results (without unnecessary complexity) for fast-moving parts and are therefore recommended for the 'D-FS' and 'D-FE' demand classes. The Croston and Bootstrapping methods have shown superior results for slow and intermittent

	Forecasting Method					
Demand Class	Manual forecasting	Exponential smoothing	Moving averages	Croston	Bootstrapping	Hypothesized demand distribution
D - NO	x					
D - LF						x
D - LS						x
D - FS		x	x			
D - FE		x	x			
D - SS		x		x	x	x
D - SE				x	x	x

Figure 4.5: Linking demand patterns to forecasting methods

demand and are therefore proposed for slow-moving parts in the 'D-SS' and 'D-SE' demand classes. In the case when very little historic demand information is available, the hypothesized demand distribution method could also be used for these two demand classes. When the demand is slow-moving but smooth (demand class 'D-SS') the Exponential Smoothing method can also be considered. It is a simpler approach to the Croston and Bootstrapping methods and could mean that the quality of the forecast is not compromised for the simplicity of the method.

In traditional sales forecasting, it is common to hold demand review meetings. In a demand review, the demand planners and the sales team meet to update the baseline forecast with promotional information. The aim of the meeting is to obtain a consensus forecast to which both the planning and sales departments agree to. Similarly, in SPM, it is proposed that the baseline forecast, generated by means of a time-series forecast, is updated regularly with reliability-based information to obtain a more accurate forecast.

Considerations:

The matrix in Figure 4.5 provides possibilities of forecasting methods per demand class. In order to find the best forecasting method for a scenario, the forecasting methods should be tested. This step therefore consists of the following sub-steps:

1. Select the possible forecasting methods based on the matrix in Figure 4.5.
2. Test the forecasting methods.

There are numerous methods to test forecast accuracy. Common methods include calculating the Mean Absolute Deviation (MAD), Mean Squared Error (MSE) and Mean Average Percentage Error (MAPE).

Output: Forecasting methods feed into inventory control policies.

4.5.3 Step 4.3 Determine inventory control policy

Determining the inventory control policy is the last step in the proposed framework before the validation. An inventory control policy is a collective term to describe the process by which stock should be managed. It provides general rules regarding when to order stock and how much to order when an order is placed. There are numerous factors which influence the choice of control policy. Previous steps in the framework concerning the SC strategy, classification of parts, service level requirements and forecasting methods all feed into this step.

The inventory policy consists foremost of the type of inventory policy by which inventory is managed (eg. continuous review or periodic review policies). Once a policy is decided on, the policy should also provide guidance regarding when to place orders and how many items to order when an order is placed. The Reorder Point (ROP) is the term commonly used to refer to the level of stock at which an order should be placed. The Reorder Quantity (ROQ) is the term used for the amount of items to order.

Objective: The objective of the inventory policy is to provide guidance to the operational team on how inventory should be managed. It should state when items should be ordered and how many should be ordered at a time.

Inputs: An inventory policy is obtained by consolidating the information retrieved in the other steps in the framework. For this reason, it is placed in the synthesize cluster in the proposed framework in Figure 4.1. The aim of the framework is to obtain an inventory policy and therefore all previous steps feed directly or indirectly into the determination of the inventory control policy. Refer to Figure 4.2, in the beginning of this section, for a graphical presentation of the relationships between the steps.

Methods:

The first decision regarding the determination of an inventory control policy is to decide which type of inventory control policy is suitable for stock items. Figure 4.6 provides a reference guide to aid the decision making process. The figure shows logical links between inventory classes and inventory control policies. Parts are classified according to the equipment's life-cycle, the criticality of the part and demand patterns in previous steps. The reference guide is not an exhaustive list of inventory control policies, but rather contains the fundamental policies. It is possible to extend each of these fundamental policies into more detail. Refer to Section 3.4 for more detail on inventory control policies and the advantages and disadvantages of each policy.

The second decision, after a possible inventory policy has been chosen, is to decide when orders should be placed by deciding on a Reorder Point (ROP).

CLASSIFICATION			INVENTORY POLICY						
						Continuous Review			Periodic Review
Life-Cycle Phase	**Criticality**	**Demand Class**	**Initial Ordering**	**Risk-Based Ordering**	**Order on Demand**	**(s,S)**	**(s,Q)**	**Base Stock Model**	**(R,S)**
Launch	V	D-NO, D-LF, D-LS	x						
	E	D-NO, D-LF	x						
		D-LS	x	x					
	D	D-NO	x						
		D-LF	x	x					
		D-LS		x	x				
In-Use	V, E, D	D-FS				x	x		x
		D-FE				x	x		x
		D-SS		x		x		x	x
		D-SE				x		x	
Phase-Out	V,E	D-NO				x			
	D	D-NO			x				

Figure 4.6: Demand class versus inventory control policy

ROPs are applicable to the continuous review (s, S) and (s, Q) policies and periodic review policies. In continuous review policies, an order is place when the stock level reaches the ROP. In periodic review policies, an order is placed when the stock level is reviewed after a certain time period and the stock level is lower or equal to the ROP. Depending on the policy, in some cases an order is placed only when the stock level is below the ROP and in other cases, an order is placed when the stock level is equal or beneath the ROP.

There are two ways to calculate an appropriate ROP: the Gaussian model or the Poisson model. The Gaussian model is the most popular model. The ROP is the average lead time demand plus a safety stock factor. The safety stock is calculated by assuming demand is normally distributed and specifying a service level. Refer to Equation 4.5.1 (Silver *et al.*, 1998). The Poisson model assumes that the amount of demand occurrences over a given interval is distributed according to the Poisson distribution. The model uses the desired service level as the probability of not running out of stock and estimates the ROP according to the Poisson distribution.

$$R = \bar{d}L + z\sigma_L \tag{4.5.1}$$

$$
\begin{aligned}
\text{where:} \quad \bar{d} &= \text{Average demand in years} \\
L &= \text{Lead time in years} \\
z &= \text{z-score for the desired service level} \\
\sigma_L &= \text{Standard deviation of demand during lead time}
\end{aligned}
$$

The third decision regarding the determination of an inventory control policy is the ROQ. The ROQ can be calculated by using the well-known EOQ model. Refer to Equation 4.5.2 (Silver *et al.*, 1998). The EOQ method is appropriate when using the continuous review (s, Q) policy. The EOQ model takes into consideration the order cost, carrying cost and average annual demand to determine the most economical order quantity. The EOQ model is not always appropriate in SPM. According to case studies performed by Moncrief *et al.* (2006), the EOQ is one unit 80% of the time for spare parts because of slow-moving, intermittent demand patterns. In such cases an order-up-to policy is commonly used and the ROQ is then equal to the order-up-to level minus the current stock level.

$$
Q = \sqrt{\frac{2DK}{h}} \tag{4.5.2}
$$

$$
\begin{aligned}
\text{where:} \quad \text{Q} &= \text{Economic order quantity} \\
\text{D} &= \text{Average annual demand} \\
\text{K} &= \text{Order cost per order} \\
\text{h} &= \text{Carrying cost per year}
\end{aligned}
$$

Considerations:

Three factors play a dominant role when considering an inventory control policy. The first is the resulting cost in following a control policy. The second is the expected service level which a policy would achieve and the third is the practicality of the implementation of an inventory control policy. A fine balance is required between the different factors to determine the most effective, yet implementable control policy.

The repairability of parts is another important aspect of spare parts to consider when determining an inventory control policy. For repairable parts, the ordering function is replaced with sending parts in for repair. The lead time is therefore equal to the time required to repair a part. In this situation, orders for new spare parts are predominantly only applicable in the following three situations:

1. In the beginning of the equipment's life-time spare parts are bought to replace the broken parts while it is in for repair. In turn, when the part is repaired, it acts as the spare part.

2. When the time to repair a part exceeds the time until the next expected failure.

3. When there is the possibility that a part could break beyond repair.

Output: The output of this step is an inventory policy which should prescribe the way in which inventory is managed, when to place orders and how many items to order. The inventory control policy would differ according to the different types of inventory items. The inventory policy is not static. It should provide guidance to the operational team, but should be updated regularly with up to date information. The update procedure should also be clearly stated in the policy.

4.6 Evaluate

The service level and total inventory costs are the key metrics to evaluate inventory control policies. In addition, the inventory cost is directly related to the average stock level and therefore it is common to also include the average stock level for the evaluation. Refer to Section 2.3.5 for a summary of the costs associated with inventory systems.

It is important to evaluate the impact of an inventory control policy before it is implemented. Physical implementation of policies are however not always possible and could be expensive. For this reason, mathematical models are used to determine the behaviour of a system prior to implementation. Refer to Section 2.1.5 for a review on SC models. Linear or mixed integer programming and simulation models are amongst the most popular models to model SC behaviour. In this case, it is proposed that inventory control policies are evaluated by simulating the behaviour of the system over time by using any appropriate method available that can take into account the stochastic nature of spare parts demand.

The evaluate step (Step 5) also acts as an important feedback loop in the proposed framework (Figure 4.1). In the evaluate step, appropriate inventory policies are reviewed and based on the outcome, any of the steps could be revisited to improve the overall inventory control policy. Fixed time periods should also be set to review implemented inventory control policies to ensure they take into account any additional information and changes in the environment. An inventory control policy is therefore not static and should be reviewed on a periodic basis by following the framework to ensure it is still optimal for the given class of spare part items.

4.7 Chapter summary

This chapter discusses the development of a decision-making framework for the management of spare parts inventory. The development of the framework is supported by a thorough literature analysis in Chapter 2 and Chapter 3. In this chapter, an overview of the framework is provided and each step within the framework is discussed in detail by considering the objectives, inputs, methods, considerations and outputs.

The proposed framework aims to provide a practical, structured guideline to managers when determining inventory control policies. The framework is unique because it emphasizes an holistic approach to the solution, encompasses the life-cycle view of the equipment and represents the decision-making process as an interacting web of activities.

In line with the overall research objectives of this study (Refer to Section 1.3). This chapter concentrated on the fourth research objectives. The following sub-objectives were achieved.

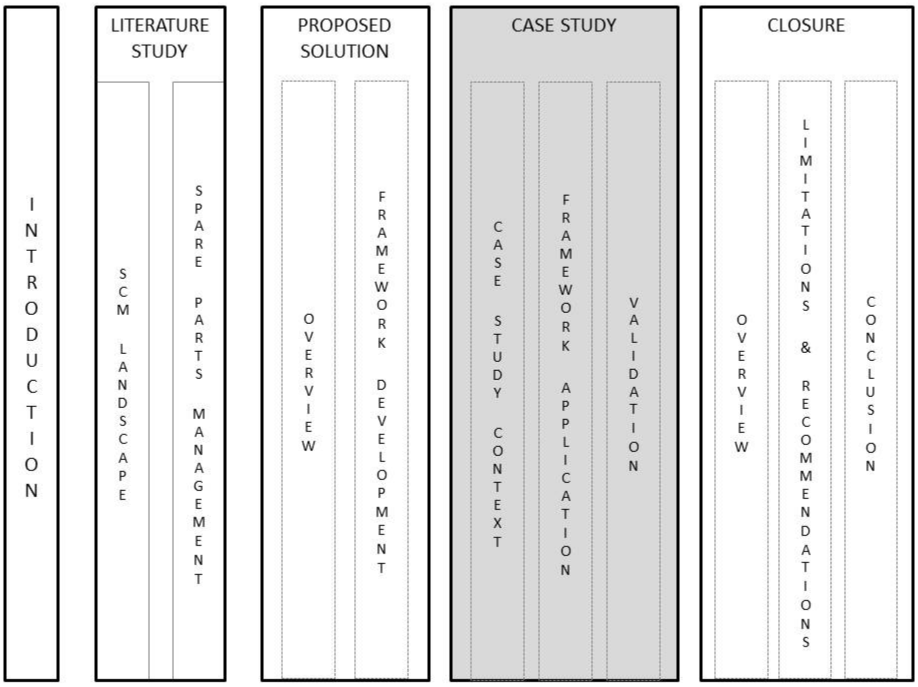
- Determine decision-making criteria for selecting methods to classify inventory, forecast demand and manage inventory
- Consolidate decision-making criteria into a structured framework

The following chapter, Chapter 5, applies the framework by conducting a case study in the capital-intensive industry with the aim to assess the validity of the framework.

Chapter 5

Case study

This chapter comprises of a case study conducted in cooperation with Anglo American. The proposed decision-making framework in Chapter 4 is applied to an operational scenario in the South African mining industry with the aim to test the validity of the framework. This chapter commences by discussing the background and preparation of the case study as well as current practices. Thereafter, the application of the case study is discussed which is notably the majority of the chapter. The chapter ends with a summary of results which leads to the final chapter, the conclusion of the study.



5.1 Case study background

The decision-making framework, developed in Chapter 4, is applied and validated by means of a case study in the South African mining industry at an open pit mine. Spare Parts Management (SPM) is an important issue in the mining industry where large capital expenditure on equipment is common. The mining industry and more specifically open-pit mining is a good representative for capital-intensive industries as a whole and therefore suitable as a case study to validate the proposed solution.

Case study research is orientated at understanding the uniqueness and idiosyncrasy of a particular case. The aim is typically to understand the dynamics of a single bounded system and the study pertains to the fact that a limited number of units of analysis are studied intensively (Welman *et al.*, 2005).

This chapter consists of five main sections: case study background, case study preparation, current practice, framework application and validation. The remainder of this section focuses on the case study background. First, the context is described and thereafter the business problem is discussed.

5.1.1 Contextual background

This research study received considerable support from Anglo American and was conducted in collaboration with the Asset Care Research Group (ACRG) at Stellenbosch University. Anglo American is one of the largest mining companies in the world, their portfolio comprises of iron ore and manganese, copper, metallurgical and thermal coal, nickel, niobium and phosphates, platinum and diamonds. The ACRG acts as an intermediary to facilitate interactions between research and industry in Physical Asset Management (PAM) related topics.

Anglo American identified SPM as an area worth exploring for improvement initiatives and directed the study towards one of their mines for further investigation. For confidentiality purposes, the mine is referred to as The Mine for the remainder of this study. The Mine is a large open-pit iron ore mine. Company specific information for the application of the case study is retrieved from The Mine, but is not referenced as such in order to treat the information confidentially.

A site visit to The Mine was conducted in January 2014 to investigate the management of spare parts from a practical perspective. The operation at The Mine is capital-intensive and makes use of a wide range of machinery. The arena of spare parts is therefore also vast. The investigation was initially focused on heavy mining equipment and later narrowed to one specific type of equipment, i.e. electric rope shovels. The next section provides an introduction to electric rope shovels.

Figure 5.1: Rope shovel in operation. Adapted from Joy Global (2012)

5.1.2 Introduction to electric rope shovels

An electric rope shovel for mining purposes is a machine designed to dig and load material in surface mines (MinePro, 2003). It is also commonly referred as a 'rope shovel' which is the term used during the rest of the case study explanation. At The Mine, rope shovels are predominantly used as primary loading equipment to load ore onto haul trucks which transport the ore to the crushers. Alternatively, they are also used during the pre-stripping process to prepare an area for drilling. Rope shovels perform a critical function in the mine and require large capital investments. The management of their spare parts is therefore an important task. Refer to Figure 5.1 for a picture of a rope shovel in operation.

A good understanding of the operations of a rope shovel and the functioning of parts is necessary to complete the case study. Electric rope shovels consists of three main assemblies: Lower, Upper and Attachment. The Lower Assembly consists of the crawler system and propel drive which act as a stable base for the machine. The Upper Assembly provides a platform for the hoist and swing machinery, electronic control cabinets, boom attachment, operator's cab and supporting equipment. The Attachment consists of the boom assembly, crowd machinery, dipper handle and dipper (MinePro, 2003). The different assemblies and parts can be seen in the schematic representation of the rope shovel in Figure 5.2. For reference purposes, the symbols in the figure refer to the following: A, dipper; B, dipper door; C, dipper stick; D, saddle block; E, boom; F, shipper shaft; G, rotating wheel; H, boom hoist line; I, operator cabin; J, A-frame; K, machinery housing; L, revolving frame; M, turntable; N, hoist rope; O, ballast box; P, crawler.

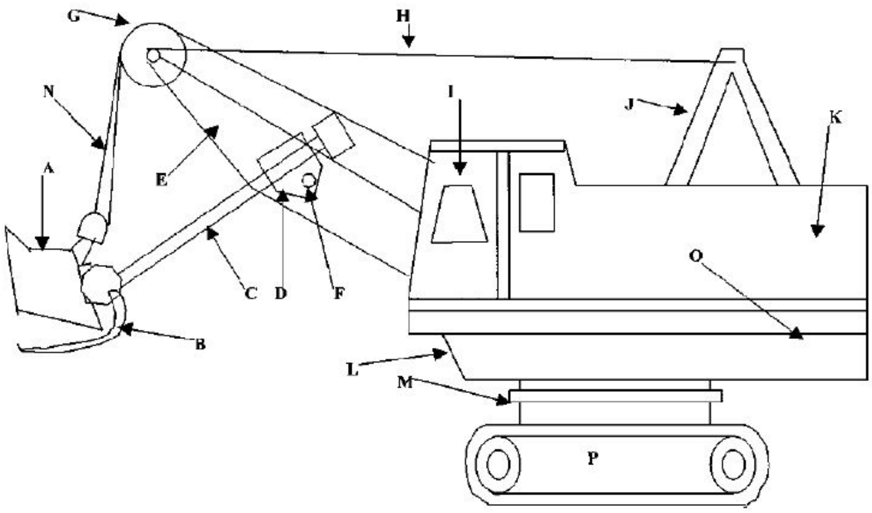


Figure 5.2: Schematic diagram of an electric rope shovel. Adapted from Roy *et al.* (2001)

The work cycle of an electric shovel consists of five stages: digging, swinging, dumping, returning and positioning. First, in the digging phase, the digging tool (bucket or dipper) is moved to the bank, hoisted to fill the bucket and retracted. Thereafter, the digging tool swings towards the offloading area where the material is dumped onto a haul truck. Lastly, the digging tool returns to its original location and positioned to repeat the process (MinePro, 2003).

The operation of an electric shovel consists of four key motions: propel, hoist, crowd and swing. The propel motion is used to move the machine from one site to another or to reposition the machine at a site. The hoist motion pulls the digging tool in an upward direction through the bank. The crowd motion controls the depth of cut by moving the dipper handle out- or inwards when positioning to dump. Finally, the swing motion is used to swing the boom in a direction towards the offloading area (MinePro, 2003). The contextual background and introduction to electric rope shovels provides an appropriate background to the study. The next section explains the business problem.

5.1.3 Business problem

SPM is essentially about achieving a balance between the risk of not having the part available and the cost to keep the part in stock. In the mining industry, inventory cost is expensive and the risk associated with unavailability of parts is high which leads to an accentuated need to find this balance.

On the one hand, mining equipment is typically expensive and their spare parts require large capital and operational expenditure. As a result, their associated inventory cost is also high. On the other hand, mining operations are throughput driven and rely on high utilization of equipment. Unexpected equipment down-time is therefore a high risk and costly to the business. SPM influences the availability of spare parts which affects the total down-time of equipment. Consequently, effective SPM can be used as a buffer against uncertainty in part failures.

The objective to find a balance between risk and cost is further complicated by contrasting objectives from different departments. For example: The Engineering department would typically like to keep a large amount of spare parts in stock to improve equipment availability. The Supply Chain (SC) department would like to keep logistics costs low. The two departments' behaviour is an offspring from their performance measures and a lack of integration between the different departments.

The struggles in the management of spare parts at The Mine are similar to the issues expressed in literature in the field. The following three questions summarize their main concerns:

1. Which spare parts should be bought?
2. When should spare parts be bought?
3. How many spare parts should be bought?

In the specific case at The Mine, rope shovels play an important part in the value chain of The Mine and are also very expensive. The need to find a balance between risk and cost in the context of SPM is therefore of utmost importance. Rope shovels have a large portfolio of spare parts with diverse characteristics which make it difficult to manage.

The proposed framework in Chapter 4 provides guidance to managers on the management of spare parts. The application of the framework aims to address the above-mentioned problems by taking an holistic view on the problem. The next section discusses the case study preparation.

5.2 Case study preparation

The decision-making framework is validated by means of a case study. This involves the application of the decision-making framework, presented in Chapter 4, to a real-world problem.

The application of a case study requires adequate preparation. Welman *et al.* (2005) mention three important aspects of case study research: demarcation of case, search for recurring patterns and triangulation. This section starts with a discussion on the validation methodology. Thereafter, the demarcation of the case is discussed by outlying the scope and boundaries of the case study. The data requirements and preparation are discussed last and include the analysis of recurring themes and triangulation.

5.2.1 Validation methodology

As mentioned in Section 5.1, the case study is performed at The Mine and the framework is tested by applying it to the management of spare parts for rope shovels. Refer to Figure 4.1 in Section 4.1.2 for a review of the proposed decision-making framework.

The validation process follows the following five key steps:

1. Scope definition
2. Data requirements
3. Current practice
4. Framework application
5. Validation

First, the study is demarcated by defining the scope, and data requirements are stated. The current practice at The Mine is then discussed, followed by the application of the framework and lastly the validation of the study.

The application of the framework follows the format of a retrospective case study. The framework is applied as if it is the beginning of 2012 at the time when the first 4100 Rope Shovel was purchased. The study provides a recommendation for inventory control policies for spare parts by following the decision-making framework proposed in Section 4. The study is validated by evaluating the performance of the proposed inventory policies to the actual data from 2012 until June 2014, verifying the model, testing the application of the framework and by obtaining management feedback. The inventory cost and service level are used as two key metrics to measure the effect of the application of the framework.

The scope and the data requirements are discussed in Sections 5.2.2 and 5.2.3 respectively. Thereafter, the current practice is explained in Section 5.3. The application of the framework is discussed in Sections 5.4, 5.5, 5.6 and 5.7 and the interpretation of the results are stated in Section 5.8.

5.2.2 Scope

It is essential to define the scope or boundary of a study. The boundary determines which activities are included and excluded in the case study. It is important to define a sensible boundary which is both large enough so that the case is representative and small enough so that it is manageable.

This study focuses solely on SPM for rope shovels at The Mine. The Mine currently owns three types of rope shovels: 2300, 2800 and 4100 Rope Shovels. The 2300 range of shovels were bought in 1997. The 2800 and 4100 shovels are new shovels bought in 2012. The case study only includes the 4100 Rope Shovels. This type of shovel is the flagship rope shovel at The Mine providing a nominal 120 ton capacity. The Mine aims to operate three 4100 Rope Shovels in the future. In 2012, only one of the shovels was already in operation and therefore only that one rope shovel is included in the scope of this study.

A rope shovel contains over 20,0000 distinctive parts (including wear and tear parts such as washers and bearings). Parts are however grouped according to the collective function they perform. It is important to identify at which level parts should be managed. This is largely determined by the level at which parts are replaced in machines. At The Mine, parts are replaced as a whole according to their function. For example, if there is a problem with the main transformer, the whole transformer is removed and replaced with a new or repaired transformer. The old transformer is then sent for repair. In the application of the framework, parts are therefore also grouped according to their function to match the way in which parts are practically managed.

The 4100 Rope Shovel is supplied and manufactured by a key supplier of The Mine. The supplier is also referred to as an Original Equipment Manufacturer (OEM). For the remainder of the study, for confidentiality purposes, the supplier is referred to as The OEM. The OEM offers comprehensive maintenance and repair services which include the stock-holding of a large portion of the parts for the 4100 Rope Shovel. For the purpose of this study, only the parts in ownership of The Mine are included in the the case study. This study is sponsored by Anglo American and is therefore performed from the perspective of The Mine and parts held at The OEM are not in scope of the case study.

In line with The Mine's recommendation, regular wear and tear items such as the hoist rope and dipper teeth are not included in the scope of the framework. This is because these parts represent a small portion of the cost and have a short lead time. The potential value of applying the framework to these parts is negligibly small in comparison to the main components.

Table 5.1 shows a summary of the elements included and excluded in the scope of the case study per boundary area. The next section describes the data required for the application of the case study.

Table 5.1: Scope inclusion and exclusion

	Scope: Included	**Scope: Excluded**
Application	4100 Rope Shovel	Other types of rope shovels
Ownership of parts	The Mine	The OEM
Type of Parts	Normal, critical and strategic	Wear and tear

5.2.3 Data requirements

The successful application of the framework is reliant on quantitative and qualitative information from The Mine. For the purpose of the study, quantitative data is retrieved from information systems and management reports. Qualitative information is obtained through discussions with different managers at The Mine. Qualitative information is typically used to perform the steps in the 'contextualize' work cluster in the proposed framework. In contrast, the steps in the 'analyze' work cluster usually require quantitative data.

During the data gathering process for the case study, it was noted that there is a vast gap between ideal data and the data available in practice. The following factors complicated the data gathering process:

1. Part coding – Multiple codes are used to refer to the same part in different datasets
2. Level of parts – Part data is recorded at different levels in different datasets
3. Lack of single source – Data is distributed amongst multiple sources across department which complicates the collection of data
4. Data availability – Some data is not recorded, or only partially recorded

The above-mentioned data issues are not seen as unique to The Mine. It is important that the proposed framework makes provision for different levels of data availability and cater for scenarios where data is limited.

5.3 Current practice

This section discusses the current practice at The Mine. The general processes and practices are discussed first, followed by the specific practice with regards to the 4100 Rope Shovel.

At The Mine, the management of spare parts is integrated into the long-term planning process. The long-term planning process starts with an estimate of the production output and required equipment to obtain the output for the next 5 years. The equipment plan is then shared with OEM's because many of the items have long lead times and orders need to be integrated with suppliers. When orders are placed for new equipment, The Mine determines the critical and strategic parts for the equipment and then collaborates with OEM's to clarify who is responsibility to keep which stock items.

A standard procedure is in place at The Mine to classify parts according to criticality. The standard procedure is stipulated in the "Engineering standard strategic & critical spares" document. Spare parts are classified according to an informal VED (Vital, Essential and Desirable) approach into strategic, critical and normal spare parts. The streamlined version of the Reliability Centred Maintenance (RCM) process followed at The Mine feeds into the classification and furthermore parts are classified subjectively according to the definitions for each of the categories. The definitions for the different categories are shown below:

- **Strategic Spares**
  "Equipment when it is in a breakdown state, will severely affect the production or safety to persons of a Production Area and negatively affect the overall production of the mine/operation for an extended period of time. Any spare component for Strategic equipment that is not readily available from the OEM or has a long lead-time to manufacture / deliver to site or is a high cost item"
- **Critical Spares**
  "Any equipment spare, when it is in a breakdown state, reduces or affects production of a Production Area"
- **Normal Spares**
  "Spares needed on a daily basis for maintenance". This category includes wear and tear spares as well as consumables.

The outcome of the classification influences The Mine's decision to stock an item or not. Figure 5.3 shows the process The Mine follows to determine which parts to keep in stock. First, critical and strategic parts are identified. Thereafter, The Mine collaborates with the OEM to determine which of the critical and strategic parts they plan to keep in stock in a warehouse which is in the vicinity of The Mine. These parts are typically kept as consignment stock and are important, because they have shorter lead times as other parts and consequently do not have to be kept in stock under ownership of The Mine. Lastly, The Mine then decides which parts they keep in stock.

The Mine also follows a streamlined version of the well-known Reliability Centred Maintenance (RCM) process. The process is followed with the aim to

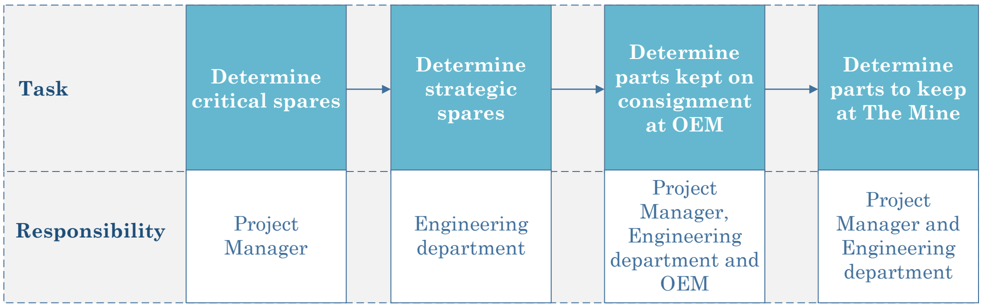


Figure 5.3: Current process to identify parts for new equipment

perform the right maintenance tasks, at the right time with the right resources to increase equipment reliability, productivity and reduce maintenance costs.

The 4100 Rope Shovel was placed into operation in April 2012. Prior to operation, the critical and strategic parts were identified. The list of critical and strategic parts was then reconciled with the list of parts The OEM is willing to keep in stock. The Mine decided to stock the resulting critical and strategic parts which The OEM was not willing to stock. This list contains 29 parts. The items in the list typically have long lead times, high purchase values and are critical to the operation of the machine. The total purchase value for the parts bought in 2012 was approximately R48 million.

The 29 parts kept under ownership of The Mine are predominantly repairable parts (28 out of 29 are repairable). This implies that when a part fails, it is replaced with a spare part and the broken part is sent in for repair. When the broken part is repaired, it is sent back to The Mine and it then takes the position of a 'spare part' in stock. The Mine is therefore predominantly concerned with the inventory control policy when ordering parts in the beginning of the equipment's life-cycle.

All new parts are ordered at the same time, in the beginning of the operating cycle of the equipment. The reason for this decision is the level of perceived uncertainty in part failures. The Mine does not want to risk running out of stock, strives for a 100% service level and therefore aims to stock parts at all times from the beginning of the operating cycle.

The stock-out cost of an unavailable item is approximately R 267 million per year. The stock-out cost in this case is calculated as the cost to hire a contractor to perform the function of the equipment. The average carrying cost rate at The Mine is between 9 - 10 % of the purchase value of parts per year. The contractor cost is therefore extremely high in comparison to the carrying cost. Nevertheless, the carrying cost as well as the locked capital cost are significant figures and it is worth reconsidering which parts to keep in stock, when parts should be bought and how many to buy. The detail calculations of the cost of the existing practice are discussed further in Section 5.8.2.

The following section discusses the application of the framework to the case study. In the end of the section, the framework is validated and results compared to the metrics of the current practice.

5.4 Study field 1: Supply Chain Management

This section is the first section discussing the application of the proposed framework in Chapter 4 to the case study. As far as possible, the application of the framework follows the numerical sequence of the proposed framework in Figure 4.1. This is to provide appropriate structure for the study. The proposed framework discussion in Section 4.1 however stresses that the numerical sequence of steps is merely a guideline. In practice, the application of the framework is an iterative process and steps are intertwined to achieve the desired outcome.

This section starts with the contextualization of the case study by discussing the Supply Chain Management study field. The other study fields, Physical Asset Management, Classification and Inventory Management are discussed in Sections 5.5, 5.6 and 5.7 respectively. Lastly, the validation of the framework is discussed in Section 5.8.

The remainder of this section is focused on the Supply Chain Management study field which includes the identification of the SC strategy, the analysis of the equipment SC and parts SC. Refer to Section 4.2 for the prescribed steps in this study field. Each of the steps are described in detail below as it applies to the case study.

5.4.1 Step 1.1 Identify SC strategy

The identification of the SC strategy is the first step in the framework. It is important because a company's strategy drives the overarching direction of the company's operations. According to The Mine, in the short term, they aim to maximize the value of the operations within their current logistical capacity and in the medium term they aim to optimize and execute their project pipeline. The company is built on four strategic pillars: optimizing value of current operations, capturing value across the value chain, delivering growth projects and organizational responsibility and capability.

SPM plays a role in optimizing value of current operations and capturing value across the value chain. In terms of Supply Chain Management (SCM) there is an emphasis on containing costs and driving value. The Mine states that "it is essential that we manage costs across the operations in such a way that allows our production to be profitable". The strategy serves as an input to the decisions regarding inventory control policies in Step 4.3.

5.4.2 Step 1.2 Analyze equipment SC

An understanding of the equipment SC assists to provide context to the problem so that succeeding decisions regarding SPM support the overall SC. In the context of the case study, the equipment SC refers to the SC in which the rope shovel participates. It can be seen as the overall or core SC of The Mine.

A summarized version of The Mine's SC is depicted in Figure 5.4. It starts with exploration to identify a suitable mining area. Thereafter, the area is prepared and drilling and blasting take place. After the blast, the blasted material is loaded and hauled to the primary crusher and thereafter also the secondary and tertiary crusher. Lastly, the resulting iron ore mass go through the beneficiary process and is loaded to customers. The majority of the ore is exported and therefore loaded onto the train at The Mine and transported to Saldanha Bay.

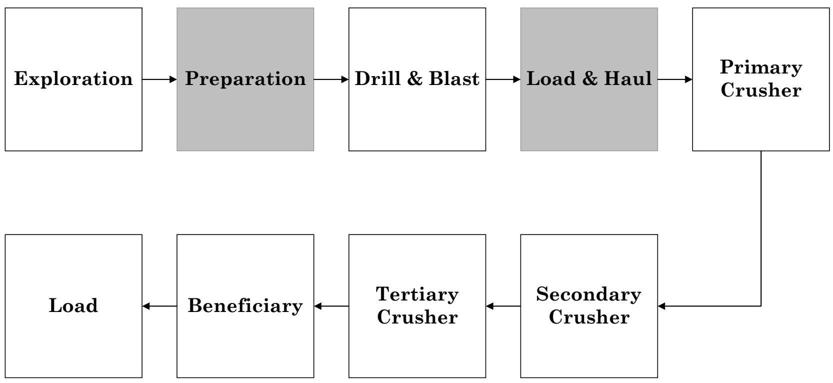


Figure 5.4: Equipment Supply Chain

The rope shovel forms part of the family of electric shovels used in mining. Electric shovels play a key part in the load and haul process of mining. There is an intricate relationship between shovels and haul trucks. The shovel is used to remove the material from the ground in a scooping action and load it onto haul trucks which are used to transport the material to the primary crusher. According to Darling (2011), loaders and truck haulers move more material than all other excavation systems combined in mining. Electric shovels are also used for preparation before drilling can take place. The processes in which the rope shovel takes part are highlighted in Figure 5.4.

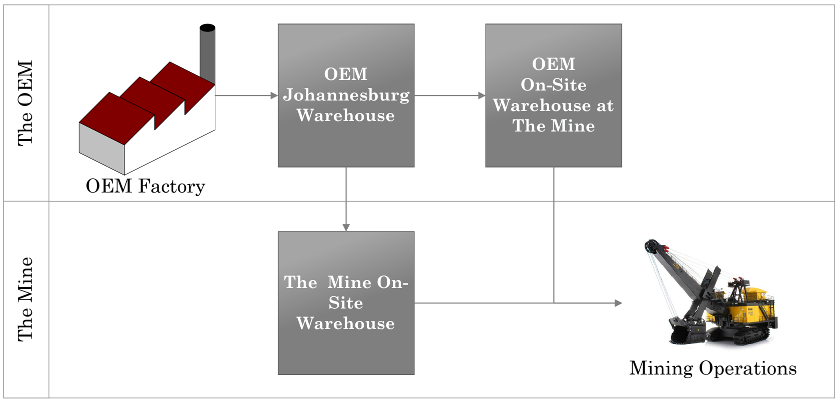


Figure 5.5: Spare Parts Supply Chain

5.4.3 Step 1.3 Analyze parts SC

The 4100 Rope Shovel is designed manufactured, supplied and supported by The OEM. The OEM is a mining and service support company based in the USA. The company is a well-known, reliable supplier of electric shovels supporting more than 90% of the world's mining operations.

The OEM has a main manufacturing plant in the USA, a warehouse and smaller factory in Johannesburg and an on-site warehouse at The Mine. In addition, The Mine also has an on-site warehouse of which the stock is under their ownership. Figure 5.5 is a graphical representation of the parts SC.

There is an intricate relationship between The Mine and The OEM in terms of the responsibility split of stock-holding and support. The OEM keeps the majority of spare parts in stock either in their on-site warehouse at The Mine or in Johannesburg. The Mine only keeps those parts which the OEM does not keep in stock and which are considered as critical to the operations of The Mine. An OEM usually favours parts with lower part costs and high demand because it results in lower 'locked' capital and better cash flow. This implies that the majority of the parts that The Mine keep are parts of high-value and low demand.

The Supply Chain Management study field provides appropriate contextualization for the remainder of the framework. The SC analysis and process maps aid to the classification of parts in Section 5.6. The strategy provides a general direction which the choice of inventory control policy should support.

5.5 Study field 2: Physical Asset Management

The Physical Asset Management study field includes the identification of the PAM strategy, the determination of the asset life-cycle and the identification of maintenance tactics. Refer to Section 4.3 for the prescribed steps in this study field. Each of the steps are described in detail below as it applies to the case study.

5.5.1 Step 2.1 Identify PAM strategy

The overall strategy is discussed in Section 5.4.1. PAM also plays a role in optimizing value of current operations and capturing value across the value chain. According to The Mine, they "seek to contain unit costs, and improve productivity and operational efficiencies through its asset optimization programme".

Although The Mine's strategy does not specify explicitly the desired service level for spare parts, their short term aim is to maximize the value of their current operations. This implies that they seek high equipment availability which translates to a high service level. The strategy feeds into the service level requirements in Step 4.1.

5.5.2 Step 2.2 Determine asset life-cycle

The 4100 Rope Shovel is placed into operation in 2012. This retrospective case study is applied as if it is year 2012 and therefore the equipment is less than two years old and in the launch phase of its life-cycle. The life-cycle phase of equipment predominantly influences the data availability for analysis. The framework differentiates between two types of data from a demand pattern analysis perspective: primary and secondary. Primary data sources include historic demand data and maintenance or inspection data. Examples of secondary data sources are OEM data and expert opinions. OEM data is typically conservative, but can give a relative estimation to predict part failures.

The equipment is in the launch phase which implies that very little to no historic data is available to assist decision-making. This leads to the use of secondary data sources. The asset-life cycle influences the demand pattern analysis in Step 3.2.

5.5.3 Step 2.3 Identify maintenance tactics

The following maintenance tactics are followed: tactical corrective maintenance, predictive maintenance, preventative maintenance and redesign. At The Mine, $60 - 70\%$ of parts are on a preventative maintenance program. Maintenance and spare parts requirements are integrated in the form of maintenance plans. Maintenance plans are shared three weeks in advance with the SC department to ensure the availability of parts necessary for the maintenance activities. The majority of the parts on the maintenance plans are wear and tear parts and therefore not included in the application of the case study.

At the time the framework is applied, in 2012, no maintenance and inspection data is yet available as the machine is not yet in operation. The maintenance tactics are therefore not considered to determine the initial stock-holding policy. As the equipment is placed into operation, maintenance and inspection information will be obtained. An opportunity should therefore be provided for the inventory control policy and demand forecast to be updated regularly in light of new information and data obtained.

5.6 Study field 3: Classification

The Classification study field is the first study field in the 'analyze' work cluster in the proposed framework (Figure 4.1). The 'contextualize' work cluster takes a broad outlook on the problem and is concerned with the equipment as a whole and parts in general. In contrast, the 'analyze' work cluster is only concerned with the parts in scope of the study. In this case, it is only concerned with the management of the 29 parts which The Mine holds in stock.

Part classification is important because it eases the management of spare parts. In the proposed framework, parts are classified according to criticality and demand patterns. Part criticality influences the desired service level requirements and the analysis of demand patterns is a determinant for selecting appropriate forecasting methods. The assessment of part criticality is discussed first in Section 5.6.1 followed by the demand pattern analysis in Section 5.6.2.

5.6.1 Step 3.1 Assess part criticality

In the proposed framework, Step 1.2 (Analyze Equipment SC) and Step 1.3 (Analyze Spare Parts SC) feed into the assessment of spare part criticality. The analysis of the equipment SC reveals that the 4100 Rope Shovel plays a key role in the primary value chain of the company and therefore the criticality of its parts should be given a high criticality rating over and above the individual part ratings. The analysis of the spare parts SC enables a better understanding of the SC and shows that the lead time for the rope shovel parts are predominantly long. This factor is included in more detail in the criticality classification.

In the proposed framework, the overall part criticality is assessed according to the following criteria: part cost, lead time and criticality. The ABC method is used to classify parts according to the part cost and lead time. The VED (vital, essential, desirable) approach is used to classify parts according to criticality.

The following methodology is used to apply the ABC method to the case study using the part cost as the criteria:

1. Sort parts in descending order according to part cost

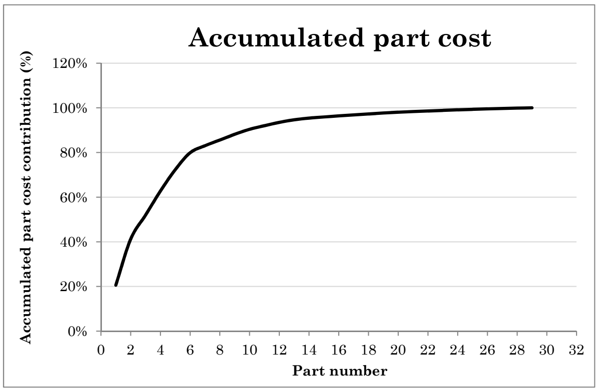


Figure 5.6: Accumulated part cost

2. Calculate the percentage which each part's cost contribute to the total cost

3. Calculate the accumulated percentage cost contribution of each part

4. Decide on a cut-off value to separate parts into high and low groups according to part cost

Resulting from the application of the above-mentioned methodology, Figure 5.6 shows the accumulated part cost contribution per part. The data follows the Pareto principle in the sense that six parts (20 %) contributes 80 % of the value. The six parts are grouped in the 'high' group according to part value. The exact lead times for parts are not known, but according to management's judgement the lead time for all these parts should be considered as 'long'. This is seen as sufficient considering that the part value and lead time classifications are mainly to filter items for the final quantitative classification based on criticality.

After the part value and lead time categorization, parts are further classified subjectively according to criticality. This is based on managers' opinions. All the parts with a high value are classified as 'vital'. Three of the parts with a 'low' value are classified as 'vital' and the rest as 'essential'. Figure 5.7 shows the resulting categorization. The number of parts in each category is shown below the last grouping.

5.6.2 Step 3.2 Analyze demand patterns

The decision logic to classify parts according to demand patterns concerns the life-cycle phase, secondary data availability, demand interval and also the demand variability. Refer to Section 4.4 for a review of the proposed method. A summary of the decision logic followed in the case of the 4100 Rope Shovel is shown in Figure 5.8.

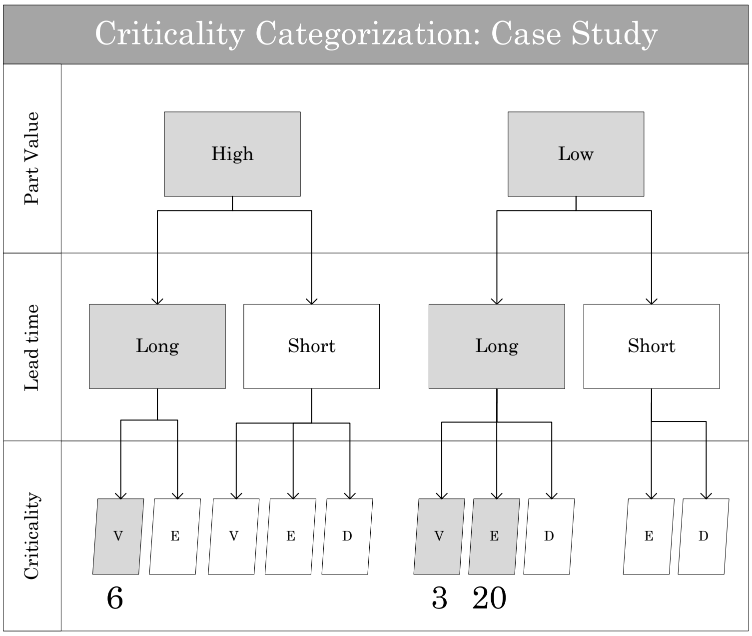


Figure 5.7: Case study: Criticality assessment

The 4100 Rope Shovel is in the 'launch' phase and therefore very little historic data is available for the analysis of demand patterns. Two sources of secondary data is however available to assist the decision-making process: OEM data and expert opinion. OEM data is in the format of average life-time per part. Expert opinion regarding the average life of parts and the demand variation was also obtained. This information is based on similar equipment at The Mine. In this case, considering the demand interval, the cut-off value is an average of one demand occurrence per year. If the part has an average demand of more than one unit per year, it is classified as a fast-mover, otherwise as a slow-mover. The demand variability is not applicable to the parts in question as the equipment is in the launch phase. The result of the decision-logic is that all 29 parts are classified in the 'D-LS' demand class.

The result of following the logic in the proposed framework is that parts are classified into two different criticality groups ('vital' and 'essential') and one demand class ('D-LS'). A summary of the parts classification is shown in Table 5.2. The table shows the number and value of the parts in each category. A detailed parts list and their respective classification is shown in Appendix A, Table A.1.

The almost homogeneous nature of the parts in scope is not a surprise as it is a result of the decision-logic followed by The Mine to determine which parts they will keep in stock. The Mine carries those items which are critical to the operations of The Mine and therefore parts are expected to fall in the 'vital' and 'essential' categories. Furthermore, OEM's typically carry items in stock

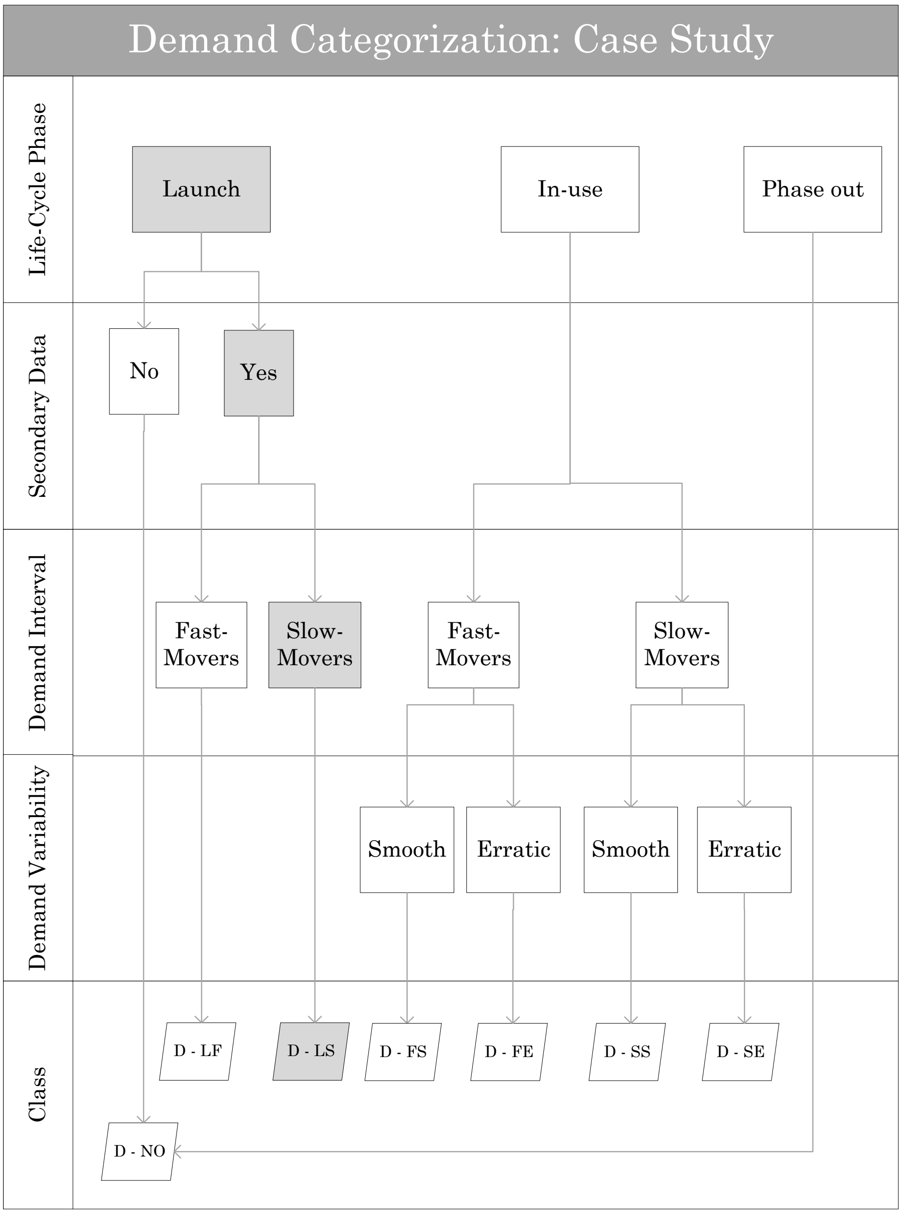


Figure 5.8: Case study: Demand pattern analysis

Table 5.2: Part classification summary

Permutation	**Life-cycle phase**	**Criticality**	**Demand class**	**Number of parts**	**Part Value**
1	Launch	Vital	D-LS	9	R 40 mil
2	Launch	Essential	D-LS	20	R 7.8 mil

with high demand. Consequently, The Mine's portfolio of parts kept under their ownership consists of slow-moving items.

The criticality measurement is important when determining the service level requirements and the demand classes are important when determining an appropriate forecasting method. The part classification is also important ultimately in determining an inventory control policy.

5.7 Study field 4: Inventory Management

Section 5.4 and Section 5.5 provide appropriate context to the 4100 Rope Shovel to enable an holistic solution to the SPM problem. Section 5.6 classifies parts according to criticality and demand patterns to divide parts into manageable groups.

This section builds onto the outcome of the previous sections with the aim to identify or develop an appropriate inventory management policy for parts. The service level requirements and forecast methods are discussed first and lead into the inventory control policy determination. Refer to Section 4.5 for a review on the proposed solution concerning this study field.

5.7.1 Step 4.1 Determine service level requirement

The service level requirements for parts are influenced by the PAM strategy and spare parts criticality classification. This can be seen in Figure 4.2 which indicates the relationships between different steps in the proposed framework.

Indications in previous steps lead to a need for a high service level of parts for the 4100 Rope Shovel. The PAM strategy focuses on improving productivity and operational effectiveness. The equipment has recently been bought and therefore throughput is important to justify expenditure. Furthermore, the 4100 Rope Shovels play an important role in the value chain of the company.

In Step 3.1, the parts were categorized into 'vital' and 'essential' groups. According to The Mine's management, The Mine strives for a 100% service level considering the availability of spare parts to minimize risk. In practice, a 100% service level is however hard to achieve and therefore the actual realistic service level is not equal to 100 %, but rather as close as possible to 100 % taking into consideration minimization of costs. The management also mentioned that the service level for 'vital' parts is required to be higher than 'essential' parts. The desired service levels acts as a guideline when determining the correct inventory control policy.

		Forecasting Method					
		Manual forecasting	Exponential Smoothing	Moving Averages	Croston	Bootstrapping	Hypothesized demand distribution
Demand Class	D - NO	x					
	D - LF						x
	D - LS						x
	D - FS		x	x			
	D - FE		x	x			
	D - SS		x		x	x	x
	D - SE				x	x	x

Figure 5.9: Case study: Demand class versus forecast methods

5.7.2 Step 4.2 Determine forecasting method

The proposed framework and the relationships between the different steps indicate that Step 3.2 (Analyze demand patterns) and Step 2.3 (Identify maintenance tactics) feed into the determination of appropriate forecasting methods for the demand of spare parts. In this case, no reliability-based forecasting information is yet available and therefore a time-series based forecast is proposed to form a base forecast. It is important however that this forecast is updated with reliability-based information when it is available.

The matrix in Figure 5.9 indicates the advised forecasting methods for different demand classes according to the proposed framework. The 4100 Rope Shovel is in its launch phase and therefore limited to no historical information is available to test different forecasting methods. As can be seen from Figure 5.9, the most practical method in this situation is to make use of hypothesized demand distributions.

In an ideal situation historical demand data should be tested (eg. Chi-Squared (χ^2) test) to determine the best fit distribution to represent the data. In the case of the rope shovel (as is the case with most new equipment), detailed historic information is however not available and assumptions have to be made regarding the most appropriate distribution fit. The Normal distribution is, more often than not, a good approximation for mechanical part failures. The only data available in this case is average part run times. Averages by definition implies a Normal distribution and in this case is assumed the best alternative considering limited data and information on new parts. Refer to Appendix B for a detailed description on the Normal distribution. In another case, where more data is available, it is possible to apply the same principles of this framework while using a different distribution. In this regard, later in the study sensitivity analysis is performed to determine the impact of different distribution assumptions (Refer to Section 5.8.3).

The average lifetime data received from the OEM and expert opinion are used as a mean average life. It was not possible to obtain standard deviation data and therefore an assumption was made that the standard deviation is one fifth

			INVENTORY POLICY						
CLASSIFICATION						Continuous Review			Periodic Review
Life-Cycle Phase	Criticality	Demand Class	Initial Ordering	Risk-Based Ordering	Order on Demand	(s,S)	(s,Q)	Base Stock Model	(R,S)
Launch	V	D-NO, D-LF, D-LS	x						
	E	D-NO, D-LF	x						
		D-LS	x	x					
	D	D-NO	x						
		D-LF	x	x					
		D-LS		x	x				
In-Use	V, E, D	D-FS				x	x		x
		D-FE				x	x		x
		D-SS		x		x		x	x
		D-SE				x		x	
Phase-Out	V,E	D-NO				x			
	D	D-NO			x				

Figure 5.10: Case study: Demand class versus inventory control policy

of the average life time. In Section 5.8.3, sensitivity analysis is also performed to test the impact of this assumption.

5.7.3 Step 4.3 Determine inventory control policy

According to the proposed framework (Figure 4.1 and 4.2), the inventory control policy is influenced by the SC strategy, the classification of parts, the service level requirements and the forecasting methods. Figure 5.10 shows the proposed inventory control policies depending on the life-cycle phase of equipment and the criticality and demand classes of the parts. The resulting outcome of the previous steps is highlighted in grey.

As an outcome to the Classification study field, parts are categorized into two criticality classes and one demand classes. Combining the criticality and demand classes, the result is two permutations of part classification: Vital (D-LS) and Essential (D-LS). Refer to Figure 5.11 for a graphical representation of the different permutations of classification.

The matrix in Figure 5.10 suggests that there are two control policies to be considered for the parts in scope: initial ordering and risk-based policy. The initial ordering policy is a possibility for both classifications. The risk-based policy is only proposed for the Essential parts with demand class 'D-LS'. These two types of policies are discussed separately in the next section.

Initial ordering policy

The initial ordering policy refers to the case where parts are ordered in advance to arrive at the same time the new equipment is placed into operation. The

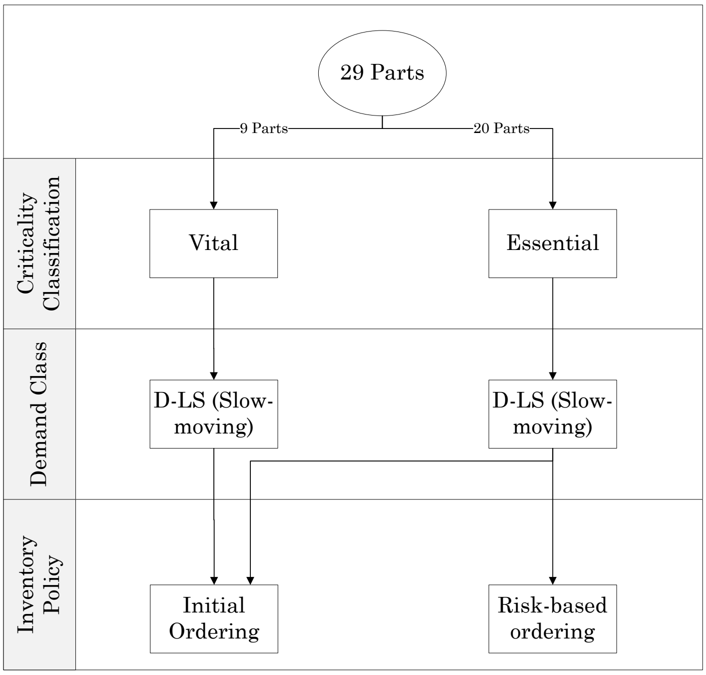


Figure 5.11: Matching criticality, demand classes and inventory control policies

time to place an order is therefore the date of operation of new equipment minus the lead time of the part. For the remainder of this section the time when new equipment is placed in operation is referred to as Year 0.

In the initial ordering policy, the time to order is Year 0 minus the lead time of the part regardless of the part characteristics. The amount to order is however dependent on a number of factors such as the estimated demand and part costs. There are two useful formulae which can be used to determine the appropriate order size. Both formulae take into consideration the effect of uncertainty in demand by assuming a demand distribution. In this case, the demand is assumed to be normally distributed. The service level is prescribed to be as close as possible to 100 %. For modelling purposes, the service level is assumed as 99.99 %.

The first formula is the Reorder Point (ROP) formula which is represented by Equation 4.5.1 in Section 4.5.3. The equation takes into consideration the demand over the lead time and variation in demand. The second formula is the EOQ formula. The EOQ formula is used to give an indication of how many parts to order at a time and is represented in Equation 4.5.2. The formula is not directly applicable to the initial ordering policy, but is useful in the subsequent life-cycle phases for recurring orders.

The outcome of applying the above-mentioned formulae and consequently the detail parameters for parts considering the initial ordering policy is presented

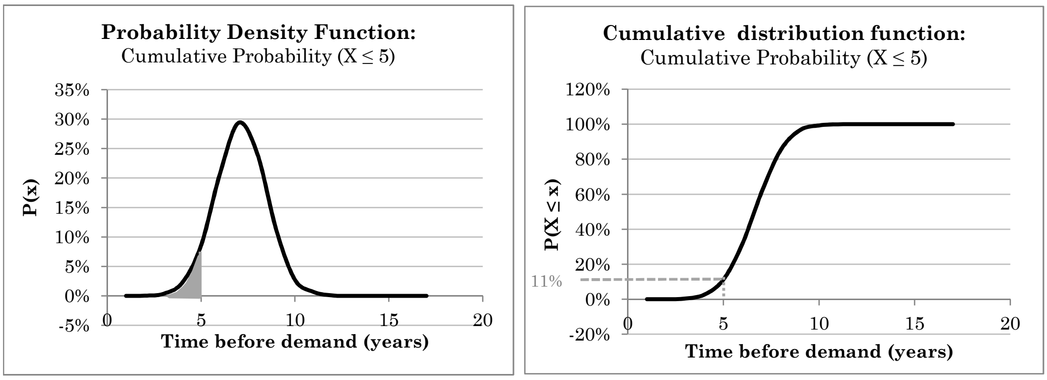


Figure 5.12: Cumulative probability demonstration

in Table A.2 in Appendix A. For all parts, the EOQ as well as the ROP is one unit. In this case, discrete values are used and it implies that an order should be placed if the stock level drops below the ROP. This phenomenon is common for items with long lead times, low demand and intermittent demand patterns. Moncrief *et al.* (2006) state that the EOQ for spare parts is one unit 80 % of the time.

Risk-based policy

According to the proposed framework, the risk-based policy is considered for the essential parts in the demand class 'D-LS'. The risk-based policy is based on the principle that parts are ordered to arrive when the probability of a demand occurrence (part failure) is more than a predefined probability. The predefined probability can be derived from the desired service level. The order size in the risk-based policy is the same as the order size in the initial ordering policy, but the time to order is different. The risk-based policy assumes that demand is stochastic and distributed according to a known distribution. In this case, as discussed in Section 5.7.2, the demand is assumed to follow the Normal distribution.

The time to order a part is based on the cumulative probability principle. A part should be ordered to arrive if the probability of a demand occurrence (part failure) before the arrival date is less than a certain percentage. Alternatively, a part should be ordered to arrive so that the probability of a demand occurrence after the date of arrival is more than the required service level. For example: Figure 5.12 shows the probability density function and cumulative distribution function for the demand occurrences of a part. If the part is ordered to arrive in year 5, the cumulative probability is illustrated in Figure 5.12. In this case, the estimated service level is 89%. The inverse scenario is that a required service level is stated and the time for the order to arrive is calculated.

Considering the risk-based policy, two approaches can be used to determine

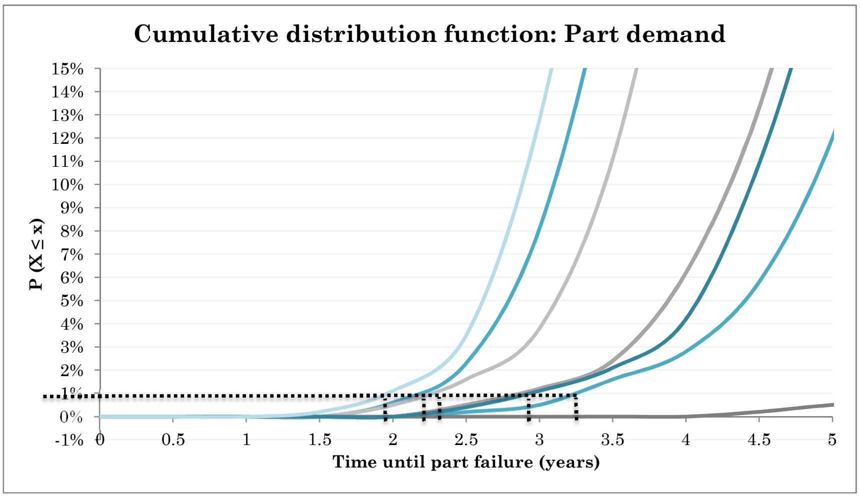


Figure 5.13: Cumulative probability of part demand

when to order parts: the service level approach and the minimum total cost approach. The first approach is based on ordering to meet a predefined required service level. The second approach is based on ordering at a time when the total cost of the inventory system is at a minimum.

In the first approach, if the required service level is 99 %, a time can be determined for each part at which the cumulative probability of a demand occurrence before this time is less than 1 %. Figure 5.13 illustrates this logic for 8 different parts. Considering this approach, refer to Appendix A, Table A.3, for the required order times for the parts.

The second approach is concerned with the total cost associated with following a policy. The main types of cost items are set-up cost, carrying cost, order cost and stock-out cost. In this case, the set-up cost and order cost do not play significant roles. The vast majority of items are ordered in single units and there is not a significant cost difference between ordering one or multiple parts at the same time. The stock-out cost is modelled to be the contractor cost during the period when there is no stock. The logic is that if a part is unavailable and it causes the rope shovel to stand, a contractor needs to be hired to perform the function the rope shovel performs. The total cost, in this example is therefore presented by Equation 5.7.1.

$$\text{Total Cost} = \text{Total Carrying Cost} + \text{Total Contractor Cost} \qquad (5.7.1)$$

$$\text{Carrying cost per item} = C \times \text{PV} \times T_{stock} \qquad (5.7.2)$$

where: Carrying cost = Total inventory carrying cost per item during period
PV = Purchase value per item
C = Carrying cost % per year
T_{stock} = Time period item is carried in stock in years

The total carrying cost is the sum of the carrying cost for each unit. The carrying cost per unit can be calculated by using Equation 5.7.2. The following definitions and assumptions are applicable to the carrying cost calculation:

1. The carrying cost percentage (C) is assumed as 10 % per year.
2. In his case, the duration an item is carried in stock (T_{stock}) is the time between the order arrives and the first failure. It is calculated in years. In traditional inventory carrying cost calculations, the average inventory level is also used for this variable.
3. The purchase value (PV) of the parts remain constant for the duration of the 10 years. Inflation is not taken into account.
4. The carrying cost is calculated only up to the first failure. (All except one of the parts are repairable. If a part fails, the part is replaced with the part from stock and sent in for repair. The policy therefore does not impact the stock-holding cost after the first failure.)
5. The average carrying cost refers to the average carrying cost over the first 10 years of the equipment's life.

The contractor cost can be calculated by using Equation 5.7.3. the following definitions and assumptions apply to the contractor cost calculation.

1. The contractor cost applies when a part fails before an order arrives.
2. The duration of the stock-out (T_{out}) is the lead time of the part, except if there is an expected order which will arrive in a time less than the lead time. In that case, T_{out} is the time between the failure and the next expected order.
3. The contract cost is a fixed cost per year. Inflation is not taken into consideration.
4. The contractor cost is only considered for the first part failure. Similar to the case of carrying cost, the policy only affects the first failure.

$$\text{Total Contractor Cost} = \text{Contract Cost} \times T_{out} \qquad (5.7.3)$$

where: Contract cost = Average contractor cost per year
T_{out} = Duration of stock-out in years

A model was built in Microsoft Excel to determine the average cost of inventory over 10 years when following the risk-based policy. The model consists of two sections: the random sampling of part failures and the inventory cost model.

Part failures is a stochastic variable and follows a specified distribution. This instigates the need for random sampling. The first part of the model draws a random sample, consisting of a 1000 variables from the demand distribution of each part. Thereafter, the sample variables act as part failure inputs into the inventory model. Therefore, the model simulates the behaviour of the inventory control policy over a period of a 1000 part failures per part. In addition, the inventory model also takes into consideration the times at which orders are expected to arrive and cost variables. For each of the iterations, the model calculates the total cost according to the above-mentioned assumptions and equations. A 1000 iterations deemed appropriate for the purpose of this calculation, because during a test the sample's average and standard deviation showed to be within 1% of the specified average and standard deviation.

It is important to note that the average cost is calculated over different time horizons for repairable and non-repairable parts. In the case study, 28 out of the 29 parts are repairable. For repairable parts, the model only considers the carrying cost and stock-out cost until the first part failure. This is because new parts are typically not ordered after the first failure. When a part fails for the first time, it is replaced with the part in stock and thereafter, the broken part is sent in for repairs. When the part is repaired, it again takes the position of the 'spare part' and is placed in stock. This model therefore assumes no failures during the repair period. The cost for the non-repairable part is calculated as the total cost over the ten years. In the cost calculations, the average cost refers to the average cost per iteration of part failures. Therefore, in the case of repairable parts, it is the average cost until first part failures and in the case of non-repairable parts, it is the average of the total cost over 10 years.

The model is used to test the relationship between the required service level and average cost. The service level is stated and accordingly the order time to achieve the desired service level is determined by using the inverse of the normal cumulative distribution. The order time is then entered into the model to calculate the average cost over 10 years. This approach assumes the same service level for all parts.

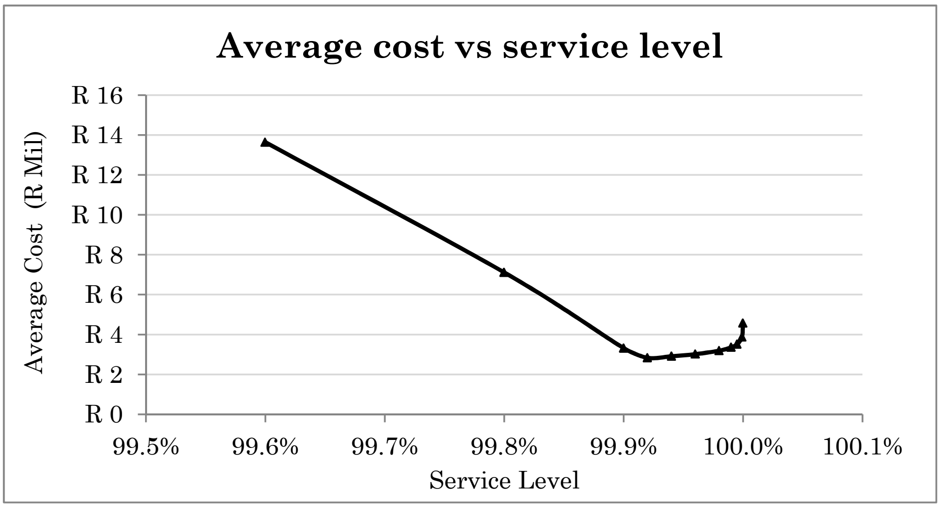


Figure 5.14: Average cost versus service level

Figure 5.14 shows that there is a service level at which the average yearly cost for inventory is at a minimum. In this case, the cost is at a minimum of R2.83 million when the required service level is 99.92 %.

It is also possible to optimize each part separately by calculating the service level for each part at which the total cost is at a minimum. This optimization however yielded only a R 17,454 lower cost than the previous optimization. Taking into consideration the added computational complexity, the first centralized optimization method is preferred.

The second approach (minimum cost approach) for the risk-based policy is preferred over the first approach (service level approach). The first approach calculates order points according to a predefined service level and therefore does not take into consideration the minimum cost of the inventory system. The second approach calculates the order points when the total inventory cost is at a minimum. The second approach is an improvement on the first approach because it takes into consideration the desired service level, but also allows for trade-off decision making regarding the cost to achieve the service level. The resulting order points for the parts to achieve a 99.92 % service level is presented in Appendix A in Table A.4.

In summary, the initial ordering policy is considered for both types of parts. The risk-based policy is an additional policy which could be considered for essential parts with a 'D-LS' demand class (Refer to Figure 5.11). This results in two sets of options for an overall inventory policy. The first is to use the initial ordering based policy for all the parts. The second is to use the initial based policy for the vital parts and the risk-based policy for the essential parts.

Tables 5.3 and 5.4 show the resulting cost and service level for the first and second options respectively. The cost for the initial ordering policy is calculated using the same methodology as described above for the risk-based policy. The second option results in a R 1.74 million lower cost as well as a 0.08 % lower service level. The final decision regarding the stock control policy is dependent on managers' discretion at The Mine. The question is whether the cost saving of R 1.74 mil is big enough to justify the lower service level in Option 2.

Table 5.3: Inventory control policy: Option 1

Demand type	**Policy type**	**Service level**	**Cost**
Vital	Initial ordering	100 %	R 23.763 mil
Essential	Initial ordering	100 %	R 4.569 mil

Table 5.4: Inventory control policy: Option 2

Demand type	**Policy type**	**Service level**	**Cost**
Vital	Initial ordering	100 %	R 23.763 mil
Essential	Risk-based	99.92 %	R 2.831 mil

The application of the framework enabled the development of appropriate inventory policies. In this case, it resulted in two possible inventory policies which can be implemented at The Mine to manage stock. The analyses of the relationship between service level and cost enable managers to make better decisions regarding stock control.

5.8 Interpretation of results

The aim of the framework is to assist the decision-making process in determining an appropriate inventory control policy for spare parts. This section discusses the interpretation of the results of the study. This section includes the considerations in the 'validate' work cluster and evaluate step (Step 5) of the proposed framework in Figure 4.1. First, the inventory model used in the above calculations is verified. Thereafter, the results are compared to the existing practice at The Mine and the sensitivity analysis is presented. Lastly, the validation of the framework is discussed.

5.8.1 Model verification

The first step in the validation process before interpreting the results of the framework is to evaluate whether the inventory system is modelled accurately. The model is explained in Section 5.7.3 and used to calculate the resulting cost and service level per policy. The aim of the inventory model is to estimate the expected behaviour of the inventory control policy if it is applied to an inventory system. The model is tested by testing the outcome of extreme input variables and testing expected behavioural trends.

First, the order time variable is adjusted to analyze the behaviour of the outcome of the model. In the first scenario (minimum scenario), orders are set to arrive in year 0 which is the earliest logical time at which orders can arrive. In the second scenario, orders are set to arrive in year 3. Technically this maximum order time is infinity, but to obtain sensible results this value is set to the minimum average run time of a part. The outcome of the model is shown in Table 5.5. As expected, if parts are ordered later, the service level is less, the carrying stock decreases and the stock-out cost increases.

Table 5.5: Model validation: Order times

Scenario	**Order arrival**	**Service level**	**Carrying cost**	**Stock-out cost**
1 (Min)	Year 0	100 %	R28.3 mil	R0
2 (Max)	Year 3	20.2 %	R14.1 mil	R157.2 mil

Second, the trend between service level and inventory costs is similar to what is stated in literature (Refer to Section 2.3.5). As can be seen from Figure 5.15, the inventory cost increases exponentially as the service level increases towards 100 %.

The model behaves as expected and is considered an adequate representation of the behaviour of the real world system. The next section compares the results of applying the framework to the existing practice. Thereafter, the model is further tested with sensitivity analysis and finally the framework is validated.

5.8.2 Results vs existing practice

The existing practice for managing the spare parts of new equipment at The Mine is discussed in detail in Section 5.3. In summary, The Mine orders all critical and strategic spare parts which the OEM does not stock to arrive when the new equipment is placed into operation. The existing policy is similar to the initial ordering policy and directly relates to the first outcome (Option 1 as presented in Table 5.3) of the proposed framework. For comparative purposes,

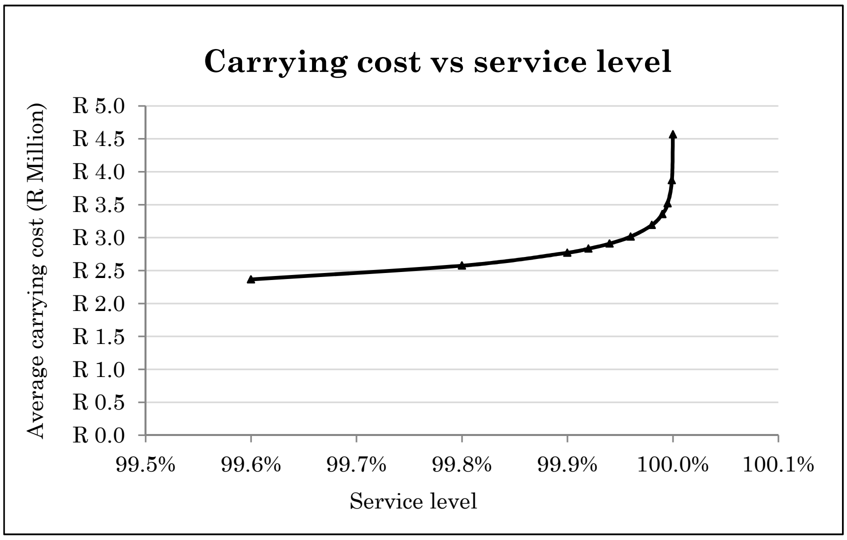


Figure 5.15: Carrying cost versus service level

the existing policy is therefore represented by Option 1 in the remainder of this section.

This section compares Option 1 and Option 2 on the basis of service level and costs. The two options are compared over the first 2 years of the life-cycle of the equipment as well as over a 10 year horizon. The summarized results are presented in Table 5.6.

Table 5.6: Option 1 versus Option 2

Option	Policy type	Service level	Cost (2 years)	Cost (10 years)
1	Initial ordering	100 %	R 9.5 mil	R 28.3 mil
2	Initial ordering and risk-based	99.92 %	R 8.08 mil	R 26.6 mil

Option 1, which is the same as the existing practice, has a higher service level, but also a higher cost than Option 2. The cost difference between the two options is R 1.74 million. Management should weigh this cost difference up against the higher risk in terms of service level of 0.08 % in order to make a final decision regarding a stock control policy. Figure 5.16 presents the accumulated cost per year for the two options which shows that the majority of the cost saving is between year 0 and year 2. This is expected as the parts in Option 2 is bought at a later stage which results in a lower carrying cost only over the first two years.

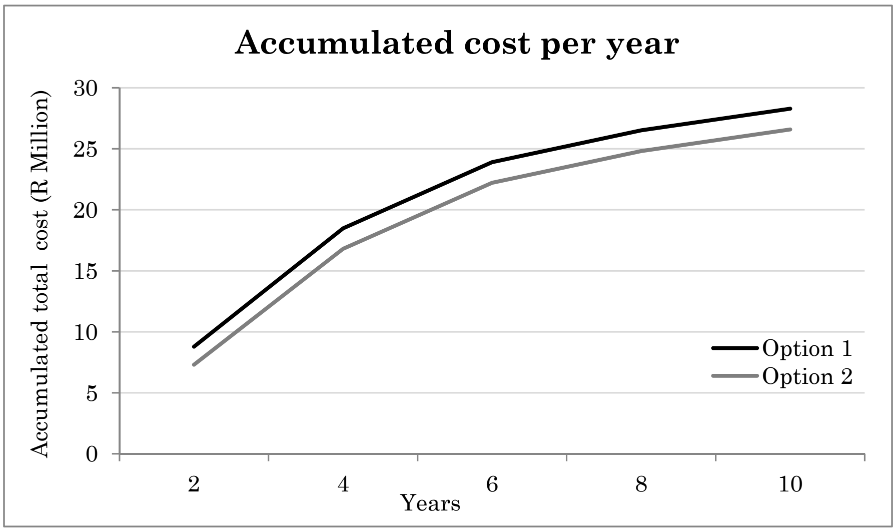


Figure 5.16: Accumulated cost over years

In this study, a retrospective case study is performed. The framework was applied as if it is the beginning of 2012. This study is however completed in 2014 and therefore the actual demand of parts can be used to evaluate the two different inventory policies. One part was demanded in November 2012. This part is an essential part which implies that the initial ordering policy is followed in both options for this part. Both policies state that the part had to be ordered to arrive in the beginning of Year 0 which is 2012 in this case. The part would have been in stock and available when the failure happened in November. Both policies would have delivered a 100 % service level. Excess inventory would have been carried for all other parts to account for the uncertainty in demand. The policies therefore seem applicable and valid.

A scenario with more part failures would have been helpful in the application and validation of the framework. The nature of the case study however does not provide an opportunity for such a scenario. The study is conducted with support from The Mine and therefore only the parts under the ownership of The Mine are included in the scope of the application of the framework. The parts are typically extremely slow-moving and have long lead times. Failures of these parts are therefore rare occurrences. This type of situation is common in the mining industry, especially if there is an intricate relationship between the company in question and The OEM of the equipment. The OEM keeps the majority of spare parts in stock. There are however certain parts which the company considers as critical which the OEM does not keep in stock. The OEM could decide not to keep these parts in stock as the chance of selling one of these parts are very low compared to the carrying cost.

5.8.3 Sensitivity analysis

In this section, sensitivity analysis is performed to determine the impact of different variables on the outcome of the model. The following variables are included in the analysis: standard deviation, lead time, carrying cost and contractor cost.

Standard deviation

First, sensitivity analysis is performed to demonstrate the impact of the standard deviation on the outcome of the model. It is difficult to determine an accurate value of standard deviation for parts without historic data and therefore it is useful to determine the influence of this variable on the results. For the purpose of the analysis only one of the parts (Blower, hoist motor) is used. Two scenarios are compared to each other. The first scenario assumes a standard deviation of 1.4 years, the second scenario assumes a standard deviation of 0.8 years and both scenarios assume an average demand of 6.6 years. A graphical representation of the demand distributions is shown in Figure 5.17 and the resulting cost for the two scenarios compared to the service level is presented in Figure 5.18.

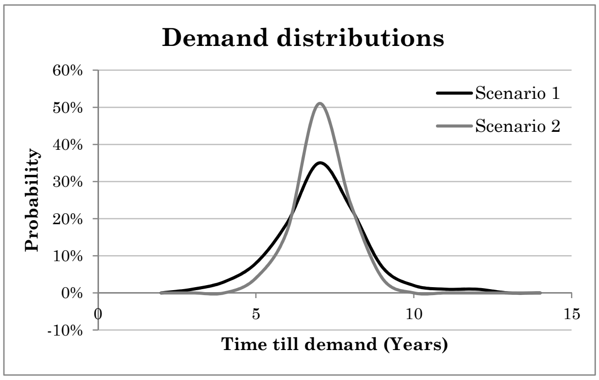


Figure 5.17: Demand distribution per scenario

As expected, the cost to achieve the same service level is lower for Scenario 2 than Scenario 1. The cost to achieve a 99.9 % service level is R 616, 973 for Scenario 1 and R 322, 142 for Scenario 2. This is as a result of the fact that the part should be ordered to arrive at a time of 2.7 years in Scenario 1 compared to 4.6 years in Scenario 2 to achieve the same service level which results in higher carrying cost in Scenario 1.

The standard deviation of part demand can be influenced either by improved maintenance practices or through redesign. This sensitivity analysis shows that there is value in lowering the uncertainty in part demand by decreasing the standard deviation of part demand. It also shows that the trend in the curve

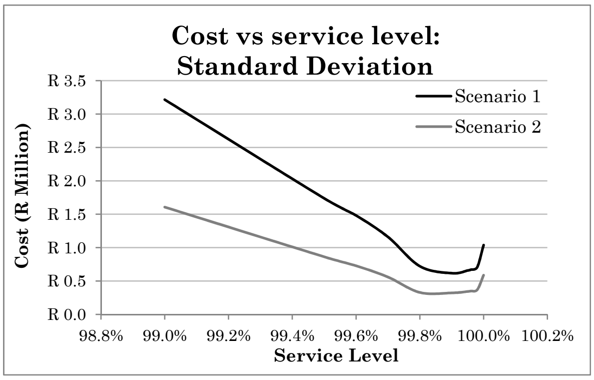


Figure 5.18: Cost versus service level: Standard deviation

does not change as the standard deviation changes. The trend representing the relationship between cost and service level for the parts at The Mine is therefore independent of the standard deviation of parts. It impacts the cost, but only slightly the service level point at which the cost is at a minimum.

Lead time

Secondly, the impact of the lead time variable is analyzed. The lead time is the time between an order placement and an order arrival. For repairable parts, after the first part failure, the lead time can also be considered as the total repair time. The lead time in the case study was assumed to be one year for all the parts. A scenario is analyzed to determine the impact if the lead time is changed to 3 months (Refer to Figure 5.19). As can be seen from Figure 5.19, a shorter lead time decreases the overall costs. However, it only decreases the costs up to the point where the total time period for which a subcontractor is needed is less than the lead time. Therefore, in this case, with the extremely high contractor cost, changing the lead time does not affect the overall result.

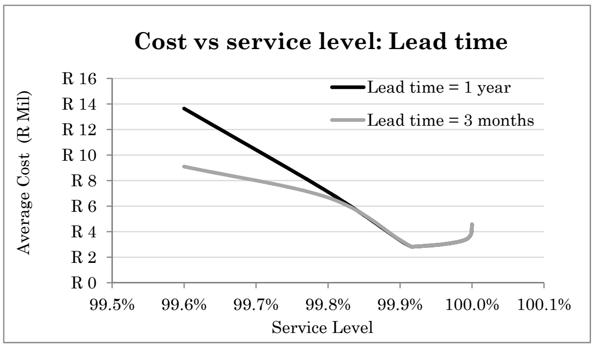


Figure 5.19: Cost versus service level: Lead time

Carrying cost percentage

Thirdly, the carrying cost percentage is adjusted to determine the impact on the results. A scenario is analyzed with a carrying cost of 25%. Figure 5.20 shows the scenario compared to the base scenario with a carrying cost percentage of 10%. The graph shows that a higher carrying cost percentage results in higher overall costs. However, it has a minute influence on the service level point at which the total cost is at a minimum. Again, this is because of the overpowering nature of the contractor cost. The carrying cost, when compared to the contractor cost, is extremely small and therefore by changing the carrying cost percentage to 25%, it does not change the overall results.

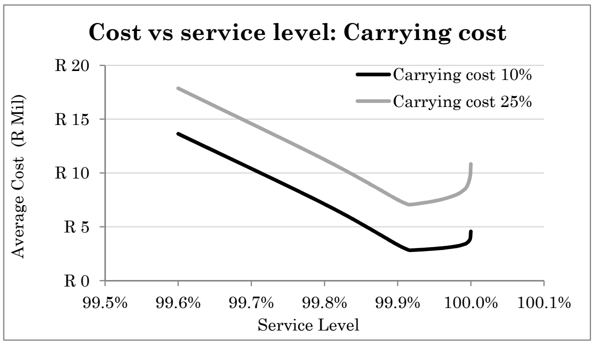


Figure 5.20: Cost versus service level: Carrying cost

Contractor cost

Lastly, the influence of the contractor cost variable is investigated. The contractor cost is very high in this case study. This causes a low ratio between carrying cost and contractor cost which drives extreme service level requirements. This is not the general case in all stock control examples and therefore it is sensible to determine the influence of different contractor costs on the results of the model. The influence of the contractor cost is determined by analyzing different scenarios using a contractor cost of ten times less and ten times more than the current contractor cost and measuring the outcome. Table 5.7 shows the resulting cost per service level for the three scenarios.

It is clear from Table 5.7 that for each contractor cost there is a service level at which the total cost is at a minimum which can be seen as the balancing threshold point between contractor cost and service level. Furthermore, the service level threshold point decreases as the contractor cost decreases (the minimum cost for the 'Contractor / 10' scenario where the minimum cost is at 99.9% which is lower than the other two scenarios.) It is interesting to note that the total cost for all three scenarios is the same for a service level higher than 99.94%. This is due to the difference between the theoretical service

Table 5.7: Contractor cost sensitivity analysis

		Total Cost (R mil)		
		Contractor cost (x 10)	**Contractor cost**	**Contractor cost (/10)**
Service level	**99%**	334.17	35.28	5.39
	99.4%	198.61	21.87	4.20
	99.8%	50.65	7.38	3.05
	99.9%	8.61	3.35	2.83
	99.94%	2.91	2.91	2.91

level and observed service level. At the point where the theoretical service level is 99.94%, the observed service level is already at 100% and therefore the contractor cost is R0 and has no effect on the outcome. The difference between the theoretical and observed service level can be decreased by incorporating a bigger sample of part failures.

The contractor cost in this case study is an overpowering variable, because the contractor cost is disproportionally high compared to the carrying cost. This explains why changing the standard deviation, lead time and carrying cost percentage does not significantly influence the service level point at which the total cost is at a minimum. A change in the minimum point is observed only when the contractor cost is decreased significantly (e.g. by a factor of 100). In such a case, the minimum point starts to shift towards a lower service level requirement. The next section discusses the framework validation.

5.8.4 Framework validation

A decision-making framework is proposed in Chapter 4 for the management of spare parts. The aim of the framework is to enable managers to make better decisions regarding the choice of a suitable inventory control policy. The study is validated by means of retrospective case study applied in the South-African mining industry.

The framework is built on a thorough literature base to incorporate the main elements in the field. This enables an holistic approach to inventory management and ensures that the framework is applicable to a wide range of potential scenarios. The structure of the framework is logical and decision steps are clear. Furthermore, the framework is relevant in the SPM industry. This is evident from matching objectives between the study and a real-world problem which is used as the case study.

The application of the framework confirmed that the framework is implementable and practical to use. Feedback of the outcome of the study was provided to the management of The Mine. According to The Mine, the framework is a relevant tool which can be applied at The Mine in the future. The outcome of the framework provides managers with factual information to enable better decision-making. The Mine considers using the framework to determine inventory control parts for spare parts of other types of equipment like haul trucks.

In summary, the outcome of the framework is comparable to the existing practice and delivers adequate results for past performance. The model is verified and behaves as expected for extreme values. The proposed solution is therefore validated and the initial hypothesis is not rejected. The proposed decision-making framework assists the management of spare parts inventory. The application of the framework enables a holistic approach to decision-making in SPM. It improves current practice by providing a structured decision-making guideline built on factual information to ease trade-off decision-making. The framework is also a practical reference guide and easy to adopt in practice.

However, during the conduction of the case study, the choice of the rope shovel as a case for this study presented certain challenges and limitations. Despite the validation of the proposed framework, it is necessary to critically evaluate the use of the rope shovel as a case for this study.

5.8.5 Reflection on case study selection

This section discusses the choice of the case study and the influence thereof on the outcome of the study. It also discusses the limitations of the current case study and provides guidelines when choosing future case studies to further validate the framework.

This study is sponsored by Anglo American and therefore the case study selection was guided by the management of one of their mines in South Africa. For the purpose of the case study, the 4100 Rope Shovel was selected. This rope shovel, at the time of writing, was a new piece of equipment, it has a high throughput and is expensive. Determining inventory control policies for new equipment is difficult because of limited data available. The management at The Mine proposed the rope shovel for the case study because of the high potential monetary benefit of applying the framework to the equipment.

The Mine recently spent approximately R48 million on acquiring new parts for the rope shovel. Decisions regarding the management of spare parts for the rope shovel are predominantly made intuitively with little factual support. In this regard, The Mine expressed a need to assess the current manner in which spare parts inventory is managed. More specifically, a structured guideline based on factual information was seen as necessary to support the decision-making process.

It is important to highlight two limitations of the current case study. These limitations are as a result of the choice of asset (rope shovel) and asset environment for the case study. The first limitation is because of the homogeneous nature of the rope shovel's spare parts in scope of the study. The second limitation concerns the relationship between the contractor cost and the carrying cost.

The homogeneous nature of the rope shovel's spare parts does not allow a test of all the possible permutations in the framework. Parts are categorized into two out of three criticality groups and only one out of seven demand classes. As a result, a limited decision-path is followed during the application of the case study. There are two main factors influencing the small number of part types: the life-cycle of the equipment and the split of stock holding responsibility between The Mine and The OEM. The 4100 Rope Shovel is in the launch phase of its life-cycle and therefore limited data is available to categorize parts. Furthermore, the scope of this study only includes parts held under ownership of The Mine and these parts are generally critical parts not held in stock by The OEM (Refer to Section 5.3). In the case of the rope shovel, The OEM keeps the majority of the rope shovel's parts in stock with the exception of a few parts which typically have slow-moving demand trends. These few parts are not kept in stock because the chance of failure is regarded too small compared to the inventory investment. Consequently, all the parts in scope of this study are categorized in the 'D-LS' demand class which refers to slow-moving parts in the launch phase.

The second limitation is the disproportional relationship between the contractor cost and carrying cost. It is evident from the policy evaluation model that the contractor cost is an overpowering variable. In the risk-based policy, this causes the service level point at which the total cost is at a minimum to be very close to 100%. It also constrains the influence of other variables on the outcome of the model. Overall, this distinctive feature of the case study limits the interpretation of results and the value that could be added by running different scenarios.

Nevertheless, the rope shovel case study did test the application of the framework, especially considering that the framework focuses on the process to determine inventory control policies and not only on the outcome of a specific scenario. The rope shovel case study is a real-life example proposed by The Mine. A selection of a trivial case, matching the framework's requirements, could have allowed a more exhaustive test of the framework. However, the framework proved to be valid even for the complex, specific case of the rope shovel.

In the future, it would be useful and add value to this study to also test the framework on other case studies. The following guidelines could assist in selecting a more ideal case to test the validity of the proposed framework:

1. The asset should have many different types of parts
2. Data should be available
3. The company should aim to improve the management of their spare parts

Firstly, an asset with many different types of parts would result in parts being categorized in multiply criticality classes and demand classes. Different classes lead to a variety of forecasting methods and inventory control policies, and therefore a wider selection of possible outcome of the framework would be tested. In this regard, an asset in its 'In-Use' phase would be most appropriate because it allows more flexibility in the choice of forecasting method and inventory control policy. Another important consideration is the scope of the case study. It could be valuable to extend the scope of the study to include also the supplier's spare parts inventory management. This will increase the variety of parts and potential benefits can be realized by optimizing the two systems as a whole.

Secondly, the 'analyze' work cluster in the framework, consisting of the classification and inventory management study fields, depends on the availability of data for optimal results. Available data will improve the accuracy of the outcome of the framework. Data types required for the application of the framework include part values, lead times, historic part failures, maintenance information and inventory costs.

Lastly, it is important to obtain management's support when conducting this type of case study. The management of the company related to the case study should aim to improve and critically evaluate their current practices. In this regard, the framework is especially useful in companies where spare parts management has received little attention in the past, the decision-making process is immature and where there is a lack of integration between the maintenance and SC department. The next section summarizes and concludes this chapter.

5.9 Chapter summary

This chapter applies the proposed solution in Chapter 4 to a case study in the South African mining industry. First, background to the case is provided and the case study preparation is discussed. Thereafter, the current practice is described. The proposed decision-making framework is then applied and each step is discussed in detail. This study concludes that the proposed framework is relevant and allows for better decision-making in the field of SPM. The following research objectives from Section 1.3 were achieved in this section:

- Validate the framework in line with the required framework features

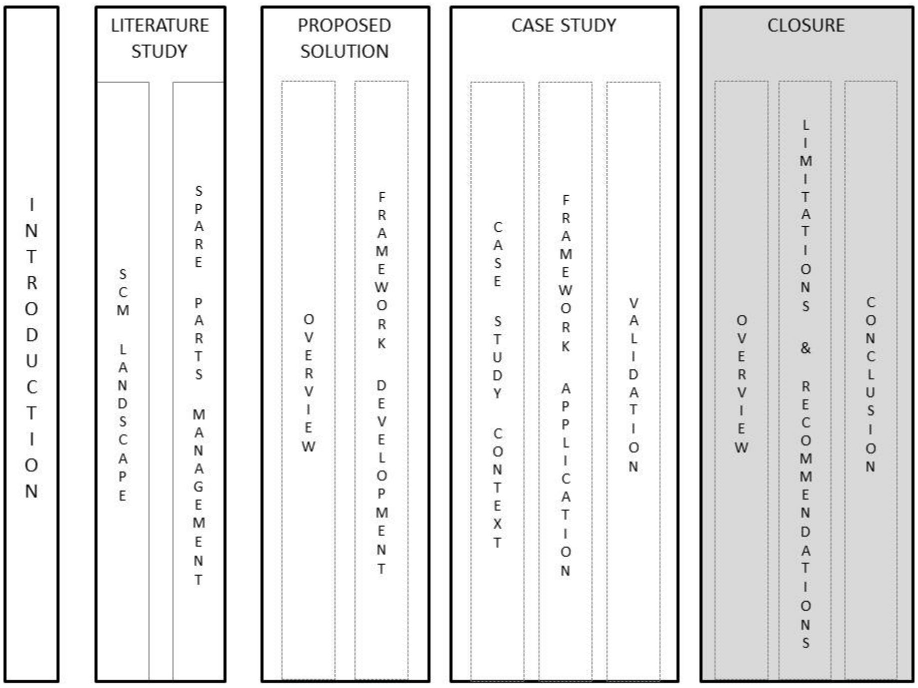
- Assess proposed inventory control policies

Furthermore, the framework also complies with the specified framework features: it is practical, provides a structured guideline for the decision-making process and enables a holistic approach to SPM. The next and also final chapter of this study provides a brief summary of the study and discusses limitations and future recommendations.

Chapter 6

Closure

The aim of this chapter is to conclude the study. The chapter consolidates previously stated information, reflects on the research process and evaluates the outcome of the study against the initial research objectives. First, a brief overview of previous chapters is provided. Thereafter, the limitations of the study are discussed and recommendations are provided for future research. The final section of this chapter presents concluding remarks.



6.1 Overview

This study proposes a decision-making framework for the management of spare parts inventory in capital-intensive industries. This is the final chapter of the study. The study consists of six chapters including an introduction, literature review, proposed solution, validation and conclusion. This section provides a brief overview of the content of the study.

Chapter 1 introduces the broad outline of the study. First, the chapter provides background to the context of the study and research problem. Thereafter, the research objectives, scope of the study and research design are discussed. Finally, a thesis outline is provided which acts as a research roadmap to guide the research process.

Chapter 2 and 3 present a literature analysis of relevant topics in the field of study. Chapter 2 introduces basic concepts in the Supply Chain Management (SCM) landscape. The chapter mentions uncertainty in the Supply Chain (SC) and focuses specifically on inventory management principles. Chapter 3 focuses on Spare Parts Management (SPM). It builds on previously defined concepts and discusses the application of inventory management in the spare parts industry. The following topics are discussed: spare parts characteristics, classification of parts, demand forecasting and inventory control policies. Related topics such as maintenance and Physical Asset Management (PAM) are also discussed.

Chapter 4 proposes a decision-making framework for the management of spare parts. The chapter discusses the development of the framework and its intended application. Each of the steps in the proposed framework are discussed in detail.

Chapter 5 elaborates on the conduction of the case study in the South African mining industry to test the validity of the framework. The chapter starts by providing background to the case study and the current practice at The Mine. The majority of the chapter is a discussion on the application of the framework to the specific scenario. The chapter concludes with the validation of the framework.

The research objectives, stated in Section 1.3, are achieved. Each of the chapters address different sub-objectives as outlined in Table 1.1, Section 1.6. Chapter 2 includes a review of the key concepts in SCM and a discussion on the relationship between SPM and SCM. The chapter also includes the fundamentals of inventory management. In Chapter 3, the literature in the field of SPM is studied extensively. An overview is also provided on PAM and its relation to SPM. Chapter 4 includes the development of a decision-making framework and finally, Chapter 5 validates the framework by means of a case study.

This section provided a brief overview of the study. The next section discusses the limitations of the study and recommendations for future research. Thereafter, the final section elaborates further on the content of the study and concludes the study.

6.2 Limitations

Limitations are an essential and unavoidable part of any scientific research study. It refers to the situations and circumstances that may affect or restrict the outcome of the study. The development and application of the decision-making framework for SPM exposed the following limitations:

1. Case study selection – The nature of the asset chosen (rope shovel) for the case study did not allow a test of all the possible decision-paths in the framework.
2. Data and information – The successful application of the framework is reliant on quantitative and qualitative data. The quality of the outcome of the study is therefore directly related to the quality and availability of input data and information. Limited data was available for the application of the case study and therefore the results could be influenced with an improved, more detailed dataset.
3. Framework extent – Practicality is one of the required framework features. The framework therefore focuses on the most common classification and forecasting methods as well as inventory control policies. The suggested methods in the framework is a valid initial list of possibilities, but does not serve as an exhaustive list.
4. Prior knowledge – The application of the framework requires a basic knowledge of inventory management concepts.
5. Industry – The framework is validated by means of a case study in the capital-intensive industry. This study predicts, but does not necessarily prove, the validity of the framework in other types of industries.

It is possible to address some of the above-mentioned limitations in future studies. The next section provides recommendations for future research.

6.3 Recommendations

Based on the limitations of this study, as well as renewed insights into the field of SPM, some considerations emerged during the research process that may be worth further investigation.

1. The framework can be applied to other case studies for a comprehensive test of all the different decision-paths in the framework.

2. The results of the comparison between the two different inventory control policies can be refined if more data is available.

3. The framework focuses on specifying the common methods and approaches for each of the steps in the framework. It is possible to extend the list with other, more complicated approaches.

4. Future research could investigate the application of the proposed framework in industries other than capital-intensive industries.

5. The issue of intermittent demand forecasting is not constrained to spare parts. The insights gained in this study can also be applied to other types of products with an intermittent demand nature.

6. Only parts held under the ownership of The Mine are included in the scope of this study. It is possible to extend this study to include the spare parts at The OEM and optimize the SC as a whole.

7. The proposed framework guides the decision-making process, but requires a large amount of manual intervention. It is worth investigating the use of artificial intelligence to develop an application tool to assist the choice of inventory model and ease the implementation of the framework.

The above-mentioned recommendations could provide interesting windows of opportunity for future research in the field of SPM as well as related fields. The next and final section of this study concludes the research.

6.4 Concluding remarks

Spare parts play an essential role in society. Their need arises whenever components fail or need replacement. Effective SPM is important in organizations because of expensive inventory costs and the impact of spare parts availability on asset utilization. Central to SPM is a trade-off decision between cost and risk: higher stock levels increase inventory costs, but decrease the risk of not having a part available when it is required. The fundamental objective in spare parts inventory management is therefore to achieve a balanced stock level so that the required service level is achieved at a minimum cost.

The management of spare parts is a complex task. Contrasting objectives and the forecasting of intermittent demand patterns are amongst many factors which complicate the management of spare parts inventory. Spare parts typically constitute a large portion of total inventory in capital-intensive companies. They differ to other inventory items mainly in the function they perform and the policies that govern them. In particular, spare parts demand is influenced by maintenance- and PAM-related decisions typically not considered in conventional inventory problems. Customized approaches are therefore required for the management of spare parts.

Decision-making is central to the management of spare parts. Key decisions faced daily in operations relate to which parts to buy, how many to buy and when to buy them. These decisions are typically addressed by an inventory control policy. The choice of inventory policy is dependent on the characteristics of the spare parts and the environment in which it operates. Therefore, there is no one-shot solution to SPM. In order to add value to the SPM study field, it is necessary to focus on the decision-making process itself. Managers are in need of a structured, pragmatic approach to decision-making, based on factual information. More specifically, the approach should guide the process of choosing or developing appropriate inventory control policies.

Another key element of SPM is the fact that it is an interdisciplinary field and requires expertise in inventory management, SCM, maintenance and PAM. Spare parts is a type of inventory item and therefore it is obvious that inventory management forms a good basis for decision-making in the field. Inventory management is however part of the broader study field of SCM. SCM contains many interlinked concepts and therefore optimizing one area of the SC in isolation could result in sub-optimization. Therefore, it is important to acknowledge the SPM problem in the context of SCM. Finally, the demand for spare parts is also influenced by maintenance and PAM decisions. Demand forecasting is an important element of inventory control and therefore it is crucial to take PAM into account in SPM decision-making.

This study proposes a decision-making framework for the management of spare parts. The framework is specifically intended for capital-intensive industries, but has potential to be expanded towards other industries. The development of the framework aims to enable better decision-making by providing practitioners and researchers with a methodology to determine appropriate inventory control policies for spare parts. Furthermore, the framework acts as a reference guide that consolidates and summarizes key elements in the field.

This study is based on a sound literature review following an explorative top-down approach. First, basic concepts in the field of SCM are introduced with a specific focus on uncertainty in the SC and inventory management. Thereafter, the study builds on previously defined concepts and elaborates on SPM. To conclude, the literature analysis further evolves to the field of PAM to identify its prominent role in SPM. The top-down approach for the literature analysis enables a comprehensive view on the SPM issue. The literature review demonstrates a thorough understanding of the field and acts as a solid base for the development of the decision-making framework.

The framework encompasses four different study fields (SCM, PAM, classification and inventory management) and the steps in the framework are divided into different work clusters according to their purpose. A structured description of the framework is provided by mentioning the objectives, input requirements, methods, considerations and outputs of each of the proposed steps. The proposed framework is unique in the sense that it takes an holistic approach, is simple to use, takes into consideration the life-cycle phase of equipment and accommodates cases with limited data.

The proposed decision-making framework is validated by means of a case study in the South African mining industry. In particular, the framework is applied to assist the decision-making process regarding the choice between inventory policies for a new type of equipment, a 4100 Rope Shovel. The application of the framework results in two appropriate inventory control policies for the management of spare parts for a new 4100 Rope Shovel. The first policy is the same as the existing practice and proposes the initial ordering policy for all parts. The second policy is a combination of the initial ordering and risk-based policy. The total inventory cost and service level are used as key metrics to evaluate the policies. The outcome shows that the second policy results in lower costs, but is also exposed to a higher risk-level.

The sensitivity analysis indicates that the contractor cost and standard deviation of demand have a significant impact on the total cost of the inventory system. The contractor cost at The Mine is high in proportion to the carrying cost. Therefore, in the risk-based policy, the point at which the overall cost is at a minimum is close to 100%. The standard deviation influences the required stock level for parts. A decrease in the standard deviation of part demand results in a lower cost for the system as a whole. This provides valuable insights into the value of maintenance activities to decrease the variance in part failures.

The application of the framework assisted management to make costly tradeoff decisions and guided the decision-making process in a structured, factual manner. Feedback from managers at The Mine confirmed that the framework is useful and provides renewed insights into the management of spare parts. Furthermore, the framework is also practical and enables a holistic approach to the problem.

The initial null hypothesis of this study is therefore not rejected. It is possible to develop a decision-making framework for the management of spare parts in capital-intensive industries. The proposed framework improves current practices by providing a structured decision-making guideline based on factual information. The research objectives of the study, as stated in Section 1.3, are achieved:

1. The fundamental principles in the relevant study fields (SCM, inventory management and PAM) have been established
2. The field of SPM has been mastered
3. A decision-making framework for the management of spare parts was developed
4. The framework was validated by means of a case study in the mining industry

In conclusion, this study proposes a decision-making framework for the management of spare parts in capital-intensive industries. The framework is validated and is sensible both from a theoretical and practical perspective. This study contributes towards a more comprehensive view of the SPM field of study and helps to bridge the gap between research and practice.

Appendices

Appendix A

Case study: Additional data

A.1 Part classification

Table A.1 shows the classification of parts according to criticality and demand patterns.

Table A.1: Part classification

Part	**Vital/Essential**	**Average life (years)**	**Demand interval**	**Demand class**
Main transformer	Vital	9.8	Slow-Movers	D-LS
Blower, hoist motor	Essential	6.6	Slow-Movers	D-LS
Gear, shipper shaft	Essential	5.8	Slow-Movers	D-LS
Shipper shaft	Essential	5.8	Slow-Movers	D-LS
Auxiliary transformer	Vital	9.8	Slow-Movers	D-LS
Shipper shaft pinions	Essential	4.2	Slow-Movers	D-LS
Fan, house pressurizing	Essential	4.7	Slow-Movers	D-LS
Compressor assembly	Vital	4.7	Slow-Movers	D-LS
Boarding ladder	Essential	11.8	Slow-Movers	D-LS
Shaft, swing	Essential	6	Slow-Movers	D-LS
Operator chair	Essential	3.9	Slow-Movers	D-LS
Brake disc, hoist, complete assy	Essential	4.8	Slow-Movers	D-LS
Boom suspension ropes	Essential	7.8	Slow-Movers	D-LS
Brake disc, crowd	Essential	4.8	Slow-Movers	D-LS
Brake disc, swing	Essential	5	Slow-Movers	D-LS
Blower, swing motor	Essential	6.8	Slow-Movers	D-LS
Pump assembly, lube, crowd transmission	Essential	4.5	Slow-Movers	D-LS
Blower, crowd motor	Essential	6.7	Slow-Movers	D-LS
Blower, propel motor	Essential	6.7	Slow-Movers	D-LS
Gearbox, cable tugger	Essential	5.9	Slow-Movers	D-LS
Pump assembly, hoist gearcase lubrication	Essential	6.6	Slow-Movers	D-LS
Motor, 30HP compressor	Essential	5.9	Slow-Movers	D-LS
Motor, W/Brake, Cable tugger	Essential	2.9	Slow-Movers	D-LS
Dipper Handlers	Vital	4	Slow-Movers	D-LS
Crawler Frame LH	Vital	4.7	Slow-Movers	D-LS
Crawler Frame RH	Vital	4.7	Slow-Movers	D-LS
Hoist Drum	Vital	13.2	Slow-Movers	D-LS
Saddle Block	Vital	5.8	Slow-Movers	D-LS
Dipper Trip	Vital	6	Slow-Movers	D-LS

A.2 Initial ordering policy

Table A.2 shows the Economic Order Quantity (EOQ) and Reorder Point (ROP) of each part. Equation 4.5.2 is used to calculate the EOQ and Equation 4.5.1 is used to calculate the ROP.

Table A.2: Initial ordering policy summary

Part	**Inventory control policy type**	**EOQ**	**Reorder Point**
Main transformer	Initial ordering	1	1
Auxiliary transformer	Initial ordering	1	1
Compressor assembly	Initial ordering	1	1
Dipper Handlers	Initial ordering	1	1
Crawler Frame LH	Initial ordering	1	1
Crawler Frame RH	Initial ordering	1	1
Hoist Drum	Initial ordering	1	1
Saddle Block	Initial ordering	1	1
Dipper Trip	Initial ordering	1	1
Blower, hoist motor	Initial ordering	1	1
Gear, shipper shaft	Initial ordering	1	1
Shipper shaft	Initial ordering	1	1
Shipper shaft pinions	Initial ordering	1	1
Fan, house pressurizing	Initial ordering	1	1
Boarding ladder	Initial ordering	1	1
Shaft, swing	Initial ordering	1	1
Operator chair	Initial ordering	1	1
Brake disc, hoist, complete assy	Initial ordering	1	1
Boom suspension ropes	Initial ordering	1	1
Brake disc, crowd	Initial ordering	1	1
Brake disc, swing	Initial ordering	1	1
Blower, swing motor	Initial ordering	1	1
Pump assembly, lube, crowd transmission	Initial ordering	1	1
Blower, crowd motor	Initial ordering	1	1
Blower, propel motor	Initial ordering	1	1
Gearbox, cable tugger	Initial ordering	1	1
Pump assembly, hoist gearcase lubrication	Initial ordering	1	1
Motor, 30HP compressor	Initial ordering	1	1
Motor, W/Brake, Cable tugger	Initial ordering	1	1

A.3 Risk-based policy

Two approaches can be followed with the risk-based policy: service level approach and minimum cost approach. Refer to Section 5.7.3 for an explanation of the different approaches.

A.3.1 Service level approach

Table A.3 presents the average life, standard deviation, order arrival and time to place orders per part. The variables are stated in number of years. The time to place an order is the required order arrival time minus the lead time.

Table A.3: Risk-based policy: Service level approach

Part	**Average life**	**Standard deviation**	**Order arrives**	**Order placed**
Blower, hoist motor	6.6	1.3	3.5	2.5
Gear, shipper shaft	5.8	1.2	3.1	2.1
Shipper shaft	5.8	1.2	3.1	2.1
Shipper shaft pinions	4.2	0.8	2.2	1.2
Fan, house pressurizing	4.7	0.9	2.4	1.4
Boarding ladder	11.8	2.4	6.2	5.2
Shaft, swing	6	1.2	3.2	2.2
Operator chair	3.9	0.8	2	1
Brake disc, hoist, complete assy	4.8	1	2.5	1.5
Boom suspension ropes	7.8	1.6	4.1	3.1
Brake disc, crowd	4.8	1	2.5	1.5
Brake disc, swing	5	1	2.6	1.6
Blower, swing motor	6.8	1.4	3.6	2.6
Pump assembly, lube, crowd transmission	4.5	0.9	2.4	1.4
Blower, crowd motor	6.7	1.3	3.5	2.5
Blower, propel motor	6.7	1.3	3.5	2.5
Gearbox, cable tugger	5.9	1.2	3.1	2.1
Pump assembly, hoist gearcase lubrication	6.6	1.3	3.5	2.5
Motor, 30HP compressor	5.9	1.2	3.1	2.1
Motor, W/Brake, Cable tugger	2.9	0.6	1.5	0.5

A.3.2 Minimum cost approach

The same average life and standard deviation applies to the minimum cost approach, but the time orders are placed and orders arrive are different. Table A.4 shows the times orders are placed and expected to arrive if the risk-based policy is followed and variables are calculated using the minimized cost approach.

Table A.4: Risk-based policy: Minimum cost approach

Part	**Order arrives**	**Order placed**
Blower, hoist motor	2.4	1.4
Gear, shipper shaft	2.1	1.1
Shipper shaft	2.1	1.1
Shipper shaft pinions	1.5	0.5
Fan, house pressurizing	1.7	0.7
Boarding ladder	4.3	3.3
Shaft, swing	2.2	1.2
Operator chair	1.4	0.4
Brake disc, hoist, complete assy	1.7	0.7
Boom suspension ropes	2.9	1.9
Brake disc, crowd	1.7	0.7
Brake disc, swing	1.8	0.8
Blower, swing motor	2.5	1.5
Pump assembly, lube, crowd transmission	1.6	0.6
Blower, crowd motor	2.4	1.4
Blower, propel motor	2.4	1.4
Gearbox, cable tugger	2.1	1.1
Pump assembly, hoist gearcase lubrication	2.4	1.4
Motor, 30HP compressor	2.1	1.1
Motor, W/Brake, Cable tugger	1	0

Appendix B

Normal distribution

The Normal distribution is a well-known and popular distribution. Even though there is some scepticism regarding the appropriateness of the Normal distribution to model the demand for spare parts, there are numerous computational advantages for the Normal distribution. Some authors argue that the Normal distribution could provide near-optimum results with less complexity than other distributions. Refer to Figure B.1 for a graphical representation of the Normal distribution, where the mean is 5 years and the standard deviation 2 years. The two graphs show the probability density function (right) and the cumulative distribution function (left).

The probability density function for the Normal distribution is represented by the following equation (Silver *et al.*, 1998):

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$$

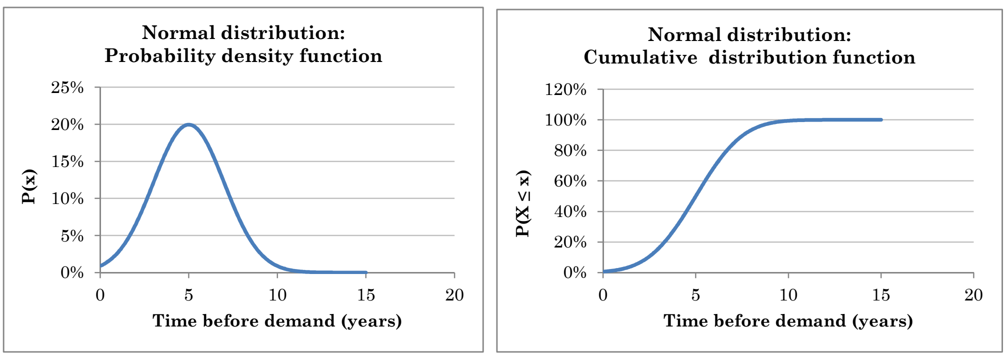


Figure B.1: Normal distribution: Probability density function and cumulative distribution

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