Coordination Aspects of Supply Chain Management for Spare Parts

Von der Fakultät für Ingenieurwissenschaften,
Abteilung Maschinenbau und Verfahrenstechnik
der
Universität Duisburg-Essen

genehmigte Dissertation zum Erwerb des akademischen Grades

eines

Doktors der Wirtschaftswissenschaften

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Tag der mündlichen Prüfung: 12.06.2018

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Abstract

A malfunctioning or failed part in a machine must be replaced as soon as possible with the same or a similar functioning part. On the one hand, it is required to have enough parts in stock to address customer requirements and avoid expensive downtimes and on the other hand, capital gets tied up in the form of non-revenue generating inventories. Finding the balance between servicing customers and reducing inventory costs is an imminent struggle for organisations large and small. This study aims at categorising spare parts into groups based on their characteristics like replenishment lead time, functional importance, unit costs etc. so as to determine the 'optimal' inventory policy for each group. Simulation optimisation methodology is developed for this problem of the two conflicting interests of service level and total costs and is implemented using MATLAB software. The program proposes the best inventory policy for all spare parts within a group and at the same time suggests the respective inventory policy parameters for each part within the group. The methodology is illustrated using an example with self-generated spare parts data. The thesis thus develops a structured approach to managing spare parts and helps to move from intuition-based to data-based inventory management and ordering behaviour for spare parts, that in some cases may cost millions of Euros.

Zusammenfassung

Eine fehlerhaftes oder ein versagendes Teil in einer Maschine muss so schnell wie möglich mit demselben oder einem ähnlich funktionierenden Teil ersetzt werden. Auf der einen Seite ist kundenseitig gefordert, genügend Teile auf Lager zu haben, um kostenintensive Maschinenstillstandszeiten zu vermeiden und auf der anderen Seite wird dadurch Kapital ohne Generierung von Umsatz in Form von Lagerbeständen gebunden. Die Balance, den Anforderungen des Kundenservices und gleichzeitig der Reduktion von Lagerbestandskosten zu genügen, ist eine große Herausforderung für kleine wie große Unternehmen. Diese Studie zielt auf die Kategorisierung von Ersatzteilen in Gruppen ab, basierend auf Charakteristika wie Wiederbeschaffungszeit, funktionale Bedeutung und Stückkosten, um so die "optimale" Lagerbestandspolitik je erstellter Gruppe zu bestimmen. Die Methodik der simulationsbasierten Optimierung wird für das Problem von den beiden in Konflikt stehenden Interessen von Service Level und Gesamtkosten entwickelt und durch die Software MATLAB umgesetzt. Das Programm schlägt die beste Lagerbestandspolitik für alle Ersatzteile innerhalb einer Gruppe vor und empfiehlt gleichzeitig die entsprechenden Parameter der Lagerbestandspolitik für jedes Teil innerhalb einer Gruppe. Die Methodik wird anhand eines Beispiels von selbst generierten Ersatzteil-Daten dargestellt. Der Ansatz stellt eine strukturierte Vorgehensweise für die Handhabung von Ersatzteilen dar und trägt zu einen Übergang von einer intuitiven zu einer datenbasierten Lagerbestandshandhabung sowie des Bestellverhaltens für Ersatzteile bei.

Acknowledgements

My sincere gratitude to Prof. Dr. Andreas Wömpener and Prof. Dr. Bernd Noche for taking over the responsibility of supervising my research work at a crucial time.

A simple ‘thank you’ is not enough to express my gratitude to my husband, my parents and parents-in-law and my brother. Whatever I do is only for you all. Sincere thanks to my colleagues and friends at the department, who not only enriched this thesis my raising the correct questions and answering mine but also by providing sincere feedback throughout the years. I am grateful to DAAD (German Academic Exchange Service) for funding my research work in the form of a scholarship.

I dedicate this thesis to my beloved ‘Doctorvater’, late Prof. Dr. Rainer Leisten. His dedication, sincerity and hard work is difficult to replicate and although he left all of us too early, he will always be very present in our memories. I also dedicate this thesis to my late maternal grandmother Mrs. Madhuri Sinha. Her continuous love and motivation helped me through some difficult phases of my research work.

I bow my head in respect to that higher power, guiding all of us. *Mera shat shat Pranam!*

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List of abbreviations

AHP	*Analytical Hierarchical Processing*
AI	*Artificial Intelligence*
CRO	*Croston's Method*
DEA	*Data Envelopment Analysis*
DIN	*Deutsches Institut für Normung*
EBO	*Expected Backorder*
EDLP	*Every-Day Low Prices*
EOQ	*Economic Order Quantity*
EWMA	*Exponetially Weighted Moving Averages*
FSS	*Forecasting Support System*
GA	*Genetic Algorithm*
IT	*Information Technology*
JIT	*Just In Time*
LDB	*Logistically Distinct Business*
LTB	*Last Time Buy*
MCIC	*Multi Criteria Inventory Classification*
METRIC	*Multi-Echelon Technique for Recoverable Item Control*
MRP	*Materials Requirement Planning*
MTBF	*Mean time between failures*
OEM	*Original Equipment Manufacturer*
SBA	*Syntetos-Boylan Approximation*
SCS	*Supply Chain Simulation*
SES	*Single Exponential Smoothing*
SKU	*Stock Keeping Unit*
SOQ	*Sustainable*
TAT	*Turnaround time*
USAF	*United States Air Force*

VED .... *Vital Essential Desirable*

VMI .... *Vendor Managed Inventory*

WIP .... *Work-In-Progress*

List of symbols

$\bar{L}$ ……………………………………………………………...Mean lead time duration

$CV^2(x)$ ……………………Squared coefficient of variation of demand size for part x

λ ………………………………………………….Mean (Poisson) demand arrival rate

Q_{opt}………………………………………………………….Optimal order quantity

A…..……………….…………………………….Fixed cost component in EOQ model

D……………………………………………….Demand rate of item in EOQ model

v…………………………………………. Unit variable cost of item in EOQ model

r………………………………….……………Carrying cost of item in EOQ model

s……………………………..………….……….…………...……Reorder level

Q……………………………..……..…………..……..……………..……Lot size

T……………………………..…………….……………..…………..…Review period

S……………………………..………….………………..…...……Order-upto level

CHAPTER 1 – INTRODUCTION

Spare parts have traditionally been a source of concern for a number of industries, be it automobile manufacturing, navy ship-building or IT majors like IBM and Dell. A large number of spare parts is kept in stock either to avoid shortages during breakdown of manufacturing equipments which can adversely affect production and hence result in delays in fulfilling orders of finished products or to service the customers that are facing the issue of failed spare part(s) and require immediate assistance and replacement. In both the cases, the downtime costs can be high, ranging from loss of revenue to loss of customer loyalty. However, stocking large number of spare parts has a negative effect on the inventory holding costs, which might be in the range of millions of Euros in capital-intensive organisations, hence making spare parts management a critical and opportunistic field of research.

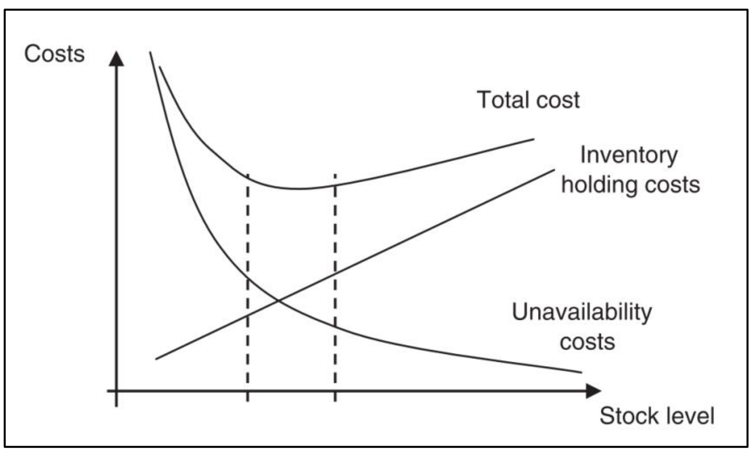

Figure 1: Trade-off between total cost and stock level; adapted from Cavalieri et al. (2008)

It is not only the trade-off between servicing a failed machine within the facility or at the customer location and keeping the inventory holding costs under control, commonly termed as cost vs. service level trade-off, but also the sheer number and variety of spare parts that an organisation has to maintain that makes the task of spare parts management a challenging one. So far, spare parts have been managed by organisations in a similar manner as raw materials for end product. There have been very limited usage of specific tools that deal with spare parts classification, forecasting, inventory and logistics management. It is important to understand that spare parts supply chain functions drastically different than the manufacturing supply chain, neatly summarized by Cohen et al. (2006) :

Parameter	**Manufacturing Supply Chain**	**Spare parts Supply Chain**
Nature of demand	Predictable, can be forecasted	Always unpredictable, sporadic
Required Response	Standard, can be scheduled	ASAP (same day or next day)
Number of SKUs	Limited	15 to 20 times more
Product Portfolio	Largely homogenous	Always heterogeneous
Delivery Network	Depends of nature of product; multiple networks necessary	Single network
Inventory Management aim	Maximise velocity of resources	Pre-position resources
Reverse Logistics	Doesn't handle	Handles return, repair and disposal
Performance Metric	Fill Rate	Product availability (Uptime)
Inventory Turns	6-50 per year	1-4 per year

Table 1: Contrast between a manufacturing and a spare parts supply chain; adapted from Cohen et al. (2006)

Historically, organisations have focussed on revenues earned through the sale of products, but with commoditization and customization of products and the increasing power of customer in the market, the margins through product sales is decreasing. This has resulted in a shift in focus to after-sales service (and therefore spare parts management) as a source of high-margin revenue and increasing customer loyalty and competitive advantage.

With organisations understanding the importance of the spare parts supply chain management, the need to take decisions in a holistic manner to result in effective planning increases. This has resulted in a need to have a methodology that acts as a guiding tool for spare part supply chain managers to achieve the basic goal of reducing overall costs and storing ‘enough’ inventory. Developing this methodology is the aim of this research work. In this thesis, the perspective is that of an organisation with a single location facility that manufactures a product, sells it to other organisations and end customers and is responsible for maintaining the equipments sold.

CHAPTER 2 - RESEARCH CONTEXT

2.1 Spare parts

Spare parts are parts that are required to replace or in support of an existing part in a machine. They can range from nuts and bolts to ball-bearings and expansion joints. The terms spare part, service part or aftermarket part are used interchangeably.

According to DIN 24420 (from the German institute of standardization or *'Deutsches Institut für Normung'*), spare parts can be defined as parts or groups of parts which replace damaged, worn or missing parts.[1] Spare parts can be classified into two major categories[2]:

Repairables: When a failure occurs, these are the parts can be technically and economically repaired. Post repair, the part becomes ready-for-use again.[3] Therefore, they do not need to be scrapped. These parts are also called repairable parts, recoverable parts, recoverables, rotation parts or rotables.

Consumables: When a failure occurs, these parts need to be scrapped since it is not possible to technically or economically repair them. They are also sometimes known as consumable parts, expendable parts, expendables, disposable parts or disposables.

Arts (2013) includes another spare parts type in the list termed as rotables. These are items that are comparatively larger and more complex than a typical normal spare part. They are generally subsystems of a machine that require a separate usage based maintenance strategy.[4] Furthermore, spare parts are used either during planned maintenance (preventive strategy) or for unplanned demand (corrective strategy).

Different types of organisational settings need spare parts, from manufacturing companies for maintenance and repair of production equipments to service-oriented

[1] http://wirtschaftslexikon.gabler.de/Archiv/82244/ersatzteil-v8.html
[2] Botter and Fortuin (2000), p. 656.
[3] Driessen et al. (2014), p. 411.
[4] Arts (2013), p. 7.

companies for timely repair of failed customer products. The following three different types of demand situations might arise for spare parts:

1. To service company’s own production facilities: This includes providing spare parts for the machines that are placed in the company’s own manufacturing facility or at a subsidiary plant (based upon the type of contract).
2. To service customer’s professional systems: The machines or products supplied by the company to other businesses form a part of this type.
3. To repair end customer products: End customers, also known as consumers, can demand spare parts when their machine fails. A company may choose to provide spare parts for products manufactured only by them or to also service same or similar products by other companies.

Whatever the demand situation may be, the company that takes the responsibility of providing its customers with high level of after-sales service must be prepared to face a large number of ‘urgent’ or ‘emergency’ situations. The company can service the customers with the required spare parts utilizing the following four sources:

1. Suppliers: In certain situations, it is economically feasible and sometimes even profitable to service a demand directly from the supplier of the spare parts to the customer. At the same time, a demand situation might arise where the downtime cost of the failed part is extremely high or the part demanded is highly critical and hence has to supplied to the customer as soon as possible and the company has no stock of the part demanded. In such cases, emergency shipments from the supplier might prove to be the ideal solution, even if costly.
2. Spare parts inventory: Most companies either own or rent warehouses so as to store enough stock of spare parts based on their own methodologies of future demand prediction. It is a strategic decision whether to have a central warehouse taking care of the demands of the variety of customers or to have a

central warehouse that services various regional/local warehouses. These decisions depend upon, among other factors, the geographical spread of the customers, planned budget and service level promised.

3. Raw material inventory: Spare parts can be sourced directly from the raw material inventory when needed. The parts in this inventory are stocked for manufacturing the end product. But in situations where there is an urgent need of a part such that the normal production flow can be compromised to service the customer spare part demand, then raw materials inventory can act as a back-up source for spare parts.
4. Additive manufacturing: A relatively new method of manufacturing spare parts is through additive manufacturing, also known as 3-D printing. This method of producing parts is currently limited by technical, material and cost factors. Airbus, in collaboration with Satair group, is actively exploring the possibilities of manufacturing parts on demand using a 3-D printer and hence are removing dependencies on supplier and bringing down the tied up capital and inventory holding costs.

2.2 Spare parts management

The demand and inventory characteristics of spare parts make their management a challenging task. Some of these characteristics are large number of parts managed, variety of parts, presence of lumpy demand patterns, high responsiveness required by customers due to excessive downtime costs and the risk of stock obsolescence.[5]

The most widely used tool for spare parts management in the industry is provided by SAP. Various studies by renowned analyst firms including Deloitte support SAP spare parts management solution as an effective tool to reduce order and processing time and to improve the customer service level. Though some authors have criticized the use of SAP tool for spare parts management. Porras and Dekker (2008) state the following two major drawbacks:

[5] Bacchetti et al. (2013), p. 263.

1. The forecasting methods used in SAP, like exponential smoothing and moving averages are not suitable with the intermittent nature of spare parts demand
2. There is no possibility to implement continuous review methods in SAP. Therefore, the widely suggested and advised *(S–1, S)* model with Poisson distributed demand over lead time cannot be applied.[6]

2.2.1 Importance of spare parts management

The nature of business has changed in the last few decades. Organisations are looking to continue what they do the best, also termed as their core competency, and are outsourcing wherever they think it would cost less while not adversely affecting their customers' satisfaction. The pressure on businesses are more than ever, with customers becoming the 'king' and this being the golden age of services, companies must look into transforming themselves to services business.[7] Particularly considering manufacturing industries, a gradual change in their role, focus and characteristics is being noticed.[8] Many organisations in North America and Europe have implemented a change in their strategy from pushing products to the customer to delivering value through after-sales services. This change can be attributed to the slowing of overall demand, intensified domestic and international competition and imploding profit margins.[9]

The primary reason why the study of spare parts management is important is because of its direct influence on customer service. In most cases, downtime costs (both operational and financial) for machines, of which a part has failed and requires a replacement, are extremely high. Unavailability of a simple and inexpensive part can result in lost production (and therefore idle manpower and inoperable machine or lost capacity), delay in delivery of finished goods resulting in cost penalty, present loss of

[6] Porras and Dekker (2008), p. 104.
[7] Cohen et al. (2006), p. 129.
[8] Duchessi et al. (1988), p. 8.
[9] Cohen et al. (2006), p. 129.

profit as well as future loss in the form of goodwill erosion.[10] With the growing importance of services and the high dependency of after-sales service on spare parts management it becomes important not to underestimate the role that timely adressal of spare part demand has so that the customers are satisfied, and if possible delighted.

Another major reason is that the margins of profit generated in services are often higher than the margins generated with the end-product sales[11]. However, with a globalized market comes globalized competition. This implies that organisations need a robust differentiation strategy to attract new customers and retain the existing ones. Service that includes efficient management of spare parts supports this objective. The increasing worldwide competition and reducing profit margins are forcing high-technology-product manufacturers to find new ways to differentiate themselves from competitors and an important way to achieve this is by providing fast, high-quality after-sales service.[12] After-sales service here refers to the bundle offering of service engineer, the necessary spare parts and the tools required for servicing.

Spare part management is an important and expanding area where significant cost reductions can be achieved through improved management and control techniques.[13] A study reveals that 40-50% of the profits made by manufacturers come from parts, maintenance and servicing making spare parts logistics a $21 billion industry[14]. At the same time, the never ending struggle between inventory cost and customer service makes the field of spare parts management all the more challenging and interesting.

2.2.2 Challenges in spare parts management

Due to the inherent characteristics of spare parts described in *Section 2.1*, there are a number of challenges that are faced by a spare parts manager. Pinder and Dutta (2011) explains how challenging spare parts management can get and how integration

[10] Sarker and Haque (2000), p.752.
[11] Bundschuh and Dezvane (2003), p. 116.
[12] Candas and Kutanoglu (2007), p. 159.
[13] Duchessi et al. (1988), p. 8.
[14] Cohen et al. (1997), p. 627-639.

between parts management and logistics can result in speeding up the time required to resolve an issue and at the same time in reducing costs associated with inventory and labour redundancies.[15] Baccheti and Saccani (2010) summarizes the major challenges in each aspect of spare parts management as follows:

Aspect	Challenges
Parts classification	Identify relevant criteria. Implement and update multi-criteria classifications for differentiating planning choices
Demand forecasting	Specific approaches and methods for demand forecasting, considering the different demand patterns (for e.g. regular vs. lumpy) and the stock control objectives
Inventory management	Multi-echelon inventory management with global information and centralized control of the supply chain
Organizational aspects	Organizational aspects are of utmost importance when implementing inventory or demand management models. Intra- and inter-organizational integration should be strengthened to adopt a system perspective. Need to combine qualitative and quantitative information and to increase communication surrounding critical issues

Table 2: Spare parts management aspects and corresponding challenges; adapted from Bacchetti and Saccani (2010)

As it can be observed, breaking down the entire problem into 4 major aspects helped the authors to dive into detail and carry out empirical analyses on the survey data collected from ten manufacturing companies based out of Italy.

[15] Pinder and Dutta (2011), p. 5.

Cohen et al. (2006) observed how poorly large companies manage service networks and how little coordination exists between a company's spare parts warehouses and its dealers.[16] Boone et al. (2008) carried out a comprehensive study with 18 spare parts managers to understand some of these typical challenges. Their work highlighted that weakness in the relationship among the supply chain entities (for example, lack of communication and data exchange), inaccuracy in demand forecasts followed by complications in inventory management (especially for new products with spare parts having no past demand data), difficulty to maintain effective levels of inventory at different stocking points in the supply chain are some of these challenges.

Farris et al. (2005) argued that although aftermarket support is an important topic in the field of logistics and supply chain, it is often overlooked.[17] Moreover, technological progress has resulted in better product quality and at the same time shorter life cycles which reduces the possibility of collecting historical demand data, demand data being an essential element in many models for inventory control.[18] As a consequence to the variable market demand situation, increased product quality and importance of efficient resource usage, it becomes the responsibility of a company to supply its customers with spare parts for products manufactured long ago.[19] Clearly, a company cannot possibly afford to keep all the spare parts for all the products that it manufactured since its beginning till now.

Studies by Duchessi et al. (1988) also provided insights into challenges in practicing spare parts management. Companies that use bottom-up approach and hence focus attention on only those parts that are important according to managerial discretion and intuition were found to have inconsistent spare parts management performance. Dependence of spare parts classification on non-quantitative methods and lack of data

[16] Cohen et al. (2006), p. 130.
[17] Farris et al. (2005), p. 7.
[18] Fortuin and Martin (1999), p. 951.
[19] Yamashina (1989), p.195.

(primarily maintenance-related) were the other major challenges highlighted in the studies.[20]

Traditionally, a comprehensive and holistic view in understanding the spare parts supply chain has been lacking and focus has been put on local interests/ optimizations.[21] Through cross-case analysis of 10 companies in the durable goods industry, it was found that most of them hold an ‘internal perspective’ to spare parts management while only a few have a ‘supply chain perspective’.[22] The difference between the two types lies in the fact that a particular department (or company) in a supply chain takes decisions without considering its influence on the others. Surprisingly, there is an absence of a comprehensive approach even in companies that run programmes especially targeted towards improving performance in spare parts management.[23]

The non-differentiated techniques used for tackling product (also called manufacturing) supply chain problems and spare parts supply chain problems is another major challenge. Common inventory management techniques stand invalid in case of spare parts management since the demand process is different and demand data is scarce.[24] Across industries, it is a well-accepted fact that delivering after-sales services is more complex than manufacturing products.[25] Particularly for consumer products, service parts are highly varied, with differing costs, service requirements and demand patterns.[26] Completely different from finished product inventories and WIP inventories, that are driven by customer demands and production processes, spare part inventories are kept to support maintenance activities and to protect in case of equipment break-down.[27] Martin et al. (2010) clearly stated that maintenance

[20] Duchessi et al. (1988), p. 9.
[21] Martin et al. (2010), p. 226-245.
[22] Bacchetti and Saccani (2010), p. 15.
[23] Duchessi et al. (1988), p. 8.
[24] Fortuin and Martin (1999), p. 950.
[25] Cohen et al. (2006), p. 129.
[26] Boylan and Syntetos (2008), p. 480.
[27] Porras and Dekker (2008), p. 101.

(spare parts) inventories are very different from other types of inventories such as work in progress or finished products inventories therefore concluding that both of these research areas are different.[28] The need for spare parts is not only based on the market demand for new products, but also on the already sold products, internal demand, failure rate of the part (which has a different value when the part is in use as compared to when a part is stored in inventory), the skill of service engineer etc. This is in contrast to product demand which in many cases is directly related to the market demand. As a result, almost 23% of parts become obsolete every year.[29] Sometimes, managers are willing to utilize specialized techniques but are not able to do so due to limited amount of resources and budget constraints.

The nature of businesses is changing and this has resulted in a number of entities to come together to deliver a product to the end customer. It has to be noted here that the entities might be physically situated within a range of a few hundred meters or might as well be located thousands of kilometres from each other. These entities interact and depend on each other to perform actions and take decisions. This means that they can have diverse interests which increases the overall complexity in the decision making process for each entity. Hence, a monolithic approach cannot be used to understand such situations.[30]

Another challenge that organisations face is choosing a means to satisfy customer demand for spare part. As highlighted in the earlier sections, there are four ways in which a particular demand can be fulfilled – existing stock, supplier or OEM, traditional production or additive manufacturing. To deliver a part to the customer, the organisation must strategically plan which method to adopt. And if it is using more than one method, then when to switch between them. The factors to be considered while making this decision is the costs associated with each method, their respective capacities and production or replenishment lead times.

[28] Martin et al. (2010), p. 230.
[29] Cohen et al. (2006), p. 130.
[30] Schneeweiss (2003), p. 1.

As already mentioned, the service requirement time for spare parts is very small (within a few hours or days) as the downtime costs associated with a non-functioning customer machine are extremely high. Non-availability of a critical spare part can lead to loss of revenues, customer dissatisfaction and in certain cases claims for refund or even a public safety hazard (for example in military settings and power plants).[31] Complexity further increases when the machine for which the spare part has to be serviced is no longer in production. Automotive companies, in some cases, offer a service period of upto 30 years after the production of the primary product ceases. In these situations, the company should decide whether to place a final order with the spare parts supplier or look for another supplier or production methods. However, in the first case, companies face a high risk of over-stocking, high inventory costs, obsolescence risk and demand estimation for a long time-period while the second case may be technically infeasible or prohibitively expensive.[32] It must be noted that still, close to 50% of customers face delays in getting their vehicles fixed because the dealers do not have the right parts to service.[33]

One of the consequences of the above stated challenges is that customers who need specialized parts quickly but unpredictably are underserved and customers needing standardized parts are overcharged.[34] At the same time, large inventories of expensive parts collect dust, while there are delays and lost capacities due to shortage of others.[35]

Despite the relevance of after-sales service and spare parts management, this area has been traditionally overlooked in many companies primarily due to the above stated challenges. At the same time, spare parts research has been mostly focused on inventory modelling[36] while ignoring the relevance of incorporating a comprehensive

[31] Driessen et al. (2014), p. 407.
[32] Kleber et al. (2012), p. 1477.
[33] Cohen et al. (2006), p. 130.
[34] Fuller et al. (1993), p. 90.
[35] Duchessi et al. (1988), p. 9.
[36] Huiskonen (2001), p. 126.

approach to spare parts planning and control. Unfortunately, the decision-making process in reality is distributed across several managers and stakeholders with varying levels of information detail (at different points in time and different levels) and it is computationally infeasible to solve one single all-encompassing model.[37] But still, the search for a practical and robust solution to spare parts management is on.

[37] Driessen et al. (2014), p. 408.

CHAPTER 3 – LITERATURE REVIEW

3.1 Spare parts classification

To start with, it has been recognised that it is important to classify spare parts into groups or families so that the consequent decisions, especially regarding demand forecasting and inventory control are assisted. Even though efficient and faster computing systems now make complex demand and inventory modelling possible, practitioners still have to choose control parameters, allocate control resources and make purchasing decisions for different types of items.[38] Incorporating different policies for each spare part is a tedious and complicated task and therefore, practitioners are interested in grouping parts with similar properties together so that forecasting and stock-control decisions can be taken on them collectively, making management of spare parts easier.

Spare parts classification serves different objectives for different decision makers. For example, while warehouse operators are interested in part weight and volume, management is more concerned about parts that can generate the most revenue and on the other hand strategic planners are interested in life cycle stage of products that need to be supplied with spare parts.[39] Hence, it is necessary to decide which relevant criteria to incorporate while classifying parts so that the resultant groups are meaningful for the particular entity and its stakeholders in the supply chain.

It is also important to realise that as a first step the spare parts have to be sorted – this means that the parts that share similar or have same characteristics should be grouped together into families where each family can eventually be treated in a particular manner. Hence, for this research work, identifying homogenous group of spare parts is important to ultimately choosing a stocking strategy for each group. There have been various attempts, methods and algorithms to carry out parts classification ranging from ABC analysis to complex clustering techniques.

[38] Huiskonen (2001), p.126.
[39] Heinecke et al. (2013), p. 455.

The spare parts classification table (*Annexure 1*) provides an overview of the existing literature in the field of spare parts classification. The following observations were made after analysing the variety of literature in this area:

1. Spare parts classification is a comparatively recent phenomenon.
2. It has only been dealt with as a standalone activity, without any consideration of future inventory implications. Of the 28 papers researched, only Wang and Kang (2007) suggest inventory control strategies post classification.
3. Most research in the recent years is concentrated on Analytic Hierarchy Process (AHP). In fact, post 2002, majority of research papers have used AHP techniques to classify spare parts
4. While 'part criticality' has been used a standalone indicator for classification, it has also been used as cumulative indicator that factors in various other indicators like price, downtime costs etc.

Another important observation post analysis of research work in this area is that three important questions constitute the activity of spare parts classification which are as follows:

1. Which criteria are used to carry out classification
2. What classification scheme/methodology is used to carry out classification
3. What are the cut-off values for these criteria for every group formed

3.1.1 Criteria for spare parts classification

Unfortunately, the topic of spare parts classification criteria has not received as much academic attention as that for finished products. Of the 29 articles analysed, 17 utilize replenishment lead time as a classification criteria, part cost/value is used in 14 articles and annual consumption in 11 articles, demonstrating that these three qualify as the most sought after ones. Very often, the criteria to adopt either depends upon the aim of the classification[40] or on the local circumstances like the creativity of spare

[40] Lolli et al. (2014), p. 63.

parts managers, their experience and their common sense.[41] The important details to be kept in mind while selecting criteria is that they should be mutually independent and they should have discriminating power and relevance.[42]

Bacchetti and Saccani (2012) neatly summarizes the contributions addressing the selection of classification criteria.[43] While it selects articles specifically focussing on spare parts, the study also includes articles on slow moving demand products that have similar behaviour as spare parts. Among the most commonly used criteria are part cost and part criticality, demand volume or value, supply characteristics (replenishment lead time, supplier availability, risk of non-supply) and demand variability. Comparatively fewer studies concern with part life cycle, specificity and reliability while filtering parts criteria.

Fuller et al. (1993) proposes a 'menu' of potential variables that can be used to segment products or spare parts that include unit value, sales volume, degree of order coordination, degree of service involvement of the field technician, order response time, order quantity, handling and storage characteristics and substitutability. Before beginning with the classification of parts, the paper suggests segmenting customers and establishing appropriate service levels for different customer groups. The logistical stages of analysis built using customer segmentation is termed as 'Logistically Distinct Business methods' or LDB methods.[44]

Duchessi et al. (1988) develops a two-principal criteria for classifying spare parts - inventory cost, which includes cycle stock and safety stock, and parts criticality. The three important constituents of parts criticality are: downtime cost, lead time and reliability.[45] Even though mathematical formulations for calculating both the criteria have been provided and it is suggested that before clustering, "logical" categories

[41] Fortuin and Martin (1999), p. 957.
[42] Partovi and Burton (1993), p. 32.
[43] Bacchetti and Saccani (2012).
[44] Fuller et al. (1993), p.93.
[45] Duchessi et al. (1988), p. 9.

should be formed to bring down the total number of parts processed, the paper does not suggest any technique to allot cut-off values in the cost-criticality matrix created.

Even though, in general, several criteria have been proposed, very limited attention has been given to identify in which context a particular criteria is preferable to the others.[46] However, a few studies tried to connect classification criteria to assist forecasting and stock control. Williams (1984) can be attributed as the first paper that proposed a method to categorize demand patterns.

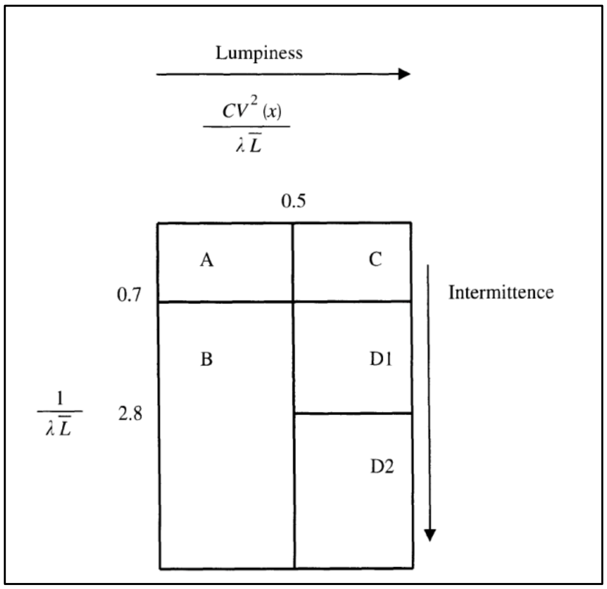

Figure 2: Williams' categorization scheme based on demand pattern; adapted from Syntetos et al. (2005)

Williams' idea of 'variance partition' requires the splitting of variance of demand during lead time for spare parts into its constituents - $\bar{L}$ being the mean lead time duration and $CV^2(x)$ corresponding to the squared coefficient of variation of demand size for part x. The λ is the mean Poisson demand arrival rate. The term $\frac{1}{\lambda\bar{L}}$ denotes the duration (in multiples of lead time) between successive demands and therefore provides an indication about the intermittency of the demand. The term $\frac{CV^2}{\lambda\bar{L}}$ on the other hand indicates how lumpy the demand is. The cut-off values of 0.5, 0.7 and 2.8

[46] Bacchetti and Saccani (2012), p. 723.

have been suggested for practical situations. This exercise divides parts into 5 categories, as illustrated in *Figure 2*; A – smooth, B – slow moving, C and D1 – lumpy and D2 – very lumpy. The methodology used by Williams will be discussed in detail in the next section.

Eaves (2002) criticized Williams' scheme stating that it does not describe the demand structure adequately and hence suggested a revised scheme based on variability of the transactions' rate, demand size variability and lead time variability. The transaction

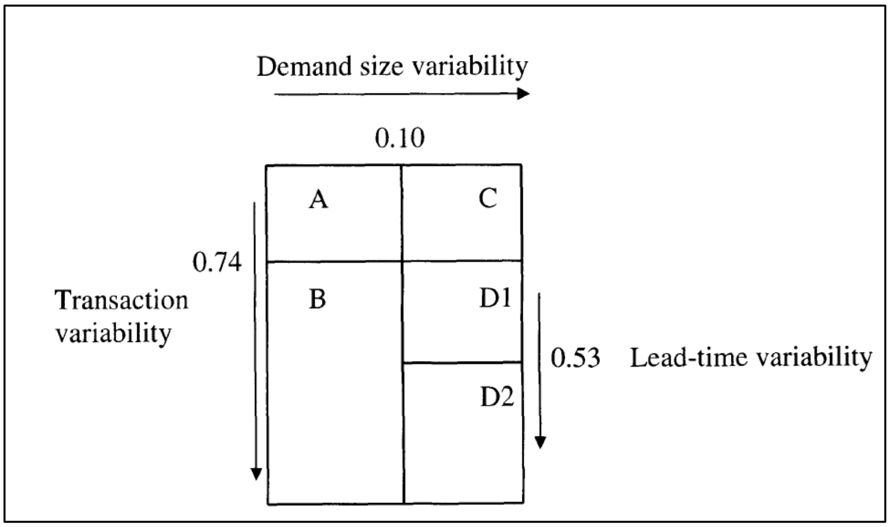

Figure 3: Eaves' classification scheme; adapted from Syntetos et al. (2005)

variability is divided into slow-moving (B) and fast moving (A) categories. The fast moving parts are further categorized based on their demand size variability into smooth (A) and irregular (C), which implies that category A constitutes of parts that are smooth, regular parts. The slow moving, irregular category is further divided based on lead-time variability into erratic (D1) and highly erratic (D2). The cut-off values were decided based on the characteristics of the considered demand data set and adequate sub-sample size considerations.[47]

Syntetos et al. (2005) on the other hand used a different technique. Instead of using characteristics for classifying spare parts so as to take demand forecasting and inventory decisions, the paper uses demand forecasting-based parts classification.

[47] Syntetos et al. (2005), p. 496.

They assumed a constant lead time and compared simulation results for three different forecasting methods (Croston's method, Syntetos & Boylan's method and EWMA) to group parts with the same method that provides the best results. The only drawback of this paper is that their method has only been used for parts with intermittent demand nature. Also, Heinecke et al. (2013) verified the claim by Kostenko and Hyndman (2006) that an alternative scheme to classify regions of superior forecasting performance between CRO and SBA performs better than that suggested by Syntetos et al. (2005). Still, Syntetos et al. (2005) will remain one of the pioneer works in classifying parts with forecasting and stock control as the aim.

Huiskonen (2001) goes a step further and classifies parts based on criticality, specificity, demand pattern and value to discuss their effects on different logistics elements like network structure, material positioning etc. Although qualitative in nature, the rules suggested in the study provided considerable base for further research. An overview of his method is illustrated in *Figure 4*. Wang and Kang (2007) followed suit and defined part criticality based on part value, failure rate and repair turnaround time and eventually suggested stock control strategies. Persson and Saccani (2009) suggest warehousing strategies for parts categorized based on supplier characteristics.

			Criticality	
			Low	High
Standard parts	Value	Low	• Order processing simplified e.g. by automated orders or • Outsourcing of inventory control to a supplier	• User's decentralized safety stocks and generous replenishment lot-sizes
		High	• Stock pushed back to the supplier	• Optimized user's safety stock (with high and smooth demand) • Time-guaranteed supplies from established service company (for lower and irregular demand) • Several users' co-operative stock pools (for very low demand)
User-specific parts			• User's own safety stock + partnership with local supplier to shorten leadtimes, to increase dependability and get priorities in emergency situations. • In the long run, standardization of parts when possible.	

Figure 4: Huiskonen's categorization of control situations and respective suggested strategies.

Out of the 29 papers in review, 13 define part criticality as a cumulative indicator – one that factors in various indicators to result in a single consolidated indicator. The definition of part criticality varies from article to article and is based on the case, empirical data and industry analysed. Some very interesting factors used to define part criticality were observed. For example, Lolli et al. (2014) included assembly stage along with consequence of failure to define criticality. The paper explains that since different parts are used in different assembly stages, a stock-out of one part may lead to more serious consequences as compared to another.[48] Another example is Shangguan (2013) that defines part criticality based on lead time, consequence of failure and safety and inventory considerations. Safety considerations include the environmental or operational dangers that can be caused by the stock-out of a part while inventory considerations considers factors like obsolescence issues, weight and dimensions of part and inventory handling costs.

Gajpal et al. (1994) is one of the first research works in the area of AHP in spare parts classification following Partovi and Burton (1993) (where AHP was used for ABC analysis of parts SKUs). The paper uses status of availability of production facility, specificity of part and replenishment lead time as factors to define part criticality and suggests that service levels can be specified based on the criticality evaluation. Similar works followed in the next years where part criticality was defined based on different factors – Flores and Whybark (1987) utilize stock-out penalty, substitutability, replenishment lead time and even political consequences among others; Winter (1990) uses replenishment lead time and part value; Celebi et al. (2008) uses part stock out penalty, degree of substitutability and commonality; Teunter et al. (2010) considers only the stock-out penalty; Schuh and Wienholdt (2011) only considers consequence of failure; Van Haperen (2013) considers commonality, substitutability and replenishment lead time; Stoll et al. (2015) utilizes multi-level hierarchy and defines part criticality as maintenance criticality (failure

[48] Lolli et al. (2014), p. 75.

frequency, installation time, lead time) and production criticality (machine priority, equipment availability and shift plan).

Braglia et al. (2004) also uses decision trees and AHP to consolidate 17 attributes into 4 factors – plant criticality, supply characteristics, inventory problems and usage rates. The study links the different classes of spare parts with possible inventory policies to identify the best control strategy.[49] More details on AHP will be illustrated in the next section.

Various classification criteria have been suggested in literature, mostly depending upon the data that is either derived from the industry or from a specific case. Even though researchers have tried to specify rules of thumb for certain cases, but still in-depth research is required. Connecting these rules to eventually assist forecasting and stock-control decision is also a research field that needs to be explored.

3.1.2 Methodology for spare parts classification

Classification methodology, also known as classification technique or scheme, is the procedure through which parts are classified once the criteria have been finalized. Qualitative research on parts classification has been long performed, for example six-factor classification by Fuller et al. (1993) for normal parts, but the most widely used methodology for finished good SKUs and spare parts classification is ABC-classification based on Pareto principle. Its simplicity and ease of use is especially suitable for set of parts having similar characteristics. The earliest recorded works in this field can be traced back to Dickie (1951) who proposed the ABC inventory classification using a single criterion – annual usage value to classify inventory. This work was carried forward by Gelders and Van Looy (2015) who implemented the study in a large petrochemical plant and suggested different models for slow and fast

[49] Braglia et al. (2004), p. 55.

moving items. In fact, it was observed that the most common approach to classify parts is ABC analysis using demand volume.[50]

However, several studies confirmed the drawbacks of using a single criterion[51]. Huiskonen (2001) argued that the one-dimensional ABC classification does not discriminate all the control requirements of different types of items. Bacchetti and Saccani (2010) carried out a case-study based analysis on 10 durable goods companies and found out that only 3 out of them followed a multi-criteria classification approach towards spare parts classification. Up to 9 different spare parts classes were identified with the most common criteria of classification being demand volume, value of part and part criticality. In contrast, most of the organisations either had no model for classification or considered only simple mono-criterion approach. With the increase in the variety and complexity of parts arises the need to have multi-dimensional classification techniques and therefore, research of multi-criteria ABC analysis gained pace. Flores and Whybark's (1987) approach for classifying various cost and non-cost criteria for manufacturing and service organisations is one of the examples. Celebi et al. (2008), Diallo et al. (2009), Teunter et al. (2010) also developed classification approaches that used multi-criteria ABC analysis. Multi-Criteria Inventory Classification or MCIC is still considered as the most desired and accepted method because of its ease of use and provision to consider multiple factors to classify parts.

Qualitative-empirical approaches have also been utilized to classify parts. Huiskonen (2001) analysed how standard and user-specific parts with varying criticalities and values influence the network structure decisions (*Figure 4*). Winter (1990) also used multiple-criteria and hierarchical coupled planning procedures, for example MIT approach by Bitran and Hax (1977), to define criticality of parts and to classify them into product groups. Similarly, Van Haperen (2013) and Bacchetti (2010) employed multiple criteria that were deemed important in the respective case studies and

[50] Bacchetti and Saccani (2012), p. 723.
[51] Guvenir and Erel (1998), p. 30.

subsequently suggested strategies for the groups formed. Similar empirical analyses were performed in many other researches, but mostly in the form of matrix analysis using quantitative data. Williams (1984) started this trend (*Figure 2*) and was followed by a two-dimensional classification scheme using inventory costs and part criticality by Duchessi et al. (1988).

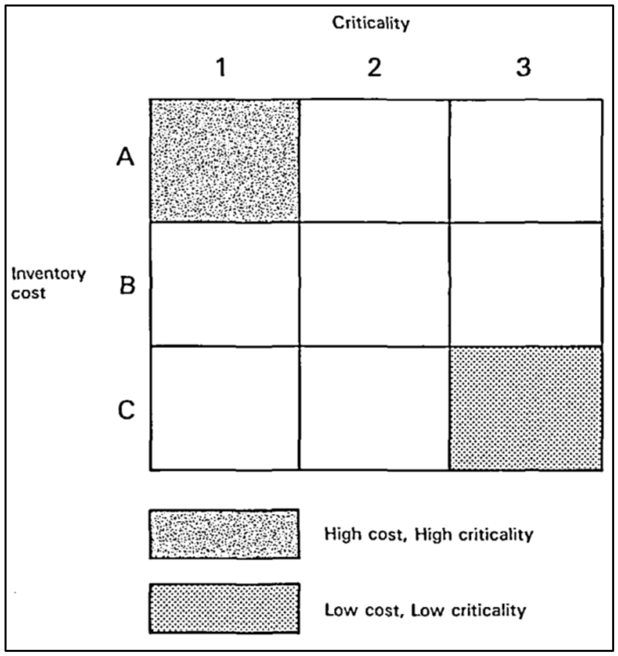

Figure 5: Cost-criticality matrix for classifying spare parts; adapted from Duchessi et al. (1988).

Similar research work followed – Schuh and Wienholdt (2011) categorized spare parts based on part criticality and wear behaviour for the wind energy industry (*Figure 6*); Shangguan (2013) also categorized parts for offshore equipments in Bohai bay area using part criticality, frequency of demand and annual usage; Geertjes (2014) analysed a typical spare parts supply chain and proposed to classify parts on the basis of demand frequency and price.

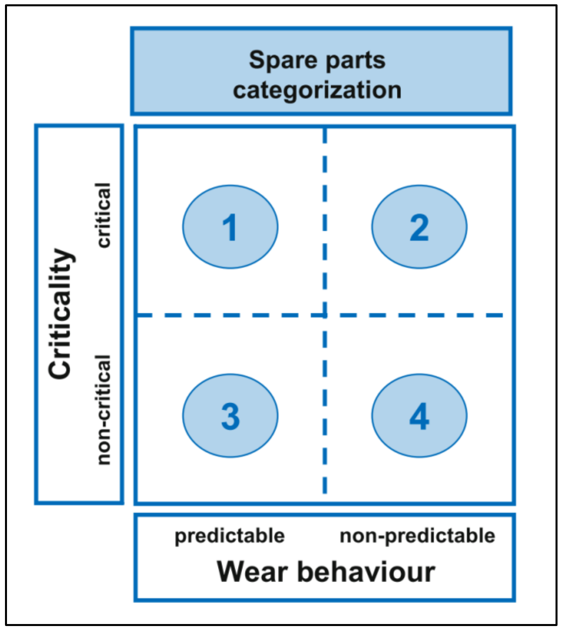

Figure 6: Spare parts categorization by Schuh and Wienholdt (2011).

A variety of other techniques that use multiple criteria to classify parts have been developed, the most well-known one being Analytical Hierarchy Processing, also known as AHP. It is a decision-making tool developed by Saaty (1990) for dealing with complex, unstructured and multi-attribute decisions. This method assigns weights or relative priorities to the different criteria and their alternatives that characterize a decision. There are three steps in using AHP[52]:

1. Description of a complex decision problem in the form of a hierarchy.
2. Pair-wise comparison to determine the relative importance or weight of the various elements in each level of the hierarchy.
3. Integration of these weights to determine the overall evaluation of the decision alternatives.

The decision model structures the problem into a multi-level hierarchy with the overall objective at the top followed by the criteria that characterizes the objective on the second level and the decision alternatives at the bottommost level.[53] The criteria

[52] Partovi and Burton (1993), p.30.
[53] Gajpal et al. (1994), p. 294.

can be subjective or objective and can be divided into sub-criteria for better explanation of the objective.[54] AHP evaluates the pairwise criteria with regard to the goal and the alternatives with regards to the criteria.[55]

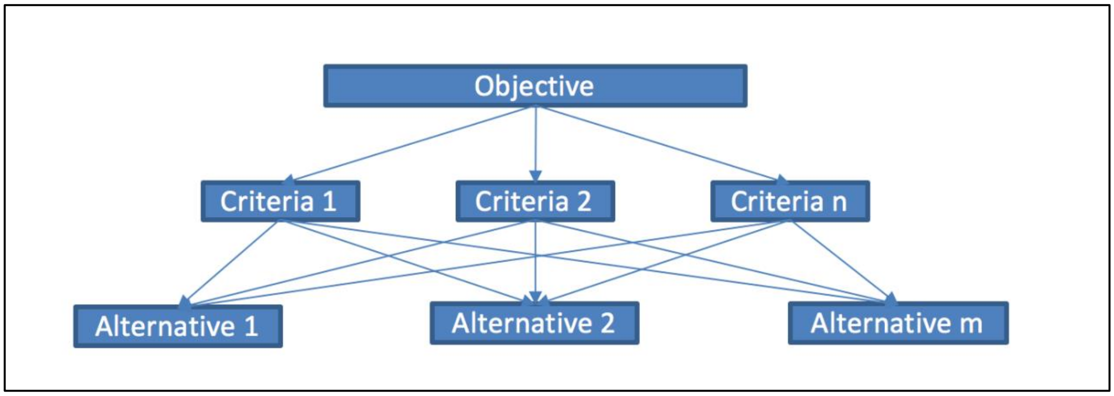

Figure 7: Hierarchy structure for VED analysis - AHP Model; adapted from Gajpal et al. (1994).

The trend of utilizing AHP for spare parts classification started from Partovi and Burton (1993). This study defines qualitative and quantitative criteria to classify SKUs and tests this model in a large pharmaceutical company. Other works utilizing AHP for spare parts classification include Gajpal et al. (1994), Sharaf and Helmy (2001), Braglia et al. (2004) and Celebi et al. (2008) among others.

Development of new AHP techniques followed, including AHP Sort and AHP-K which use robust clustering algorithms. The latest in this line is the AHP-K-Veto technique that adjusts for the hidden poor scores for items by introducing a veto system. Lolli et al. (2014) also proposes a 'Clustering Validity Index' for benchmarking this technique against other previously known inventory classification techniques. Ernst and Cohen (1990) developed a comprehensive methodology using statistical clustering to classify parts. The major advantage of this technique is the utilization of a large range of attributes that can be chosen on managerial discretion.[56] The drawbacks, as highlighted by Partovi and Burton (1993) among other papers, are the complexity and impracticability of the model and the problem of carrying out re-

[54] Partovi and Burton (1993), p.30.
[55] Lolli et al. (2014), p. 68.
[56] Ernst and Cohen (1990), p. 574-598.

clustering with the inclusion of a new part in the assortment which may result in some parts being allotted to a totally different cluster.[57] AHP has been integrated and extended with many other techniques like Data Envelopment Analysis (DEA), Artificial Intelligence (AI) and Genetic Algorithm (GA) but unfortunately, all these models present disadvantages with respect to the complexity of application.[58] Hence, striking a balance between the utility of classification to create parts families and the ease of carrying out this activity becomes important. Also, it is often argued that limited attention has been paid to identifying the cases where the importance of one criterion is higher than the other.[59]

3.1.3 Cut-off values

Also known as threshold values, these are defined for each criterion (or a group of criteria) depending upon the classification methodology used so as to consolidate parts into families. Research suggests that in several studies, the cut-off values are arbitrarily chosen such that they make sense for the particular empirical case.[60] The setting is extremely subjective in nature and depends upon the available knowledge about the criteria and the parts portfolio. Researchers argue that cut-off values should be well-assessed and carefully chosen since the solution sensitivity to the threshold values is high.[61]

[57] Partovi and Burton (1993), p.29.
[58] Axsaeter and Marklund (2010), p. 5, Lolli et al. (2014), p. 67.
[59] Bacchetti et al. (2013), p. 264.
[60] Syntetos et al. (2005), p. 496.
[61] Van Haperen (2013), p. 4.

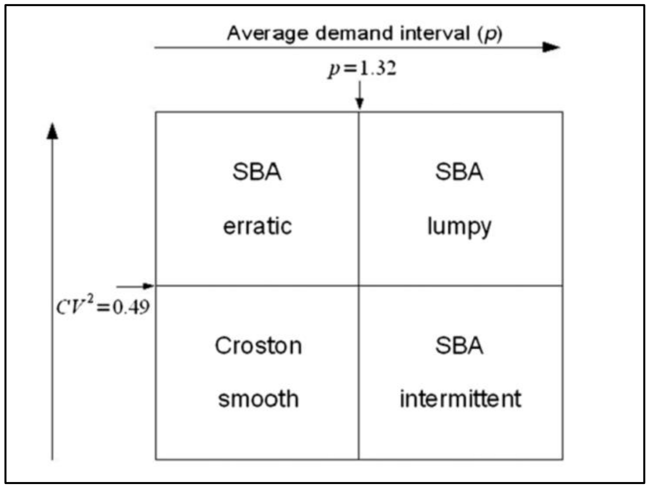

Figure 8: Classification according to Syntetos et al. (2005); adapted from Heinecke et al. (2013).

A classic example of the most widely-used set of cut-off values used in spare parts classification was proposed by Syntetos et al. (2005) (*Figure 8*). Bacchetti (2010) clearly states that the cut-off values for each criterion in their classification method was decided after consultation with the company's management.[62] Although Bacchetti's work followed Syntetos et al. (2005) to define the cut-off for ADI, it has been mentioned that Boylan et al. (2007) demonstrated through experimentation that the insensitivity of the ADI cut-off in the range of 1.18 – 1.86. Several other papers like Partovi and Burton (1993), Ghobbar and Friend (2002) and Molenaers et al. (2012) expressed the need to use extensive discussions with expert teams to finalize upon cut-off values.

3.2 Spare parts demand and forecasting

Spare parts observe irregular and unpredictable demand due to the random nature of occurrence of failure in the machine(s) where they might be required. This results in added complications to the process of forecasting their demand to better plan their inventories and more importantly, to reach the goal of 100% machine uptime. Spare parts demand pattern can be classified into four categories.

[62] Bacchetti (2010), p. 99.

Smooth: A demand pattern is termed as smooth if the demand sizes in different time periods are relatively similar and demand occurs regularly. Most products have smooth demand, although they might experience seasonal trends. Such demands can be easily forecasted and unfortunately, few spare parts fall under this category.

Erratic: Silver (1970) defines an erratic demand as one having relatively small demand transactions with occasional very large transactions. Such a demand pattern is characterized by demand instances in almost every time period but with very high variation in demand sizes. Many fast-moving spare parts constitute this category.

Intermittent: According to Silver, Pyke and Peterson (1998), a demand pattern is termed as intermittent if it is infrequent such that the "average time between consecutive transactions is considerably larger than the unit time period, the latter being the interval of forecasting updating". Here, many time periods go without observing any demand instance whereas the demands that do occur are of almost the same size and volume.

Lumpy: When a demand pattern demonstrates both erratic and intermittent behaviour, it is termed as lumpy. Often spare parts observe lumpy demand which implies that they have high variability in the time interval in which they might be needed and have high variability in the amounts in which they might be required. Lumpiness is a result of several factors like the number and variety of customers, their order frequency, heterogeneity of customer requests and correlation between customer behaviour.[63]

[63] Bartezzaghi et al. (1999), p. 499.

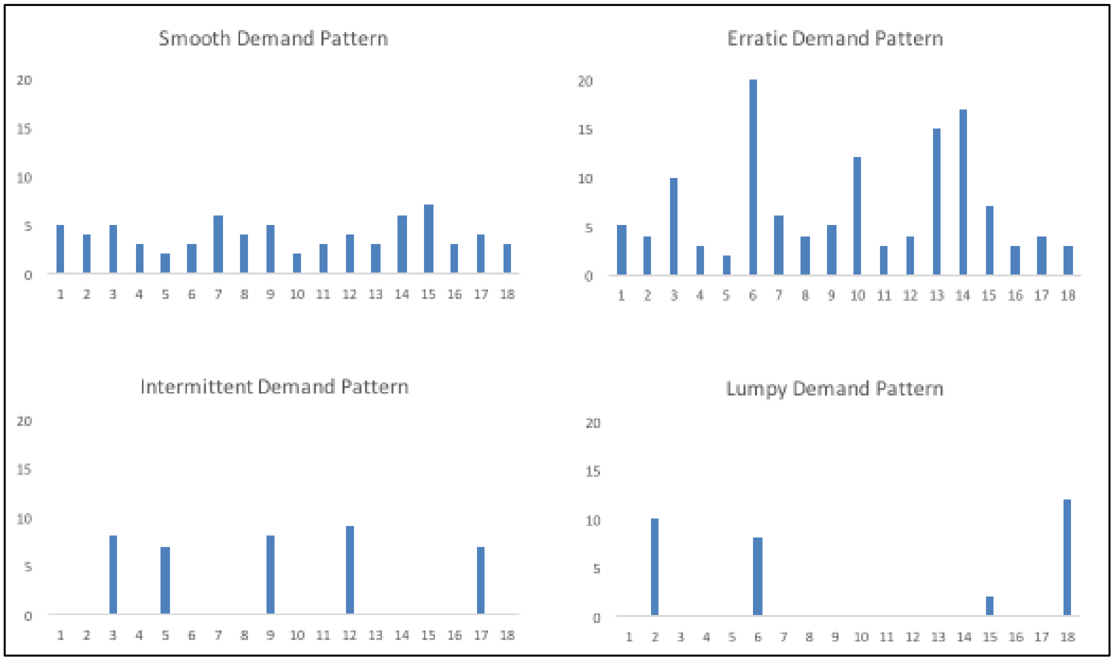

Figure 9: A depiction of four kinds of demand patterns for spare parts

Bartezzaghi et al. (1999) identifies the factors that contribute to the unpredictability in demand patterns:

1. Numerousness of potential customers in the market
2. Heterogeneity of customers
3. Frequency of customer requests
4. Variety of customer requests
5. Correlation between customer requests

Subsequently, Boylan and Syntetos (2008) explained how each factor plays a role in rendering the demand pattern lumpy. The chart can also serve as a guiding tool for root-cause analysis for unpredictable nature of a spare part demand. Spare parts manager can then act accordingly. For example, to reduce the erratic nature of a spare part type, it can be suggested that homogenous customers with low demand volumes be consolidated into one so that variability in the demand sizes can be lowered. Such tools help managers take decisions in an accurate and faster manner.

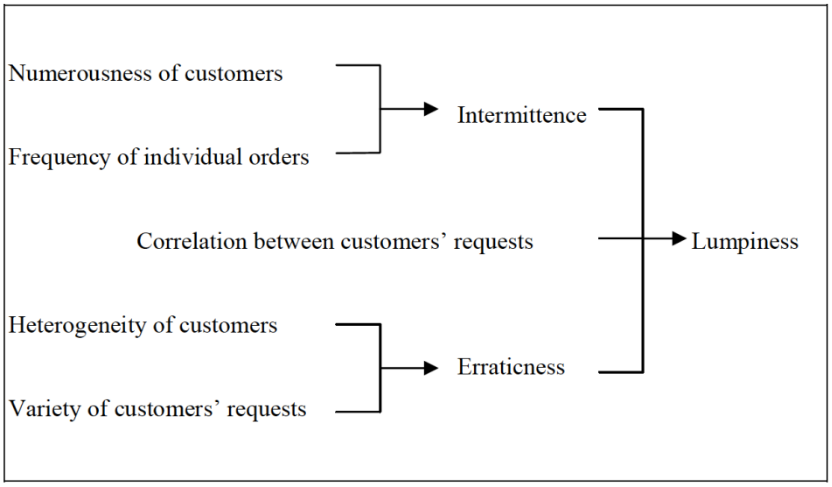

Figure 10: Categorization based on sources of demand characteristics; adapted from Boylan and Syntetos (2008)

It has been explained how complicated the spare parts demand pattern can be, ranging from the variety in not only the demand sizes but also in the frequency of demand instances. Since the decision on inventory policies for spare parts is directly influenced by the current step of demand forecasting, therefore the process of spare parts demand forecasting is a crucial one. Strasheim (1992) summarizes the existing techniques for forecasting spare parts demand as follows:

1. Simple averaging methods including moving average, weighted average and double moving average methods.
2. Exponential smoothing methods termed as the most widely used technique; include single exponential smoothing that allots exponentially decreasing weights to data points. Other variations are:
   a. Double Exponential smoothing: Brown's one parameter method is widely used as well while Holt's two parameter method, that uses a separate constant value to smooth the trend, is another variation in this category. Winter's three parameter method takes into consideration trend and seasonality.
   b. Chow's adaptive smoothing which can be used for non-static time series. Other variations include Brown's one parameter adaptive smoothing and Harrison's harmonic smoothing.

3. Regression methods that can range from simple linear regression to multiple and logistic regression.
4. Decomposition method wherein time series consists of four components - trend, seasonal, cyclical and random.
5. Box-Jenkins Method, also known as ARIMA time series method, is one of the most data-intensive techniques to forecast lumpy demand.
6. Focus Forecasting, a technique by Bernard Smith, involves evaluation of all forecasting methods for the immediate part period and selecting the best one for the next period.

Several metrics to evaluate the various techniques available have also been suggested by Strasheim which include Theil's U value, Durban-Watson value and Forecasting Index. It was eventually inferred that Brown's one parameter method gave the best results, especially for fast moving items.

Single Exponential Smoothing (SES) is the most simplistic and widely used technique to forecast demand, but unfortunately, it works without any special consideration to intermittent (or lumpy) demand patterns. Croston proved that SES method is biased in cases of intermittent demand and proposed a new methodology, now known as the Croston's method[64] commonly referred to as CRO, which is also the most relied upon and extensively used method in the industry and in software packages like Forecast Pro, SAP Advanced Planning & Optimisation – APO 4.0. It uses two separate estimates for the size of demand and frequency of demand. Though it was later proved that CRO is positively biased.[65] At the same time, Willemain et al. (1994) found distributions and correlations in data from the real-world that defied Croston's assumptions. Thereafter, Syntetos-Boylan Approximation (SBA) method was introduced which adjusted the positive bias in CRO. Research reveals that using SBA method results in significant reductions in the stock levels while achieving the

[64] Croston (1972).
[65] Syntetos and Boylan (2001).

specified service level targets.[66] Later on, areas where SBA or CRO perform better in the Intermittence-Lumpiness Matrix were established (*Figure 8*).[67] As depicted in the figure, intermittence is captured by squared coefficient of variation of demand sizes (CV^2) and lumpiness by the average inter-demand interval (p).

Hierarchical Forecasting is another technique that has rendered useful models to predict spare parts demand[68] and has found application in the Navy[69].The hierarchical structure can be in multiple levels and analysis can be carried out top-down, bottom-up or combinational. Hierarchical Forecasting has been found to be relevant especially in cases of long forecasting horizon[70], high degree of substitutability[71] of a part and seasonality trends. Significant work has also been carried out in developing Forecasting Support Systems (FSS) that take care of the intermittent, erratic demand patterns of spare parts. The FSS divides the entire procedure of forecasting into 3 major sections: pre-processing, processing and post-processing wherein special importance has been given to judgemental adjustments.[72] The paper also explains the relevance of Bootstrapping method.[73]

Boylan and Syntetos (2008) broadly divide spare parts forecasting into two categories:

1. Dependent on explanatory variables, also known as causal methods;
2. Dependent only on the history of demand, also defined as time-series method.

The paper also suggests that the choice of a forecasting approach depends upon data availability, like demand history which is determined by the life-cycle stage of the service part (*Figure 11*).

[66] Eaves and Kingsman (2004).
[67] Syntetos and Boylan (2005).
[68] Fliedner (2001), Zotteri et al. (2005).
[69] Moon et al. (2013).
[70] Shlifer and Wolff (1979).
[71] Widiarta et al. (2008a).
[72] Boylan and Syntetos (2008).
[73] Willemain et al. (2004).

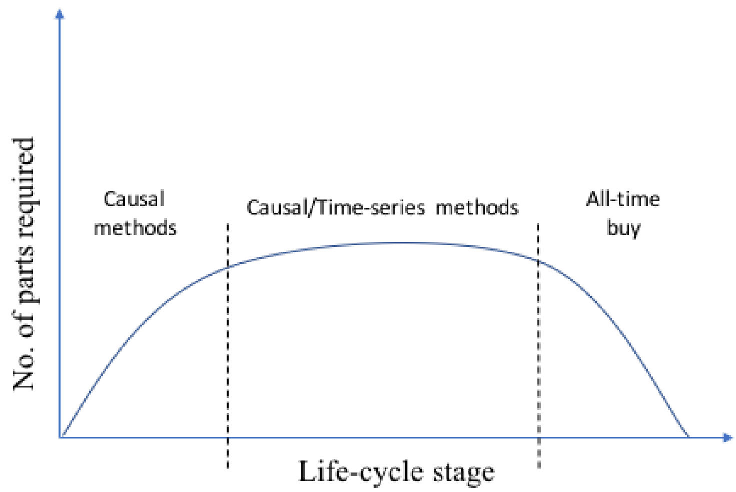

Figure 11: Forecasting approach to life-cycle stage of a spare part as suggested by Boylan and Syntetos (2008)

Forecasting methods can also be allotted based on demand characteristics. Fast-moving parts are usually forecasted using the time-series methods wherein for parts with non-intermittent demand pattern, exponential smoothing methods are used. Ghodrati (2011) suggests various models that exist for spare parts forecasting, ranging from the most prevalent Poisson process model to the normal distribution model and constant interval model, each accompanied by the criteria and conditions for use. The paper also clearly states that the use of any of the models depends upon the conditions of an individual case and it is extremely difficult to derive rules-of-thumb for spare parts demand forecasting. Although, all the methods utilize the basic concept of 'failure rate' of spare parts. Ghobbar and Friend (2002) compare 13 different forecasting methods for management of spare parts in the aviation industry. Diallo et al. (2009) suggest a spare parts forecasting method selection guide based on the demand characteristic.

	Demand	Suggested forecasting models
Fast moving items	Stationary (constant failure rate)	Simple moving average Weighted moving average Exponential smoothing
	Stationary (constant failure rate)	Moving average Two parameters exponential smoothing Linear regression
Slow moving items	Non-intermittent	Moving average Exponential smoothing
	Intermittent	Croston method Bootstrap method Moving average

Figure 12: Spares parts forecasting techniques selection guide as proposed by Diallo et al. (2009)

A number of other methods for demand forecasting that utilize the knowledge developed and experience gained by people over time like Delphi technique, structured analogies, expert systems etc. are very prevalent in practice. Unfortunately, since these methods are usually based on intuition and are not backed by data, they are difficult to completely reply upon, especially when complex parts portfolios have to be worked with or when stakes are very high, sometimes ranging in millions of Euros.

3.3 Spare parts inventory management models

The main aim of any inventory management system is to achieve targeted service levels with minimum inventory holding and administrative costs. A large amount of research has been done on developing inventory models in various settings. The EOQ model is the most well-known amongst all. Here, the minimization of total costs is targeted to determine the optimal replenishment order quantity Q_{opt}.

$$Q_{opt} \text{ or EOQ} = \sqrt{\frac{2AD}{vr}}$$

where,

A = fixed cost component

D = demand rate of the item

v = unit variable cost of item

r = carrying cost of item

The drawback of this model is the large number of assumptions that are required to be fulfilled, like a constant deterministic demand rate, no backordering, zero lead time, etc.[74] When demand is uncertain, backorders increase and then arises the need to introduce a buffer or safety stock to provide a cushion against stockout. This, along with service level measures has resulted in the following inventory review policies, generally categorized into two areas:

a. Continuous review systems – Within a continuous review system, the status of the stock is typically known, hence, stock levels are continuously monitored.
b. Periodic review systems – In such systems, stock status is determined after every T units of time.

Although more expensive to implement, the major advantage that continuous review system has over periodic review system is that it guarantees the same service level but with lesser safety stock. The various models within each of these two categories are explained below. It must be clarified that while on-hand inventory denotes the actual units of stock in the warehouse, inventory position, on the other hand, is on-hand inventory plus the pipeline inventory (ordered items that have still not arrived) minus the backorders. The term inventory level and on-hand inventory are used interchangeably. The three major policies within the continuous review system are:

1. **Order-Point, Order-Quantity *(s,Q)* model**

The *(s,Q)* policy works as follows: whenever the inventory position drops to or below the pre-defined reorder level *s*, a replenishment order with constant lot size

[74] Silver et al. (1998), p. 150.

of *Q* units is triggered which arrives after a lead time *L*.[75] Since it is a continuous review policy, inventory level is monitored at all times. This model works very well in cases of low demand variability, but in the cases of spare parts, where demand variability is usually high, the applicability of *(s,Q)* needs to be verified.

2. *(s,S)* model

In this case, inventory is continuously reviewed to check if the position has dropped below the pre-defined reorder level *s*. In that case, a replenishment order will be placed such that the inventory position reaches a pre-defined value of *S* after lead time *L*.[76] *(s,S)* model is relatively difficult to apply in real-life situations since each time, the replenishment order is of a different size and convincing a supplier to agree on it might prove to be a daunting task. Anyhow, in the case of spare parts, this model can turn out to be more robust than *(s,Q)* since the constraint of definite lot-size does not exist here and hence, large variabilities in demand sizes can be absorbed by varying the replenishment quantity.

3. *(S-1, S)* model

In this case, an order-upto level *S* is pre-defined and the attempt is to bring the inventory position to *S*. Hence, whenever a demand occurs, say even if for 1 unit and the inventory position drops down to *S-1*, a replenishment order of the quantity that brings the inventory position back to *S* is triggered. Therefore, it can also be said that *(S-1,S)* is a special case of *(s,S)* model wherein *s* has been set to *S-1*. This model is often used in cases of slow-moving products or products with very high backorder costs. Hence, it has been termed by researchers as probably the most appropriate model for handling spare parts.

In the case of periodic review systems, inventory level is monitored after every pre-defined time period *T*. Hence, it requires lesser effort on the part of the inventory

[75] Agrawal and Sheshadri (2000), Melchiors et al. (2000).
[76] Zheng and Federgruen (1991).

manager to implement such a system, even though overall it might prove to be more costly as compared to continuous review systems (due to stockouts, emergency shipments etc.). There are two major periodic review systems:

1. ***(T,Q)* model**

   Here, inventory is monitored after every T time periods and irrespective to the inventory position, replenishment order of quantity Q units is placed every time. This system is usually observed when companies order from the same supplier for a long period of time. Again, similar to the *(s,Q)* model, it has a major disadvantage in cases where demand variability is high.

2. ***(T,S)* model**

   In this review system, after every *T* units of time, a replenishment order is placed such that the inventory position reaches the pre-defined value of *S*.[77] Therefore, the size of the replenishment order varies every time.

Another model that combines the concepts of periodic and continuous review systems has been introduced. In the ***(T,s,S)*** review model, inventory is monitored after every *T* time periods. If the inventory position is below the pre-defined reorder point *s*, a replenishment order is placed that brings it back to level *S*. In case the inventory position is above *s*, no action is taken and after *T* time periods, inventory is reviewed again.

This purpose of such a replenishment control system is to answer the following three major issues:[78]

1. How often should the inventory status be determined.
2. When should a replenishment order be placed.
3. How large must this order be.

[77] Chen and Krass (2001), Silver et al. (1998).
[78] Silver et al. (1998), p. 235.

Spare parts inventory management is often considered as a special case of general inventory management with some special features like lumpy demand patterns and high service levels.[79] Because of the typical nature of spare parts, traditional models like EOQ and MRP systems cannot be utilized since these models run with the assumption of constant demand or normal distribution and MRP works with fixed lot sizes.[80] Another disadvantage is that traditional inventory control theories deal primarily with consumable items, that is, once having satisfied the demand, the inventoried items leave the system forever.[81] On the other hand, spare parts are often repairable in nature and may be returned to a repair centre and afterwards brought back to the supply chain. Kennedy et al. (2002) provide an interesting overview of the recent literature in spare parts inventory management but the proposed models are mostly either traditional inventory management models or their extensions. Therefore, unfortunately, until very recently, the inventory management practice of spare parts has mostly relied on very basic theories.[82]

Repairable spare parts inventory research was started in 1968 by the RAND Corporation for the United States Air Force (USAF) with the introduction of METRIC (Multi-Echelon Technique for Recoverable Item Control).[83] This model considers compound Poisson item demand with mean value determined by a Bayesian approach within a base-depot supply system which tries to optimize the Expected Backorders (EBOs) at the base subjected to cost constraints. MOD-METRIC[84] and VARI-METRIC[85] techniques evolved from his work. A variety of research followed, ranging from Markovian approach to limited repair capacity approach, multiple stocking centres etc. Tao and Wen (2009) provide a neat summary

[79] Huiskonen (2001), p. 126.
[80] Smith and Babai (2011), p. 129.
[81] Matta (1985), p.395.
[82] Cohen et al. (1997), p. 627-639.
[83] Sherbrooke (1968).
[84] Muckstadt (1973).
[85] Sherbrooke (1986).

of the related works and propose a simulation model for a closed-loop multi-echelon repairable inventory system.

One of the earliest works in multi-echelon inventory management for spare parts is Muckstadt and Thomas (1980). Reasonable amounts of work was carried out by Silver et al. (1998) and Muckstadt (1973). Hopp et al. (1999) propose a simplified heuristic to calculated the inventory control policies for a two-echelon spare parts distribution system. Thonemann et al. (2002) present a system approach to control spare parts inventory instead of the usual item approach. Howard et al. (2010) consider a two-echelon inventory system consisting of a central warehouse and multiple local warehouses and demonstrate the effect of utilization of pipeline information. The information on outstanding orders is used to determine whether an emergency shipment should be requested or not. Kleber et al. (2012) suggest buy-back strategies for broken products from the customers to improve control demand for spare parts and supply for recoverable items. Arts et al. (2014) formulate a decision tool for find out the best expediting policy and turn-around stock of repairable parts with uncertain demand. Behfard et al. (2015) introduce the Last Time Buy (LTB) concept for parts required to service out-of-production machines during the promised service period and develop a heuristic method to determine the LTB quantity. Basten and Arts (2017) determine the ‘fleet readiness’ of trains assuming continuous review and base-stock control and develop a greedy algorithm for joint optimization of spare parts inventories and fleet size.

Within multi-echelon parts inventory management, research has also been done to suggest inventory policies by minimizing costs. Candas and Kutanoglu (2007) suggest an integrated approach to logistics network design and inventory decisions. Their model achieved the same service level at lower costs as compared to the sequential, decoupled approach. Porras and Dekker (2008) carry out an empirical study on various inventory models using actual data to determine the approach with minimum holding costs. Tiemessen and van Houtum (2010) consider a system with one repair shop and one stockpoint and determine scheduling policy and initial stock levels for parts with the objective of minimizing holding and backorder costs. Aisyati et al. (2013) use continuous review model to find out the optimal policy for aircraft spare parts.

A very interesting article by Digiesi, Mossa and Rubino (2014) argues that the main goal of spare parts logistic is to design an efficient distribution network and to manage the stock level that ensures a given target service level[86]. This cannot be achieved sustainably unless environmental factors of new parts production and old parts disposal are incorporated into the overall calculation of optimal inventory levels. The authors went on to expand the Sustainable Order Quantity (SOQ) model in place of the traditionally used EOQ model and tested it with industrial field results. Cohen et al. (1997) carried out a study for benchmarking the after-sales logistic system and reported interesting trends and best practices in this field. This was followed by another benchmarking study, Pfohl and Ester (1999), that analysed the German mechanical industry and created a quality matrix that can be used by companies to evaluate their status quo and recognise areas of improvement.

An extremely interesting concept has been introduced recently named Performance Based Logistics (PBL)[87] where the customer does not pay for the spare parts but for the number of hours the customer obtains power from the engine.[88] The customer communicates his specific requirements to the supplier, but not the means of achieving it. The supplier on the other hand gets more flexibility. The key goal of PBL is Performance.

It can be clearly deduced that inventory management for spare parts has been carried out with a variety of objectives and under various sets of conditions, even though research in this area is relatively new. There have been some works that concentrate on suggesting appropriate inventory policies under certain conditions that can serve as guideline for spare parts managers. Literature suggests that even though class B

[86] Digiesi et al. (2014), p. 186.
[87] Mirzahosseinian and Piplani (2011)
[88] Ng et al. (2009)

inventory items like screws, springs, coils, disks, valves, bearings, bushings etc. require less frequent attention, it is recommended to use continuous review systems with *(s,S)* inventory policy.[89] Also, fast moving items are generally dispersed closer to the customer, hence it has been suggested to store them in the local warehouses.[90] At the same time, for spare parts inventory control, Compound Poisson models[91] have traditionally proven to be effective, especially for larger transactions. Otherwise, the *(S-1, S)* and *(s,S)* models[92] with Poisson distribution have been used as a norm. Use of modified EOQ model for fast moving parts with a risk of unexpected obsolescence has been suggested in literature as well.[93] The feasibility of such suggestions existing in literature shall be tested using the proposed simulation optimization model.

3.4 Classification for effective inventory management

The previous sections gave an overview on the various research work within spare parts classification, demand and its forecasting and state-of-the-art inventory management methods. All these three research topics have usually been dealt with in a standalone manner resulting in a dearth of research in fields that look into, say for example, spare parts classification to determine forecasting techniques. An important work in this area was done by Heinecke et al. (2013) which highlighted regions of superior performance between two major intermittent-demand estimation techniques: Croston's method and Syntetos-Boylan Approximation (SBA) method.

Intensive literature review further revealed that classifying spare parts with inventory management in perspective is a concept that has not been thoroughly researched upon. On broadening the scope, it was found that the earliest efforts in this direction, but for SKUs and not spare parts, were made by Williams (1984) who focused on a public utility in United Kingdom (UK) and developed a classification methodology for identifying the most appropriate forecasting and inventory control methods for the

[89] Sarker and Haque (2000), p.752.
[90] Cohen et al. (1997), p. 631.
[91] Schultz (1987).
[92] Feeney and Sherbrooke (1966).
[93] Cobbaert and Van Oudheusden (1996).

resulting groups. Eaves and Kingsman (2004) modified Williams' method and applied it in the Royal Air Force, UK. Although, later on their arbitrary assignment of cut-off values differentiating different spare parts groups faced several challenges from other researchers.

The case-based research by Bacchetti and Saccani (2010) illustrated that only 2 out of the 10 companies adopted an integrated approach to demand forecasting a inventory management.[94] Not surprisingly, both these companies were operating in the automotive industry which highlights the fact that this industry is more advanced than others in terms of understanding and applying "supply chain perspective" to spare parts management. Optimization of multi-echelon inventory systems[95] was also introduced in theory. But the concepts of forecasting and inventory control of spare parts were still alien to each other. tried bridging this gap. The limited amount of research that considers spare parts classification for effective inventory management includes Strijbosch et al. (2000) and Wang and Kang (2007). The papers states that spare parts inventory management till now has been mostly looked at from the economics point of view.[96] The authors suggest AHP method using 3 criteria – MTBF, repair TAT and price of spares to classify spare parts into Vital, Essential and Desirable groups and go on to suggest the following:

Type of spares	Storage policy
Vital	(s, S) system Continuous review
Essential	(s, Q) system Continuous review
Desirable	(R, s, S) system Periodic review

Figure 13: Storage policy based on spare type (Wang and Kang, 2007)

[94] Bacchetti and Saccani (2010), p. 16.
[95] Van der Heijden et al. (1997).
[96] Wang and Kang (2007), p. 2037.

Botter and Fortuin classify the entire spare parts portfolio based on price, response time and usage and suggest stocking strategies for each of the group formed. For example, in Figure 14, they suggest stocking parts in large quantities in local warehouses for Group 1 whereas for Group 8, they suggest centralized stocking due to their long response time.[97]

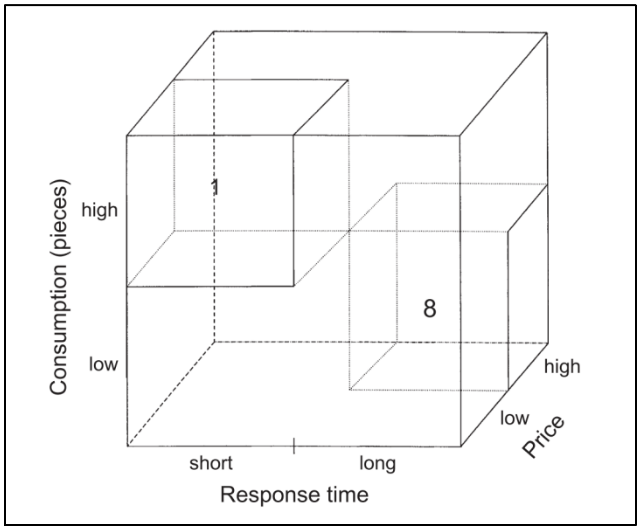

Figure 14: Framework suggested by Botter and Fortuin (2000)

Braglia et al. (2004) develop an inventory management policy matrix. They classify spare parts into four groups using 17 different attributes and provide a qualitative suggestion for each of the group.

	Spare part classification			
Inventory policy	**A**	**B**	**C**	**D**
No stock	X	X		
Single item inventory	X	X		
Just-in-time policy		X	X	
Multi item inventory				X

Figure 15: Inventory management policy matrix; adapted from Braglia et al. (2004)

[97] Botter and Fortuin (2000), p. 665-666.

Persson and Saccani (2009) present a case-based simulation research to allocate spare parts inventory. The paper groups spare parts based on lifecycle phase, volumes, criticality and competition into 26 different classes and allot these groups to different warehouses in the logistics network.[98] Meanwhile, literature suggests primarily AHP and matrix-classification methods respectively to classify parts for inventory management. Gordian proposed 'auto-order-assessment' for implementing decision rules for fast to medium-moving and low to medium-priced parts and carried out a pilot at the Royal Netherlands Navy.[99] Unfortunately, there does not exist a quantitative, industry-independent model for spare parts classification and inventory management.

3.5 Simulation methods for spare parts management

Simulation is the operation of a model of the system, which means that when reconfiguration and experimentation of a system is too expensive or too impractical to be carried out in real life, a model of the system is simulated to study and understand the behaviour of the actual system.[100] It is a strong tool to analyse system behaviour without touching the actual system. This provides the user flexibility to induce and understand changes and their implications on a system and at the same time not suffer any losses or alterations in it. Infinite scenarios can be built and simulated on a model giving the user the upper hand of predicting the future or in many cases understanding the past.

Supply Chain Simulation (SCS) is the use of simulation methodology, mostly discrete event simulation, to analyse and solve problems pertaining to supply chain management.[101] Not only is there a material flow in SCS, but also an information flow.[102] The major advantages of using simulation in this field are the possibility to

[98] Persson and Saccani (2009)
[99] Geertjes (unpublished, 2014), p.2.
[100] Maria (1997), p. 7.
[101] Persson and Saccani (2007), p. 316.
[102] Banks et al. (2002), p. 1653.

include dynamics and the ease of modelling.[103] At the same time, simulation has the capability of capturing the uncertainty and complexity that are common in supply chains.[104] It is already a popular methodology for defining intrinsic complexities in large-scale supply chains.

A considerable amount of spare parts supply chain research has been carried out using simulation modelling. Williams (1984) uses simulation assuming continuous demand to compare forecasting and inventory control methods for the three parts categories – smooth, slow-moving and sporadic. Syntetos et al. (2005) compare various forecasting techniques for the four pre-defined demand categories – smooth, erratic, intermittent and lumpy, by means of simulation. Heinecke et al. (2013) highlighted regions of superior performance between two major intermittent-demand estimation techniques: Croston's method and Syntetos-Boylan Approximation (SBA) method also using simulation methods. Gelders and Van Looy (2015) used simulation methodology to weigh their proposed inventory model against the existing model for normal and fast-moving parts in a large petrochemical company. All the above mentioned works have concentrated on using simulation to validate results.

Optimization, on the other hand, aims at either maximising or minimising a function that relates to a set that offers a definite range of options. The function compares the range of options to find out which one provides the 'best' results. The most common applications of optimization methodology are to maximise profit, minimize cost, minimize error etc. Whenever the range of options for the variables, known as decision variables, lies within a finite set of real values, the problem is termed as finite-dimensional optimization. The function is generally known as objective function and is accompanied by a set of constraints that limit the range of the decision variables. Research also suggests carrying out optimization using simulation. Simulation optimization refers to the optimization of an objective function subject to

[103] Persson and Saccani (2009), p. 127.
[104] Jain et al. (2001)

constraints, both of which can be evaluated through a simulation model.[105] Using simulation-based optimization provides flexibility in designing a system. While mathematical optimization techniques mostly incorporate many assumptions which drifts the model further away from reality, simulation optimization helps in finding the optimal solutions in real life circumstances. While traditionally, simulation has been used to mainly experiment with a system and test various scenarios, linking a simulation model to an optimisation engine results in faster and better results. In a simulation optimization system, the optimization engine feeds decision variables into the simulation model which in turn evaluates the functions utilized in objective function and allows the optimization engine to return a solution. Since it is an iterative process, the feed-in feed-out process goes on until a satisfactory solution is reached or is terminated due to prescribed conditions.[106]

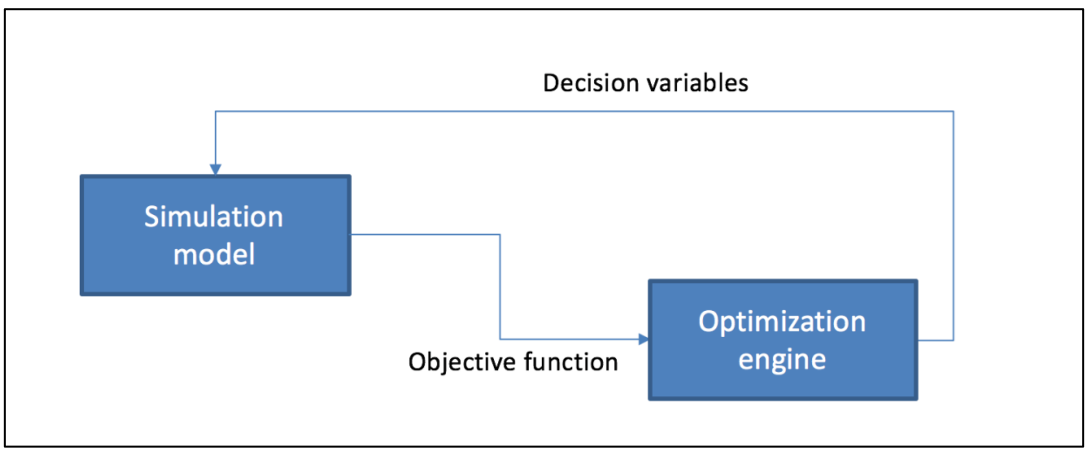

Figure 16: Simulation optimization approach

Porras and Dekker (2008) carry out a case study in a large oil refinery and compare different re-order point methods so as to minimize stock-outs. They utilize simulation optimization methodology to evaluate different inventory parameters, for *(s, nQ)* review policy, based on single target service level for all parts that belong to a single

[105] Amaran et al. (2016), p. 351.
[106] Amaran et al. (2016)

family. Adhitya and Srinivasan (2010) propose a dynamic model for a multi-site global enterprise using MATLAB/Simulink, with the aim that it serves as a quantitative simulation and decision support tool. Arts (2013) in his doctoral thesis also derived the base-stock level that minimizes the cost for a backorder system using simulation optimization methods. Behfard et al. (2015) propose that simulation optimization can theoretically be used to compute the repair policy and Lead Time Backorder (LTB) quantity, but due to the large number of parameters, the risk of a high computation time arises and hence it ultimately not used.

3.6 Existing gaps in literature and research objectives

With the importance highlighted in the previous sections and an overview of some of the major works carried out in this area, it becomes clear that spare parts management is an important area of research. But still, in the past decades, spare part research has mostly focused on the inventory modelling aspects while ignoring a more comprehensive view that includes other elements too.[107] It has been continuously argued that there is an absence of a comprehensive approach to spare parts management in existing literature as previous research evolved in two directions: industry-specific studies and general quantitative studies for spare parts control.[108]

The only paper, that was found, with the focus on dealing with the spare parts supply chain in a holistic manner is Martin et al. (2010). In this paper, the authors have argued for the importance of having a combination of quantitative and qualitative information exchange between the different entities of the supply chain. At the same time, the authors have criticized the existing approaches with the reason that most of them are limited in their capacity to incorporate into their scenario-building the broader interactions (that may influence decision-making) between ‘players’ within the supply chain as a whole.[109] Even though the authors have proved the importance of both qualitative and quantitative information, no methodology has been suggested

[107] Huiskonen (2001), p. 125.
[108] Duchessi et al. (1988), p. 9.
[109] Martin et al. (2010), p. 229.

on how to integrate the qualitative aspect into decision making. Research has also demonstrated that significant cost reductions can be achieved through an integrated approach as compared to a decoupled approach or same service level can be achieved at lower costs by incorporating an integrated approach.[110] These efforts, therefore, help in moving the efficient frontier for the Cost-Service level trade-off curve.

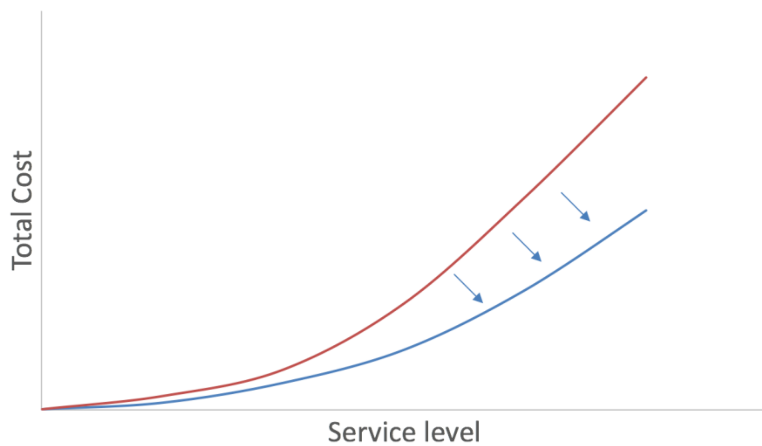

Figure 17: Cost vs Service trade-off curve, attempt to change the efficient frontier

The ever growing importance of service parts industry and the urge to develop methods to move the efficient frontier of the Cost-Service curve serve as the motivation for this research work. The attempt is to find a solution to the status quo of the fact that there is no go-to methodology to find out which inventory model to utilize for which spare part and how to classify them and better manage them. Unfortunately, methods existing currently are either too complicated and act like a 'black-box' for practitioners or are too simplistic and unusable in practical situations. The aim of this study is to develop a methodology that serves as a guiding tool to practitioners and acts as an easy-to-understand and robust method to manage spare parts for a company. It must be noted that the intention of this research work is not to dive deep into the repair centres and develop models to plan their inventory. Rather,

[110] Candas and Kutanoglu (2007), p. 159-176.

this work shall be focussed on spare parts required in a manufacturing set-up with warehouses that store spare parts and the management of inventory therein. Therefore, this thesis attempts to answer the following three research questions:

1. How does a spare parts supply chain look like?
2. Is there a tool that can be implemented to find out the optimal inventory policy for a spare part?
3. How can simulation optimization methodology be implemented to create such a tool?

The following chapters will explain the step-by-step methodology developed to tackle the issue of inventory management for spare parts and attempt has been made to answer the research questions raised above.

CHAPTER 4 – DEVELOPING A PROTOTYPE OF SPARE PARTS SUPPLY CHAIN

The importance of understanding the spare parts supply chain has been established in the previous sections. The associated challenges and the need to tackle them have also been justified. As explained in *Section 2.2.2*, one of the major challenges that spare parts managers face is the lack systems perspective in the definition of objectives resulting in sub-optimal decisions.[111] It has also been argued that true integration within the supply chain, i.e. an active and co-operative attitude among the different organisations can be beneficial for all parties involved.[112] This necessitates the need for a comprehensive framework for analysing spare parts supply chain so that various decisions that lie within each (part of the) organisation can be understood and at the same time, the interactions between these entities can be realised, observed and addressed to. In this section, a model is developed to attain deep clarity on the overall decision mechanism that exists in a typical spare parts supply chain while paying attention on the dependence of one decision on the other. The model has been developed following these guidelines and drawing information and insights primarily from works of Driessen et al. (2014), Stadtler and Kilger (2005), Silver et al. (1998) and Schneeweiss (2003).

4.1 Spare parts supply chain – a model

To address the apparent lack of a comprehensive management framework to support managerial decision-making in spare parts management, an advanced planning systems approach is used. As highlighted by Fleischmann et al. in the book Stadtler and Kilger (2005), an advanced planning system has the following characteristics:

1. It allows for integral planning of the entire supply chain
2. Through proper objectives, alternatives and constraints definition, it focusses on true optimization (through exact methods or heuristics)

[111] Boone et al. (2008).
[112] Martin et al. (2010), p. 227.

3. It builds a hierarchical planning system which allows for the combination of time horizons and planning tasks

Even though vast differences exist between a production supply chain and a spare parts supply chain (*Section 2.2.2*), they still share some common characteristics. As an example, both these supply chains are complex and thus require thorough planning. The first step towards developing a plan consists of identifying the various planning tasks involved at different timeline levels. It should be noted that planning can only be carried out for a definite period of time. A very intuitive manner in which timeline can be segregated is long-term and short-term planning. Planning tasks are usually classified into the following three planning levels[113]:

- **Long-term planning**: Also termed as strategic planning, decisions at this level are taken for the next 5-10 years (depending upon the industry). These decisions have long term effects, noticeable over several years.[114] For example, setting overall budgets, defining key customers[115], designing supply network etc.
- **Mid-term planning:** Decisions at this level are also called tactical[116] decisions. These decisions fall within the scope of strategic decisions with planning horizon ranging from 6 to 24 months allowing for seasonal developments to be taken into consideration.[117] For example, transport planning between warehouses, personnel planning etc.
- **Short-term planning:** The decisions at this planning level are also termed as operational decisions. This is the lowest and the most detailed planning level where the planning horizon is usually a few days/weeks. For example, setting order quantities based on inventory levels etc.

[113] Anthony (1965).
[114] Stadtler and Kilger (2005).
[115] Roeloffzen (2007).
[116] Silver et al. (1998).
[117] Stadtler and Kilger (2005).

Seamless and real-time flow of information between the planning horizons is necessary for overall planning to be successful. Martin et al. (2010) has noted that progressive incorporation of data and information through the three levels of timeline – strategic, tactical and operational should be effective in reducing the complications arising by the lumpy demand pattern of spare parts.[118] With the high responsiveness expected by the customers, which simply means service delivery within the stipulated time, the interaction between strategic and tactical levels of the distribution planning task becomes stronger. This is because the service-level adherence does not only depend upon whether the demand has been satisfied by a close-by storage facility (termed as 'coverage issue') but also on whether required part is available at the nearest storage facility or not (termed as 'availability issue').[119] This highlights the importance of not just having the three time levels but also of the interactions between them.

Another advantage of having three planning horizons is that it assists in dividing the planning tasks into planning modules, which are partial disaggregated plans and can be better understood and dealt with. The proposed spare parts supply chain planning matrix consists of the above mentioned three planning horizons and five supply chain processes in the form of planning tasks:

1. Production: This planning task comprises of all the decisions pertaining to manufacturing the spare parts, either within the facility or outside, through traditional methods or additive manufacturing . Parts that can be sourced from OEMs are also considered here.
2. Storage: Spare parts have to be stored in a warehousing facility that is owned/leased by the company or at a third-party warehouse. Decisions

[118] Martin et al. (2010), p. 238.
[119] Candas and Kutanoglu (2007), p. 159-176.

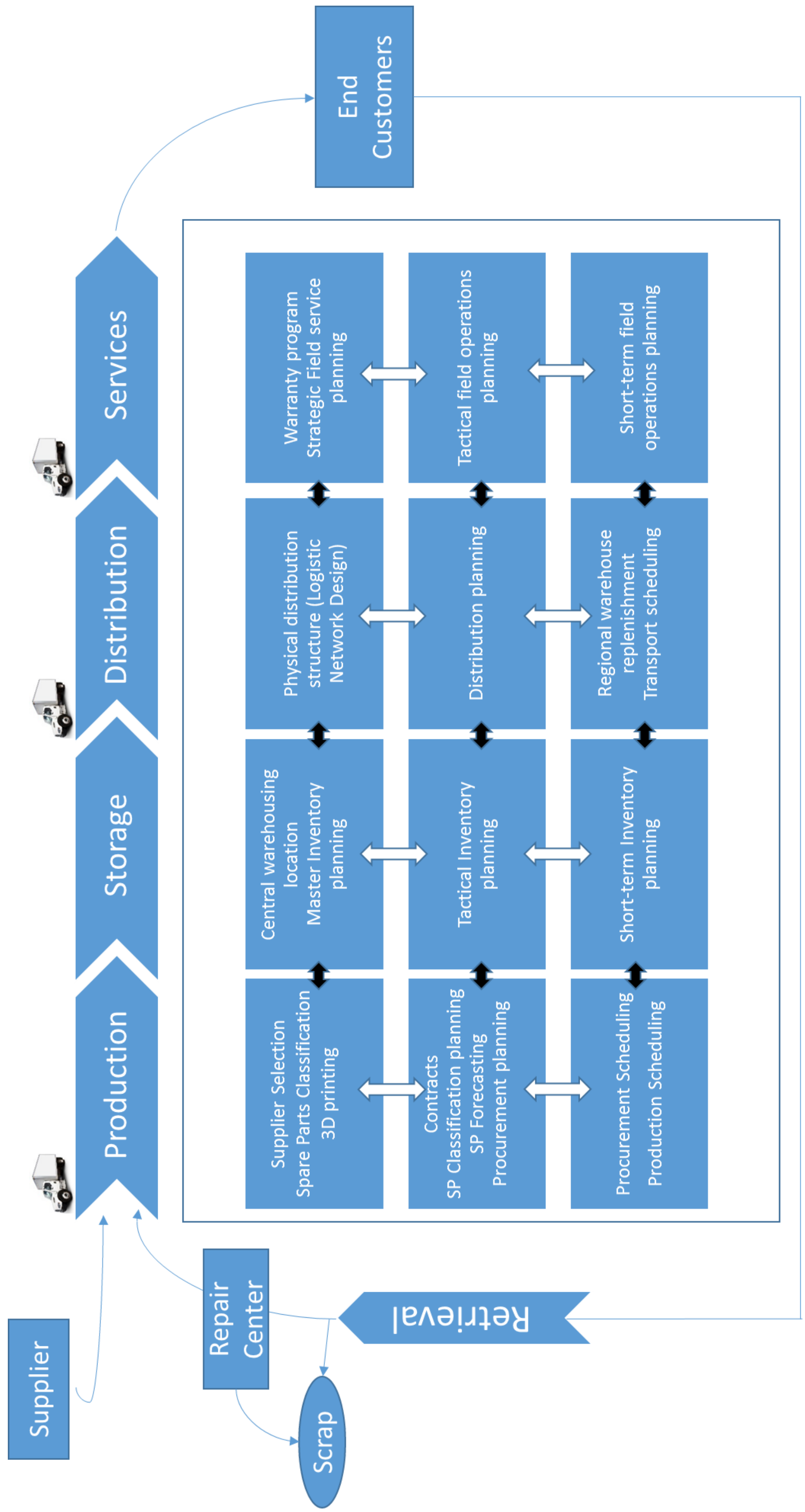

Figure 18: Spare Parts Supply Chain - an overview

regarding where to store, what warehousing policy to use, when to store etc. are taken here.

3. Distribution: This planning task focuses on the distribution structure of storage facilities. Decisions regarding regional/local warehouses, logistic network design etc. are taken here.
4. Services: Decisions on parts availability, order replenishment, customer prioritization, operational costs etc. and striking an optimal balance between these factors are taken within this planning task.
5. Retrieval/Recovery: This task concentrates on the collection of failed part from the customer and sending it to repair or scrap, based on what is economically more profitable. Parts that are successfully repaired are sent back to the supply chain through the planning task 'Production'.

4.2 Long term planning tasks

Within the long-term planning, also known as strategic planning, decisions are taken with a comparatively longer time-frame in mind. The focus of the spare parts supply chain shall be on four planning tasks – Production, Storage, Distribution and Services. Recovery will also be described, but not in as much detail. As illustrated in the figure, long term planning tasks constitute the following -

Spare part assortment definition, supplier selection and 3-D printing opportunities: Decisions whether or not to include a spare part in the assortment and hence maintain technical information of these parts are taken here. This decision primarily considers the trade-off between the operational costs of including a part on the assortment and the expected cost of downtime caused by the unavailability of the part.[120] The assortment selection is also dependent upon the warranty program to be offered by the company, substitution opportunities, price and quality of the part etc. If the parts' technical information is available, organisation can decide whether or not to

[120] Driessen et al. (2014), p. 410.

house a additive manufacturing facility (also known as 3-D printer) for reducing lead times and produce parts in case of unavailability of supplier.

It is important to make sure that at least one option for part supply is available for each part included in the assortment. For selection of supplier(s), rating procedure based on supplier characteristics like lead time, quality etc. is beneficial, especially in case of critical items. Strategic cooperation with suppliers using Vendor Managed Inventory (VMI), Every Day Low Prices (EDLP), Just-In-Time (JIT) for operational excellence and *simultaneous engineering* and *consolidation centres* as strategic cooperation decisions can be exploited.[121] As mentioned in *Section 2.1*, along with reaching out to suppliers (external or internal), 3-D printing as a possible source for certain special items to reduce dependency can be explored.

Central warehousing location and Master inventory planning: Choosing a location for a central warehouse is a strategic decision that many service organisations have to take. Spare parts can then be checked for their suitability to be stored there. It has been observed that on an average, central warehouses carry only 63% of part numbers and 57.3% of the inventory value whereas regional/local warehouses carry 16% of the part numbers and 36% of the inventory value highlighting that slow-moving parts are usually stored in the central warehouse.[122] Thus, strategic inventory positioning, that includes where the parts are to be stored, how much has to be stored and when, is a part of master inventory planning. Even though these decisions are more tactical/operational in nature, a fair idea of the which parts and how many of them helps in taking a decision on the central warehouse.

It must be noted that the decision of central warehousing location and master inventory planning is often made together with physical distribution structure decisions.

[121] Stadtler and Kilger (2005).
[122] Cohen et al. (1997), p. 631.

Physical distribution structure: With companies looking to globalize, customers are spread all around the world evolving the need to locate multiple storage centres or warehouses locally. Sometimes, it is economically better to deliver one part required by a customer from a warehouse located ‘farther’ away because of its non-availability in the ‘nearer’ one. Or in some cases, part needed is sent via an emergency shipment to the ‘nearer’ warehouse from where it can be further delivered to the customer. The decision as to how many stocking centres to have, where to have them, owned by the company or managed by third-party provider, shipment rules etc. are taken at this stage. Candas and Kutanoglu (2007) termed the strategic and long-term inventory stocking location decisions that are typically made before any detailed operational decision–making as Logistic Network Design (LND).

Warranty program and strategic field service planning: A warranty is offered by a seller as an assurance that the sold product will function satisfactorily with the customer. Based on the terms of warranty, it also ensures that in case the product fails to do so, the buyer shall address the issue and make sure that the product is repaired and sent to the customer or shall be replaced at no additional cost. This, in turn, has repercussions for the seller who has to make sure that the required spare parts and service engineers are available to address these issues. Therefore, based on the product, sales and life-cycle/usage characteristics, the seller (or the company) has to decide upon the warranty terms, service lead time, service level promised and pricing details (*Figure 19*).[123] The field service planning eventually is planned as a response to the promises that a company makes to its customers.

[123] Murthy et al. (2004), p. 115.

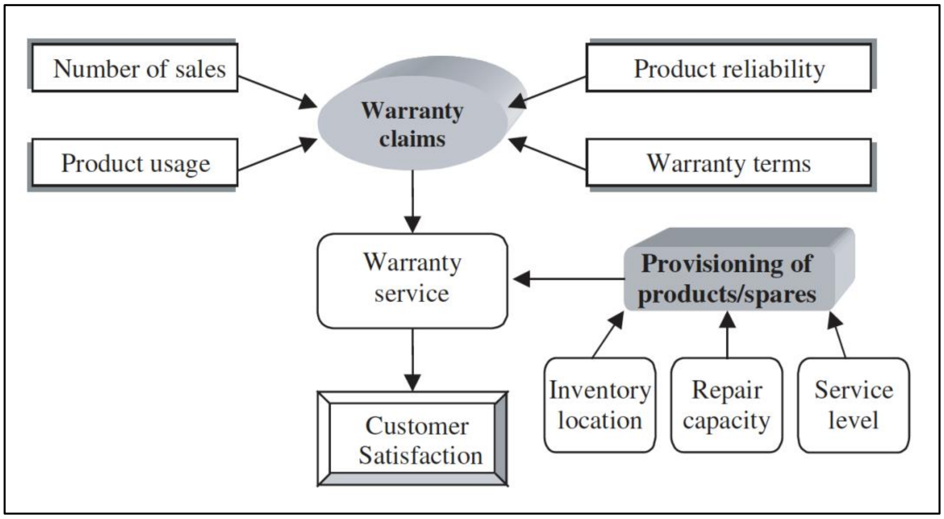

Figure 19: Warranty servicing process; adapted from Murthy et al. (2004)

Repair Centre planning: A repair shop can be an internal or an external unit where a repairable part is inspected and repaired or refurbished.[124] Capacity decision of a repair shop, materials requirement, supplier selection etc. are taken here. The load on the repair centre is automatically reduced if the product being manufactured by the company is reliable. Hence, this planning module is directly influenced by the 'Production' planning module where reliability characteristics of the product design and product support are influenced.

4.3 Mid-term planning tasks

A typical feature of a hierarchical production planning system is that decisions made at higher levels impose restrictions at lower level decisions.[125] This way, the scope is defined for the lower-levels and hence decisions can be made with specific boundaries in place. In the spare parts supply chain model, the mid-term tasks, which are planned taking into account the long-term decisions, constitute the following planning modules-

[124] Driessen et al. (2014), p. 1.
[125] Schneeweiss (2003).

Contracts decisions and procurement planning: Based on the spare parts portfolio and possible suppliers decided upon at the top-level, contracts can be made with carefully chosen A-class suppliers. Maintaining and timely updating these contracts is necessary as they might expire in case the time-period and/or the predetermined order quantity of parts is reached.[126] The forecasted requirements of spare parts can be used to specify the suggested price, total amount etc. in the contract for the parts to be delivered during the next planning horizon. The procurement lead time should also be well known for each part-supplier combination. It is also important to define alternate supply sources to ensure that in case the current supplier stops production, future resupply is maintained. In such a situation, companies can also choose to place a Last Time Buy (LTB) order.[127]

Tactical Inventory planning: The stocking policy at the central warehouse needs to be determined at this stage. As highlighted in *Sections 3.3* and *3.4*, based on the type of spare part, either continuous review or periodic review models are allotted. The inventory policy parameters can also be determined here. Based on the transportation facilities available, option to include emergency shipments to local stocking points or directly to customers are included in the calculation of stock levels so as to reduce the downtime costs for the customers. The aim is to use the available storage capacity of the central warehouse in the most cost efficient manner while not compromising on the customer demand fulfilment.

Distribution planning: This module includes setting review policies for the regional/local warehouses with consideration of central warehouse policy, planning transportation between warehouses etc. The planning is usually implemented in buckets of days, weeks or months based on the management's decision and the MRP

[126] Driessen et al. (2013), p. 15.
[127] Behfard et al. (2015).

system used. Distribution activities can either be carried out using own fleet or the required capacity can be bought from a third-party carrier.[128]

Tactical field operations planning: The production capacity, parts forecasts, number of machines with end customers and inventory planning provides a fair idea about the personnel required to handle the customer spare parts demand. This planning step also takes into account the specific know-how of personnel groups and their availability based on labour contracts.

Repair planning: Agreements on lead time for repair on each part are made here. Since, the capacity planning has already taken place in the form of a strategic decision, the tactical or mid-term planning focuses on preparing a list of parts to repair internally and/or externally, resource required per part per repair type, number of engineers and specialists to hire, number of shifts, tools to acquire. The resource capacity decisions are dependent on the work-load estimate, the repair workload variability and the estimated repair time. As explained by Driessen et al. (2014), these factors are dependent upon parts demand forecasting and parts returns forecasting. It also helps in ultimately making a buy-or-repair decision.

4.4 Short-term planning tasks

The short-term planning tasks are operational in nature and refer to the day-to-day decisions that the business has to take. After the strategic and tactical planning has been carried out, it becomes important to make sure that the real-time implementation of these plans takes place. Within the scope of spare parts supply chain, the short-term modules include the following:

Procurement and production scheduling: The decision of which source to utilize to fulfil the demand by customer for a part that is not in stock i.e. how to fulfil the latest order is taken here. Even though in the mid-term contract agreements, commitments to deliver specified quantity of parts have been made, but still the fulfilment in real-

[128] Fleischmann et al. (2010), p. 90.

time remains to be done in a cost-efficient manner. Emergency shipment decisions are also taken here. In case the part has to be produced internally, the production scheduling also needs to be done. This is usually done at the expense of the normal production process and in case the shop floor activities experience interruptions and delays, customer orders have to be rescheduled accordingly. Hence, companies are trying to reduce dependence on this method.

Warehouse replenishment and short-term inventory planning: This comprises the daily monitoring of parts, especially the A-class (continuous review) items, in the central warehouse. The decisions on how often the local stocking points have to be replenished and what quantity of which units have to be sent are also taken here. Day-to-day forecasts govern the stock levels and it is ensured that the transportation scheduling is well coordinated with the ‘production’ and ‘distribution’ planning tasks.

Regional warehouse replenishment and transport scheduling: The tactical transport planning suggests weekly/monthly transportation quantities for part families, the short-term transport scheduling formulates a plan for daily quantities for single part types, based on customer orders, short-term forecasts and at-the-moment available trucks through a cost-minimising route. Not only in distribution, but also for procurement, transport is required. This maybe controlled by supplier or the company. The regional warehouses are monitored for their stock levels that were set at the mid-term planning level and orders are placed at the central warehouse in case parts are needed.

Short term field operations planning: This directly depends upon the service level promised by the company to its customers. A field technician cannot go to the customer location without service parts, and hence availability in the local stock-point is a pre-requisite. He checks whether the part is available or not, and if not, then orders for an emergency shipment. Short term personnel planning determines the detailed schedule of the staff taking into consideration the working hours, employee agreements and labour costs.[129]

Repair-shop scheduling: Focus is on minimizing the repair time and therefore optimization of maintenance task and repair shop is carried out.[130] Repair jobs are scheduled such that their due dates are met while adhering to the resource constraints which are a consequence of the strategic and tactical decisions wherein specific resources are allotted to specific jobs for a specific amount of time so as to reduce job tardiness.[131] Batching of repair jobs is also be tried so consolidate and reduce the resource usage. Increasing the rate of repair is also tried by companies, although it can either be carried out by better product design or by better field technician scheduling. Schneeweiss and Schroeder (1992) use hierarchical modelling to plan and schedule repair shops for recoverable parts at Deutsche Lufthansa AG.

The process of designing a logistics system cannot be done in isolation without considering the various links that exist with different departments within the organisation or with other organisations that are part of the supply chain.[132] It is as relevant for spare parts supply chain as it is for a normal product supply chain. The proposed spare parts supply chain model addresses the need for collaborative planning.

4.5 Three stages of spare parts planning

A common theme that emerges out of all the tactical and operational decisions mentioned in the spare parts supply chain planning matrix is that there appears to be a need of three major information sets for the above decisions to be taken - spare parts classification, demand forecasting and inventory control mechanism. Without knowing which parts, how much and where to keep, it is impossible to take subsequent decisions on the other aspects like which transport methods to use,

[129] Fleischmann et al. (2010), p. 92.
[130] Tadj and Ouali (2011), p. 231.
[131] Driessen et al. (2014), p. 423.
[132] Huiskonen (2001), p.127.

warehouse and transport capacity, personnel planning etc. Hence, after finalising on the strategic decisions, the following 3 macro-phases have to be fulfilled in order to take well-informed tactical and operational decisions:

1. Spare parts classification
2. Spare parts demand forecasting
3. Spare parts inventory management

Hence, it can be concluded that the planning tasks are governed by the above mentioned 3 drivers.

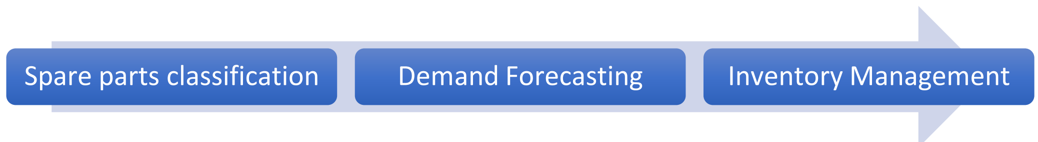

Figure 20: Spare parts management outline - Interconnected macro-phases by Bacchetti (2010)

These three drivers shall form the basis of the spare parts management methodology proposed in this thesis. A spare parts classification model is developed using AHP techniques and simulation optimization model, also referred to as Verma-Leisten model, is developed to identify stocking policies for each group formed. It must be noted that since spare part demand data from the past is used as an input to the VL model, the step 'demand forecasting' is automatically skipped. This is because the VL model, along with returning the most suitable method for the group, also returns the inventory policy parameters and therefore, the need of having a separate forecasting model for the spare parts is avoided. Therefore, the spare parts management outline can be re-depicted as follows:

Figure 21: Spare parts management outline – using simulation optimization

CHAPTER 5 –SPARE PARTS CLASSIFICATION MODEL

Classifying spare parts into groups or families is the first step towards their effective management. *Section 3.1* provided an overview of the range of work carried out in this area and also highlighted how research has either been concentrated on extremely simplistic and short-sighted methods or on case-specific methods. Only a few papers discuss the importance of developing a mechanism to classify spare parts that is independent of the industry or the case-in-hand. The need for a method, that surpasses the restrictions caused by innumerable and impractical assumptions and allows a spare parts manager to simply group parts for their easy management, is imminent. This chapter focuses on developing a multi-criteria classification model to categorize spare parts for inventory control.

5.1 AHP analysis for part criticality

The criticality of an item has been considered as an extremely important factor to specifying service levels, especially in the case of spare parts inventory systems.[133] As per the spare parts classification literature review, part criticality has been used as a classifying factor in 13 of the 29 papers analysed, either as a standalone factor or as a cumulative factor. In the proposed method, Analytic Hierarchy Process (AHP) is used to score and classify each spare part under analysis into three groups of part criticality - vital, essential and desirable. Also known as VED analysis, classifying parts into these three distinct groups from the point of view of their functional necessity, price, downtime costs etc. helps in ultimately setting a high target service level for vital parts, a comparatively lower target service level for essential parts and not a strict one for desirable parts. Therefore, vital parts could include items which, if unavailable, can result in losses for the company whereas unavailability of essential parts could result in moderate losses. For example, when a 'essential' spare part is not available, the machine can still run but not with full functionality. Desirable parts

[133] Gopalakrishnan and Banerji (1991).

could be those that cause minor disruptions or are only required for the appearance of the machine and therefore, lower target service levels can be set for such parts.

5.1.1 Criteria for part criticality

The interesting aspect of VED analysis is that it can be defined directly by an organisation. This essentially means that organisation can define what the terms – vital, essential and desirable mean to them. For example, for some organisations, importance of a set of spare parts is so high that their unavailability might result in serious losses that might reach to the point of shutting down the company itself and therefore, such parts are grouped under 'vital' and their service level is set to 100%. Therefore, AHP for VED analysis provides that flexibility of defining what the meanings, cut-off values and service levels for the vital, essential and desirable part groups.

For defining the part criticality, the following three criteria:

1. Consequence of failure: It is defined as the importance of a part in the full functionality of a machine, which implies that the unavailability of a part with a high consequence of failure can result in non-operation of the machine and therefore either its partial or full breakdown.
2. Unit cost: This refers to the cost of one unit of a spare part. The cost is an indication of the value of a part and is often used in the industry to calculate the inventory holding cost for the spare part.
3. Replenishment lead time: This is the time period required by the spare part manufacturer (either OEM or in-house) to deliver the ordered parts. Normally, the replenishment lead time is pre-defined in supplier contracts although due to unforeseen circumstances, delivery can be delayed. In this case, lead times are assumed to be deterministic.

As illustrated in *Figure 7,* AHP is a hierarchical process that is utilized here for VED analysis using Saaty's procedure to carry out absolute measurement of priorities. The level 1 objective is 'VED Analysis', the level 3 criteria are consequence of failure, unit cost and replenishment lead time. The alternatives at level 3 need to be defined now.

5.1.2 Alternatives for criteria

Each criteria is accompanied by a number of alternatives. The alternatives help in categorizing the criteria into different levels and therefore assist in overall scoring and segregation of spare parts. The definition of alternatives is again, case dependent. Each spare part manager has the freedom to discuss and decide which alternatives to allot to the criteria. As an example, the following alternatives are defined for the three chosen criteria for VED analysis using AHP:

1. Consequence of failure:

a) Failure of the part causes serious consequences

b) Failure of the part can result in near future downtime

c) No consequences affecting the machine

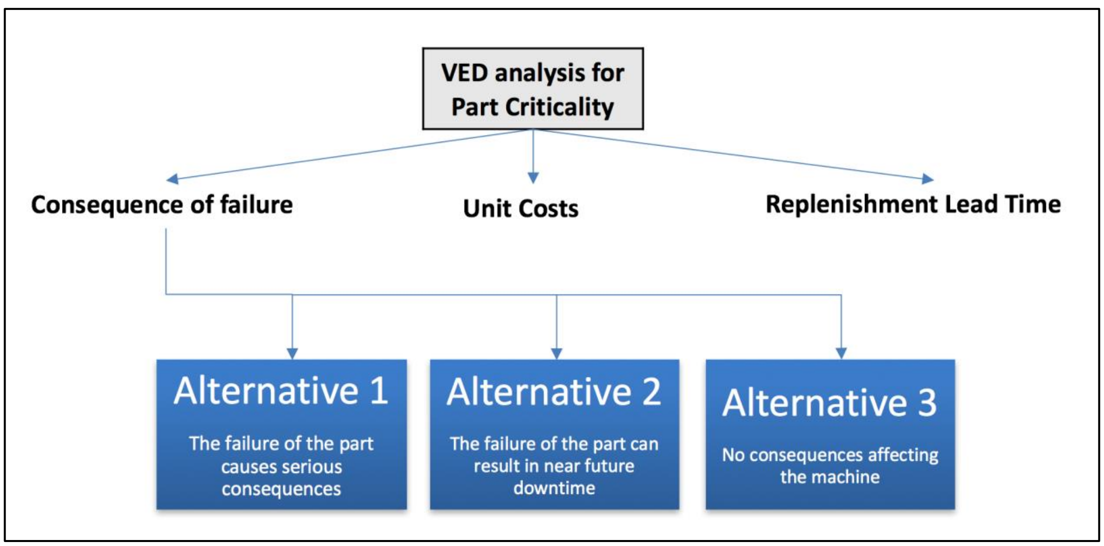

Figure 22: Alternatives for criteria - Consequence of failure

2. Unit Cost:

a) Item value > 15000 Euros

b) Item value between 2000 Euros – 15000 Euros

c) Item value < 2000 Euros

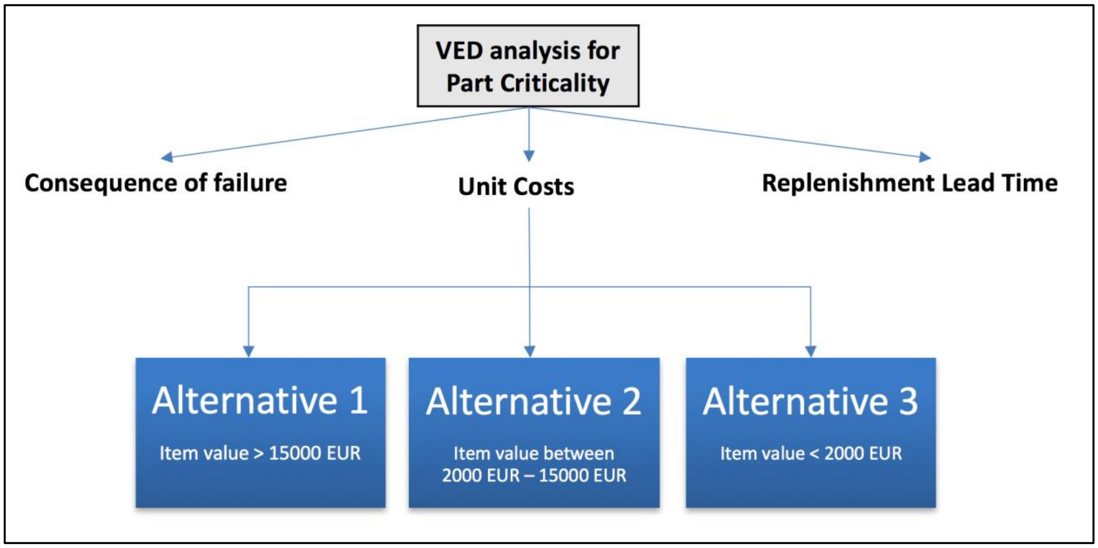

Figure 23: Alternatives for criteria - Unit Costs

3. Replenishment lead time:

a) Lead time > 2 weeks

b) Lead time between 4 days and 2 weeks

c) Lead time < 2 weeks

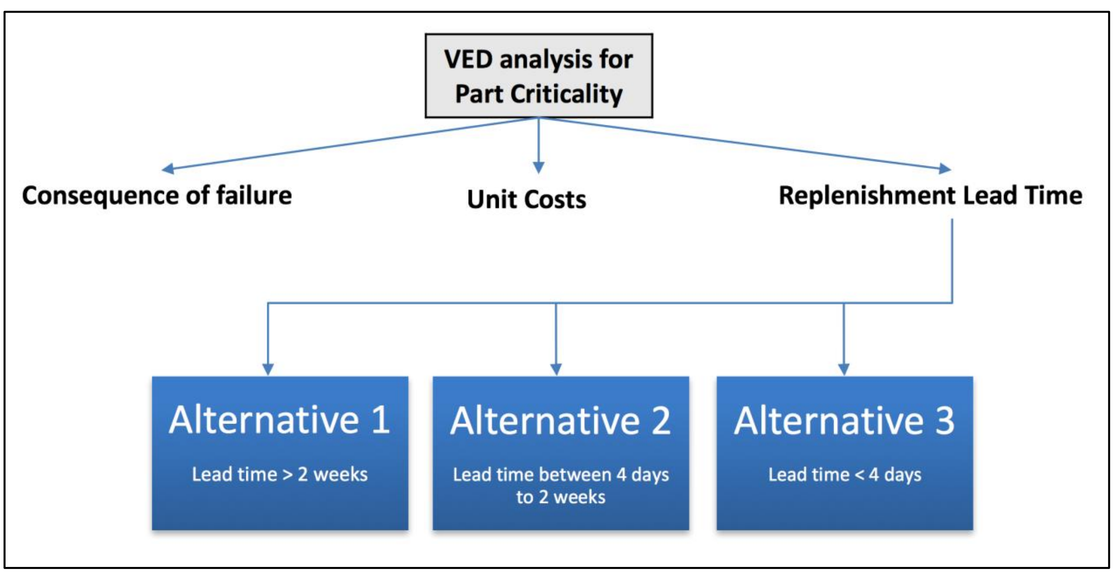

Figure 24: Alternatives for criteria - Replenishment lead time

Before proceeding towards scoring each spare part based on the three criteria, judgement matrices are created. These are essentially comparisons of criteria and alternatives against each other so as to assign a compound weightage, and hence a score, to each alternative. The procedure to create the judgement matrix as explained by Gajpal et al. (1994) is followed. As a first step, pairwise comparison of criteria (Level 2) is carried out with reference to the overall objective, which is this case is VED analysis. This results in a reciprocal symmetric matrix similar to *Table 3*.

Criteria comparison	**C1**	**C2**	**C3**	**Normalized Eigenvector**
Consequence of failure (C1)	1	2	4	**0.571**
Unit costs (C2)	1/2	1	2	**0.286**
Replenishment lead time (C3)	1/4	1/2	1	**0.143**

Table 3: Reciprocal Symmetric Judgement Matrix for Level 2 – An example

The normalized principal eigenvector of the above matrix is calculated by summing up the values in each row and then dividing it by the overall total. As the next step, pairwise comparison matrix for level 3 corresponding to criteria is calculated and normalized eigenvector is again computed for each of these matrices. The judgement matrix hence computed is depicted in *Table 4*.

Alternatives comparison	**A1**	**A2**	**A3**	**Normalized Eigenvector**
Consequence of failure (C1)				
A1	1	3	4	**0.611**
A2	1/3	1	2	**0.255**
A3	1/4	½	1	**0.134**
Unit Costs (C2)				
A1	1	2	4	**0.535**

A2	1/2	1	3	**0.344**
A3	1/4	1/3	1	**0.121**
Replenishment lead time (C3)				
A1	1	2	3	**0.493**
A2	1/2	1	3	**0.370**
A3	1/4	1/3	1	**0.137**

Table 4: Judgement matrix for Level 3 - An example

Before advancing towards the next steps, it must be clarified that the ratings or scores in the above two judgement matrices are for depiction purposes only. Spare parts managers can assign their own rating based on their judgement, experience and parts portfolio. Although, the methodology and steps to follow stay the same, the values will vary based on the case. After calculating the normalized eigenvector for each level, the composite priorities or weights are calculated for each criteria-mode combination to result in the absolute measurement of the criticality of a spare part.[134]

Criteria	**Level 2 priorities**	**Alternatives' priorities**			**Composite weights**		
		A1	*A2*	*A3*	*A1*	*A2*	*A3*
C1	0.571	0.611	0.255	0.134	**0.3489**	**0.1456**	**0.0765**
C2	0.286	0.535	0.344	0.121	**0.1530**	**0.0984**	**0.0346**
C3	0.143	0.493	0.370	0.137	**0.0705**	**0.0529**	**0.0196**

Table 5: Composite weights for criterion-mode combination; adapted from Gajpal et al. (1994)

Each spare part goes through an extensive discussion on all the three criteria and one of the alternatives for each criteria is chosen for a spare part. The composite weights derived in the above table are ultimately used to calculate the criticality of a spare part. An illustration is provided in *Section 5.3*.

[134] Gajpal et al. (1994), p. 295.

5.2 Demand pattern analysis

The proposed model not only utilizes the part criticality to classify spare parts but it also considers spare part demand pattern to ultimately result in 12 different groups. Demand pattern has an important role to play when it comes to finalizing the inventory policies for spare parts. As discussed in *Sections 3.1* and *3.2*, there have been various attempts to connect demand pattern with forecasting method or warehousing and inventory policies. The most commonly used matrix was developed by Syntetos et al. (2005) where they classified spare parts into four distinct demand pattern categories – smooth, erratic, intermittent and lumpy. The categorization is based on two factors:

1. Demand size variability (CV^2): Calculated as the squared coefficient of variation, demand size variability indicates how spread out the demand sizes are. The standard deviation of all the demand sizes is divided by their mean to result in the coefficient of variation.
2. Average Demand Interval (*ADI*): This denotes the average time gap between any two consecutive demand instances.

For the proposed classification methodology, the demand pattern classification by Syntetos et al. (2005) is used. The break-points for CV^2 and *ADI* is 0.49 and 1.34

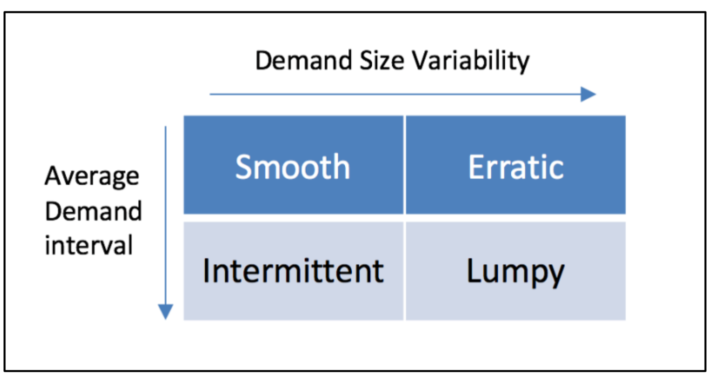

Figure 25: Demand pattern classification as proposed by Syntetos et al. (2005)

respectively.

5.3 Proposed classification model

The classification model proposed in this work utilizes both – AHP for VED analysis and demand pattern analysis, to classify spare parts into 12 distinct groups. While the demand pattern occupies the *xy* plane, VED is plotted on the *z*-axis. Therefore, the *x*-axis corresponds to the demand size variability (CV^2), *y*-axis to Average Demand Interval (*ADI*) and *z*-axis to part criticality.

As a first step, each spare part is made to go through the process of part criticality analysis. Here, an expert group has to responsibility of scoring each spare part based on the 3 criteria defined for AHP by choosing the alternatives corresponding to each criterion. As an example, for spare part SP1, if the expert group observes that corresponding to consequence of failure (*C1*), the second alternative – failure of the part can result in near future downtime, matches to the spare part the most, then the composite weight for this criterion-alternative is allotted to SP1. Hence, the first score for SP1 is 0.1456 (See *Table 5*). Similarly, the expert group allots alternative 3 to the criterion unit costs and alternative 1 to criterion replenishment lead time resulting in two more composite weights – 0.0346 and 0.0705. Therefore, the total score for SP1 is the sum of the composite weights of the three chosen alternative-criterion combination, which is 0.1456 + 0.0346 + 0.0705, which equals 0.2507.

Criteria	Alternative	Weight
Consequence of failure (C1)	A1	0.1456
Unit costs (C2)	A3	0.0346
Replenishment lead time (C3)	A1	0.0705
Total		**0.2507**

Table 6: Criticality score evaluation for SP1 - An example

Similarly, the entire spare parts portfolio is analysed and scored. Based on the final scores, cut-off values are decided for VED. Therefore, this methodology provides the freedom and flexibility to the manager/expert group to decide, based on the spare parts portfolio and strategic priorities, what is meant by vital, essential and desirable. After deciding the cut-off values, the spare parts are segregated into these three categories. Target service levels can now be defined for them. As an example, the target service level for the vital spare parts is set at 95%, whereas for essential and desirable at 80% and 65% respectively.

The *xy*-plane, as mentioned earlier, can be formed using the demand data for each spare part in the past. With sufficient past data, CV^2 can be easily calculated as the square of standard deviation divided by the mean of demand sizes. Similarly, average demand interval can also be calculated by finding out the mean of time between consecutive demand instances. The cut-off values used are 0.49 for CV^2 and 1.32 for *ADI* forming 4 classes – smooth, erratic, intermittent and lumpy. Hence, the entire spare parts portfolio is divided into 4 by 3, that is, 12 groups. The following figure depicts how the grouping can look like:

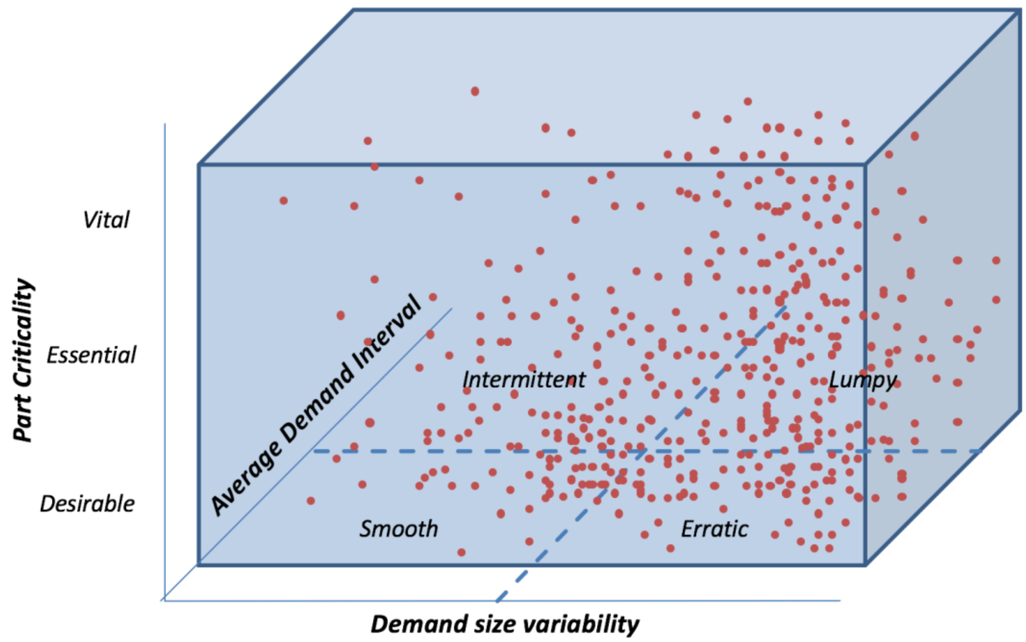

Figure 26: Proposed classification methodology

For clarity purposes, the differentiation markings between vital, essential and desirable have not been drawn on the figure. Please note that the red dots denote individual spare part type, therefore, the spare parts spread is bound to vary from case to case and Figure 26 is just an example.

The 12 groups formed are as follows:

1. Lumpy-Vital: Parts in this group observe lumpy demand and at the same time are vital to the organisation. While availability of these parts has to be made sure at all times, these are one of the most difficult to manage groups.

2. Lumpy-Essential: Spare parts in this group also observe lumpy demand but fall under the ‘essential’ category of part criticality. Although difficult to manage, availability requirement of these parts are not too strict.

3. Lumpy-Desirable: These parts with lumpy demand pattern and not critical to the organisation, hence, their availability is not strictly required at all times.

4. Intermittent-Vital: Parts in this group observe intermittent demand, therefore, demand sizes are relatively easy to predict but the timing of demand instances is difficult to forecast. Intermittent demand also includes the 0-1 demand pattern which is one of the most prevalent demand type for high value spare parts. Along with being intermittent, parts in this group are very critical, which means that high availability needs to be ensured.

5. Intermittent-Essential: There are parts with intermittent demand nature but with medium criticality. Therefore, very strict service levels need not be imposed on parts belonging to this group.

6. Intermittent-Desirable: These are also parts observing intermittent demand pattern although they're not critical to the organisation. Hence, their availability can be compromised.

7. Erratic-Vital: The spare parts in this group observe varied demand sizes although demand occurs at regular intervals. At the same time, these are vital parts and hence, high service levels are ensured for such parts.

8. Erratic-Essential: Although erratic in demand pattern, these parts have medium criticality level and therefore, very strict service levels are not made compulsory for this group.

9. Erratic-Desirable: This group constitutes parts observing erratic demand but not vital to the organisation.

10. Smooth-Vital: Spare parts falling in this category observe smooth demand and therefore demand sizes and instances are comparatively easier to predict. But

these are parts with high criticality level and hence, a high target service level is imposed on this group.

11. Smooth-Essential: This group with parts observing smooth demand and medium criticality are easier to manage as compared to the above 10 groups.

12. Smooth-Desirable: Parts falling in this group have smooth demand pattern and not critical to the organisation. This group is the easiest to manage amongst all.

Once the spare parts have been categorized into these groups, the simulation optimization model can be run.

CHAPTER 6 - SIMULATION OPTIMIZATION MODEL

The main purpose of the simulation optimization model is to determine which inventory policy results in achieving the desired service level at minimum costs for the spare part. At the same time, the model also helps in collecting information concerning average downtime, percentage of shortage occurrence, min/max inventory levels. The model also helps in carrying out sensitivity analysis of the results with respect to inventory levels, holding costs, demand etc.

Three types of costs for the considered for the model:

1. Unit cost: The unit cost of a spare parts is calculated as Euros per unit. For this model, it is the cost paid by the company to a supplier or OEM to buy the particular spare part. In this model, quantity discounts are not considered, hence, total unit cost is a linear function of the number of units bought. Inclusion of unit costs is important since the total acquisition costs per year and the cost of carrying the inventory depends upon it.[135]
2. Inventory Cost: The cost incurred by the company for carrying parts in inventory are termed as inventory costs. It includes opportunity cost of the money invested, expenses incurred in running the warehouse, counting and handling costs, costs for special storage requirements, stock obsolescence, damage, theft, insurance, taxes etc.[136] Inventory costs are usually calculated as a percentage of annual average inventory value.
3. Order cost: This is a fixed cost incurred by the company every time it has to place a replenishment order with the supplier/OEM. It includes administrative costs that includes costs for telephone calls, order forms, postage, authorization and employee wages.

Backorder costs are costs incurred when there is no more stock of the part demanded by a customer. These include emergency shipment costs or costs of substituting the

[135] Silver et al. (1998), p. 44.
[136] Silver et al. (1998), p. 45.

demand. Whereas downtime costs are costs incurred by the customer for every unit of time their machine is in a non-working state (because of a failed spare part). In the current case, backorder and downtime costs are not considered explicitly. Instead, backorder costs are taken care of by ensuring that at any point in time if a backorder occurs, the entire order is considered as a missed order, even though the backorder might be of a single unit. Similarly, downtime costs are handled by the classification model by setting the part criticality to 'vital' and hence ensuring a high target service level for them.

In this model, Service level is measured as the percentage of customer order requests that are filled immediately from the inventory on the shelf. In case of a multi-echelon system, the option of fulfilling the order faced by a local warehouse via an emergency shipment from a remote central warehouse is also available. Although, in this case, only a central warehouse is considered. The service level used in this model is also termed in literature as *Fill rate*.[137]

6.1 Model assumptions

The following assumptions are considered while building the simulation optimizations model:

1. The model is being built from the perspective of a company that receives orders for replenishment of spare parts from its customers directly. The company owns a central warehouse to store the spare parts inventory and receives replenishments from various OEMs and its own manufacturing facility.
2. For each time period, the company receives customer orders cumulated across all customers for a spare part, so as to not differentiate between customers.
3. Replenishment lead times are deterministic and already known for each spare part.

[137] Cohen et al. (1997), p. 633.

4. Unit cost for each spare part (the cost that the company pays to the supplier (OEM) to buy each unit of that spare part) is deterministic and is known by the company.
5. A replenishment order with order quantity of either Q or S-Inventory position or 1 (based on the inventory model used) is received at time t = 0.
6. Holding costs are calculated as a percentage of the unit costs. Hence, a higher price of a spare part implies a higher holding cost.
7. A replenishment order is generated based on the inventory position at the end of time t. This results in a replenishment order received by the company at time t plus the deterministic replenishment lead time for the part ordered.
8. Replenishment orders due at time t are received at the start of time period t.
9. A customer order, if applicable, is received by the company at the start of time period t.
10. The customer order is satisfied using the items in inventory including any replenishment orders that are received at time t.
11. Any customer order that is not completely satisfied is considered as a missed order, resulting in a backorder. The units of parts available in the inventory are sent to the customer whereas the shortage is recorded and fulfilled at the earliest opportunity available.
12. Only the customer orders fulfilled and missed contribute to the service level calculation. Periods of no customer order are not considered as order fulfilled/missed and hence do not contribute to the calculation of service level.

6.2 Input and output parameter definition

The following indexes, parameters and variables are used for the formulation of the simulation optimization model:

G	*The number of spare part groups*
g	*1,2,.....,G index for the spare part group*

N_g	*Total number of spare parts in group g*
i	*1,2,……, N_g index for the spare part*
T	*Total number of time periods*
t	*1,2,…….., T index for the time period*
IM_{max}	*Total number for inventory policies*
y	*1,2,……., $\mathrm{IM}_{\mathrm{max}}$ index for inventory policy*
x_{it}^{g}	*Customer demand for spare part i belonging to group g at time t*
LT_i^g	*Replenishment lead time for spare part i belonging to group g*
UC_i^g	*Unit cost of spare part i belonging to group g*
h	*Percentage factor (of unit cost) calculated as holding cost per unit per time period*
OC	*Ordering cost incurred so as to place a replenishment order*
s_i^{gy}	*Reorder point for spare part i belonging to group g for inventory policy y*
Q_i^{gy}	*Order Quantity for spare part i belonging to group g for inventory policy y*
S_i^{gy}	*Order upto level for spare part i belonging to group g for inventory policy y*
Tm_i^{gy}	*Time period between inventory position review of i belonging to group g for inventory policy y*
OP_i^{gy}	*Counter variable for outstanding replenishment orders placed by the company for spare part i belonging to group g for inventory policy y*
OR_{it}^{gy}	*Binary variable denoting whether a replenishment order has been received by company for spare part i at time t belonging to group g for inventory policy y*
OQR_{it}^{gy}	*Order quantity received by the company for spare part i at time t belonging to group g for inventory policy y*
OQ_{it}^{gy}	*Number of units of spare part i received at time t . This variable has been used in models where lot-size is not defined and hence is dependent upon S_i^{gy} or s_i^{gy}. Therefore, this variable has to be recalculated for every time period t .*
Q	*Number of units in pipeline. This variable has been used in models with varying lot-sizes for each time-period.*
BO_i^{gy}	*Cumulative back ordered quantity for spare part i belonging to group g for inventory policy y*
IP_{it}^{gy}	*Inventory position (inventory on-hand + outstanding orders – backorders) for spare part i at time t belonging to group g for inventory policy y*
OIP_{it}^{gy}	*On hand inventory at the start of time period t for spare part i belonging to group g post receival of any orders (if applicable) in that time period for inventory policy y*

EIP_{it}^{gy}	*On hand inventory at the end of time period t for spare part i belonging to group g post delivery of customer demand (x_{it}^{g}) in that time period for inventory policy y*
OF_{i}^{gy}	*Counter variable for customer orders fulfilled for spare part i at time t belonging to group g for inventory policy y*
OM_{i}^{gy}	*Counter variable for customer orders missed for spare part i at time t belonging to group g for inventory policy y*
HC_{it}^{gy}	*Holding cos for spare part i at time t belonging to group g for inventory policy y*
THC_{i}^{gy}	*Sum of holding cost over all time periods (0 to T) for spare part i belonging to group g for inventory policy y*
TUC_{i}^{gy}	*Total unit costs of orders placed by company all time periods (0 to T) for spare part i belonging to group g for inventory policy y*
TOC_{i}^{gy}	*Total ordering costs for orders placed by company all time periods (0 to T) for spare part i belonging to group g for inventory policy y*
TOP_{i}^{gy}	*Total order placed by the customer demanding spare part i belonging to group g for inventory policy y*
SL_{i}^{gy}	*Service level for spare part i belonging to group g for inventory policy y*
TC_{i}^{gy}	*Total cost for spare part i belonging to group g for inventory policy y*
TSL^{g}	*Target service level for group* g
TGC^{g}	*Sum of the minimum total cost of all spare parts within group g*

6.3 Simulation model

The simulation model makes sure that each spare part goes through all the defined combinations of inventory model parameters (reorder point s and order quantity Q in the case of an *(s,Q)* inventory policy) so as to result in the best solution – one that provides the desired service level for the group to which the spare part belongs and at the same time pushes the total cost (ordering cost + inventory handling cost + unit cost) to the minimum. As a result, it can be possible that the resulting service level achieved is actually higher than the defined target service level since a higher service level might be possible by incurring the same costs that are incurred at a lower service level.

The Simulation model was programmed on MATLAB version 9.0.

For $y = 1$, an *(s, Q)* inventory policy is defined. An *(s, Q)* model is a continuous review model … The following model is executed for each spare part i = 1 to N_g from time t = 1 to T .

$$OQR_{it}^{gy} = \begin{cases} Q_i^{gy}, \ if \ OR_{it}^{gy} = 1 \\ 0, \ otherwise \end{cases}$$

The variable OQR_{it}^{gy} converts the orders received into order quantity received and makes sure that if an order is received in time period t, Q units of spare part *i* is recorded in this time period.

$$OIP_{it}^{gy} = \begin{cases} Q_i^{gy}, \ if \ t = 1 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy} + BO_i^{gy}, \ if \ t \neq 1 \ and \ BO_{it}^{gy} < 0 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy}, \ otherwise \end{cases}$$

The opening inventory position variable OIP_{it}^{gy} denotes the actual number of units of spare part *i* at the start of time period *t*. As stated in the assumption, Q units are received when *t* is 1. In other cases, the opening inventory position is calculated as the sum of the previous time period's ending inventory position, order quantity received at *t*, if any, and back ordered quantity. This means that if there are any backorders, they are addressed as a priority, before the demand in t is faced and processed. This adheres to the assumption in *Section 6.1* where it is stated that backorders are to be fulfilled at the earliest opportunity available.

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} - x_{it}^{g}, & if \ \ OIP_{it}^{gy} \geq x_{it}^{g} \ and \ x_{it}^{g} > 0 \\ 0, & if \ \ OIP_{it}^{gy} < x_{it}^{g} \ and \ x_{it}^{g} > 0 \\ OIP_{it}^{gy}, & if \ x_{it}^{g} = 0 \end{cases}$$

The ending inventory position EIP_{it}^{gy} is the actual number of units of spare part *i* at the end of time period *t*. A demand instance in time period *t* is fulfilled using the opening inventory and the remaining results in the ending inventory but in case the inventory on-hand is unable to satisfy the demand, the ending inventory position is recorded as 0 and backorder arises. In case of no demand in a particular time period, the ending inventory stays the same as the opening inventory.

$$OF_i^{gy} = \begin{cases} OF_i^{gy} + 1, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g} and\ x_{it}^{g} > 0 \\ OF_i^{gy} \qquad otherwise \end{cases}$$

$$OM_i^{gy} = \begin{cases} OM_i^{gy} + 1, \quad if \ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ OM_i^{gy} \qquad otherwise \end{cases}$$

Order finished and order missed are counter variables that record the total number of customer demand orders fulfilled/missed out of the total orders placed. Since it is assumed that the company receives orders cumulated for all the customers for the spare part *i* at time period *t*, order finished actually record the time periods when the customer demand was completely satisfied and order missed records the time periods when the company was short of even 1 spare part to fulfill the demand in that time period.

$$IP_{it}^{gy} = \begin{cases} Q_i^{gy},\ if\ t = 1 \\ EIP_{it}^{gy} \ + \ OP_i^{gy} * Q_i^{gy} + \ BO_i^{gy}, otherwise \end{cases}$$

The inventory position is the sum of on-hand inventory at the end of time period *t*, the pipeline inventory due to outstanding orders minus the backorders. When time *t* is 1, The inventory position is assumed to be equal to lot-size is case of an *(s,Q)* inventory policy.

$$OP_i^{gy} = \begin{cases} OP_i^{gy} + 1\ , if\ \ OIP_{it}^{gy} > x_{it}^{g}\ and\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ OP_i^{gy} + 1\ ,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ OP_i^{gy} - 1, if\ OR_{it}^{gy} = 1 \\ OP_i^{gy}, otherwise \end{cases}$$

The variable OP_i^{gy} counts the orders placed by the company for the replenishment of spare part *i* that have not yet been received by the company. The order placed variable is decreased by one in case an order is received, therefore keeping a count of the outstanding orders. An order is placed in case the inventory position drops below the specified reorder point s_i^{gy}. And an order is also immediately placed in case an order is missed due to shortage of inventory.

$$BO_i^{gy} = \begin{cases} 0\,, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g}\ and\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ OIP_{it}^{gy} - x_{it}^{g}\ ,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ BO_i^{gy}, otherwise \end{cases}$$

Backorder quantity denotes the number of units of short when an order is missed. Whenever the opening inventory level is less that the incoming customer order, the inventory level drops down to zero and whatever quantity that remains unfulfilled is recorded as backorder.

$$OR_{i\,t+LT_i^g}^{gy} = \begin{cases} 1\,, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g}\ and\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ 1\,,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ 0\,, otherwise \end{cases}$$

Order received $OR_{i+LT_i^g}^{gy}$ is a binary variable that records an order being received at current time *t* plus the replenishment lead time LT_i. Whenever the value of this variable is 1, order quantity equal to the lot-size is added to the inventory to raise the opening inventory position for that time period.

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1\,, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g}\ and\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} \leq s \\ TOP_i^{gy} + 1\,,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ TOP_i^{gy}\ , otherwise \end{cases}$$

The variable TOP_i^{gy} counts the total number of replenishment orders placed by the company for spare part *i* across all time periods from 1 to *T*.

$$HC_{it}^{gy} = h * UC_i^{g} *\ EIP_{it}^{gy}, if\ EIP_{it}^{gy} \geq 0$$

The holding cost is the cost of holding the inventory of spare parts. It is calculated in each time period whenever the ending inventory position is greater than zero using the percentage factor *h* and the unit cost of the spare part *i*.

For $y = 2$, a *(T, Q)* inventory policy is defined. The following model is executed for each spare part i = 1 to N_g from time t = 1 to T .

$$OQR_{it}^{gy} = \begin{cases} Q_i^{gy}, \; if \; OR_{it}^{gy} = 1 \\ 0, \; otherwise \end{cases}$$

Similar to the first inventory model, in the case of *(T, Q)* inventory policy, the variable OQR_{it}^{gy} assists in converting the received order signal to order quantity Q_i^{gy} in time t.

$$OIP_{it}^{gy} = \begin{cases} Q_i^{gy}, \; if \; t = 1 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy} + BO_i^{gy}, \; if \; t \neq 1 \; and \; BO_{it}^{gy} < 0 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy}, \; otherwise \end{cases}$$

The variable OIP_{it}^{gy} calculated the inventory position at the start of time period t for spare part i. As per the assumptions, at the start of the simulation period, i.e. when $t = 1$, Q units of spare part i are received. In the following time periods the opening inventory position is calculated by adding the ending inventory position of the previous time period and the order quantity received, if any, at the start of the current time period. In case of a backorder, an additional variable BO_i^{gy} denoting the backordered units in the last time period is subtracted from the opening inventory position. This reinstates the assumption that backorders are addressed as soon as possible, before the demand in time t is processed.

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} - x_{it}^{g}, & if \;\; OIP_{it}^{gy} \geq x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ 0, & if \;\; OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ OIP_{it}^{gy}, & if \; x_{it}^{g} = 0 \end{cases}$$

The ending inventory position variable EIP_{it}^{gy} calculates the actual number of units of spare part i at the end of time period t. Whenever the opening inventory position is sufficient to address the incoming customer order, the value of EIP_{it}^{gy} is updated to opening inventory position minus the demand size. Whereas, if the opening inventory position is less than the incoming customer demand, then the EIP_{it}^{gy} is automatically updated to 0. The EIP_{it}^{gy} helps in determining the inventory holding cost at the end of each time period t.

$$OF_i^{gy} = \begin{cases} OF_i^{gy} + 1, & if \quad OIP_{it}^{gy} \geq x_{it}^{g} and\ x_{it}^{g} > 0 \\ OF_i^{gy} & otherwise \end{cases}$$

$$OM_i^{gy} = \begin{cases} OM_i^{gy} + 1, & if \ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ OM_i^{gy} & otherwise \end{cases}$$

The order finished and order missed are variables that keep a count of the number of customer orders successfully finished and number of orders missed during the simulation period out of the total customer demand orders placed. As emphasized earlier, if on-hand inventory is short even by one unit, the order is considered unfulfilled and the entire stock of the demanded spare part if sent to the customer.

$$IP_{it}^{gy} = \begin{cases} Q_i^{gy},\ if\ t = 1 \\ EIP_{it}^{gy} \ +\ OP_i^{gy} * Q_i^{gy} +\ BO_i^{gy}, otherwise \end{cases}$$

The inventory position of spare parts i at time t is calculated as the sum of on-hand inventory at the end of time period t and the pipeline inventory due to the outstanding orders (calculated by multiplying the outstanding orders OP_i^{gy} by the order quantity Q_i^{gy}) and subtracting the backorder BO_i^{gy}. Please note that the variable BO_i^{gy} takes negative value whenever there is a backorder, hence it is added in the equation. In case of the *(T,Q)* inventory model, it is assumed that the inventory position at time t = 1 is equal to the lot size Q_i^{gy}.

$$OP_i^{gy} = \begin{cases} OP_i^{gy} + 1,\ if\ t = n * Tm_i^{gy} \\ OP_i^{gy} - 1\ ,\ if\ OR_{it}^{gy} = 1 \\ OP_i^{gy}, otherwise \end{cases}$$

OP_i^{gy} is a counter variable that keeps a track of the outstanding orders placed for replenishment of spare part i till the current time t since the start of the simulation period. In this case, a replenishment order is placed after every $* Tm_i^{gy}$ units of time and the variable OP_i^{gy} increases by one unit whereas whenever a replenishment order is received by the company, the variable OP_i^{gy} decreases by one unit.

$$BO_i^{gy} = \begin{cases} 0\,, & if \;\; t = n * Tm_i^{gy} \\ OIP_{it}^{gy} - x_{it}^{g} \;, & if \;\; OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ BO_i^{gy}, & otherwise \end{cases}$$

The backorder quantity BO_i^{gy} keeps a track of the number of units of spare part i that is falling short for a successful and complete customer order. When an incoming customer order size for spare part i is more than what the inventory holds, a backorder equal to the number of units short is registered in the system and it is made sure that it is addressed as a priority in the next time periods.

$$OR_{i\,t+LT_i^g}^{gy} = \begin{cases} 1, & if \; t = n * Tm_i^{gy} \\ 0, & otherwise \end{cases}$$

The variable $OR_{i\,t+LT_i^g}^{gy}$ records a replenishment order that is received for spare part i at time t after the stipulated lead time LT_i. It is a binary variable and in the case of *(T,Q)* inventory model, it takes the value 1 after every Tm_i^{gy} units of time.

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1, & if \; t = n * Tm_i^{gy} \\ TOP_i^{gy}, & otherwise \end{cases}$$

The counter variable TOP_i^{gy} increases by one every time an order is placed. Hence, by the end of the simulation period, it returns the total number of replenishment orders placed by the company for spare part i .

$$HC_{it}^{gy} = h * UC_i^{g} * \; EIP_{it}^{gy}, if \; EIP_{it}^{gy} \geq 0$$

Similar to the first case, the holding cost calculates the total cost of holding spare part i throughout the simulation period.

For $y = 3$, a *(T, s, S)* inventory policy is defined. As explained earlier, *(T, s, S)* is a combination of continuous and periodic review policies. The following model is executed for each spare part i = 1 to N_g from time t = 1 to T .

$$OQR_{it}^{gy} = \begin{cases} OQ_{it}^{gy},\ if\ OR_{it}^{gy} = 1 \\ 0,\ otherwise \end{cases}$$

Similar to the first two inventory models, the order quantity received variable OQR_{it}^{gy} converts any order received for spare part i at time t into the number of units in the order which, in this case, is can be varying based on the inventory on-hand, order-upto level and re-order point. The quantity received is governed by the variable $OQ_{i\,t+LT_i^g}^{gy}$.

$$OQ_{i\,t+LT_i^g}^{gy} = \begin{cases} S_i^{gy} - EIP_{it}^{gy}, if\ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ 0, otherwise \end{cases}$$

The variable $OQ_{i\,t+LT_i^g}^{gy}$ calculates the exact size of replenishment order that will be placed at time t and delivered to the company by the OEM at time $t + LT_i^g$. An order is placed after every Tm_i^{gy} units of time only when the inventory position is less than or equal to the re-order point s_i^{gy}.

$$Q = \begin{cases} Q - OQ_{it}^{gy},\ if\ OR_{it}^{gy} = 1 \\ Q + OQ_{it}^{gy}, if\ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ Q,\ otherwise \end{cases}$$

Q keeps a track of the pipeline inventory during the simulation period. Every time an order is received, the value of Q drops down by the number of units received in the replenishment order. On the other hand, as soon as a replenishment order is placed, the value of Q goes up by the size of the order.

$$OIP_{it}^{gy} = \begin{cases} S_i^{gy},\ if\ t = 1 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy} + BO_i^{gy},\ if\ t \neq 1\ and\ BO_{it}^{gy} < 0 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy},\ otherwise \end{cases}$$

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} - x_{it}^{g}, & if \quad OIP_{it}^{gy} \geq x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ 0, & if \quad OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ OIP_{it}^{gy}, & if \; x_{it}^{g} = 0 \end{cases}$$

The OIP_{it}^{gy} and EIP_{it}^{gy} denote the actual number of units of spare part i at the start and end of time period t respectively. It is assumed in the case of *(T, s, S)* inventory model that an order with a size of S_{i}^{gy} is received at the start of the simulation period. Thereafter, the opening inventory position is calculated by adding any replenishment orders received whatsoever at time t to the ending inventory at time $t-1$ and subtracting the backorders so as to address them as a priority. The ending inventory position is calculated by subtracting the customer order received from the current stock level. In case no customer order is received, the ending inventory position stays the same as the opening inventory position. Whereas, when the stock is not able to address the customer order, the ending inventory position is set to zero and backorder is registered.

$$OF_{i}^{gy} = \begin{cases} OF_{i}^{gy} + 1, & if \quad OIP_{it}^{gy} \geq x_{it}^{g} and \; x_{it}^{g} > 0 \\ OF_{i}^{gy} & otherwise \end{cases}$$

$$OM_{i}^{gy} = \begin{cases} OM_{i}^{gy} + 1, & if \; OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ OM_{i}^{gy} & otherwise \end{cases}$$

The order finished and order missed variables keep a count of the total number of customer orders successfully completed or missed. An order is processed as soon as replenishment orders are received and stocks are updated. In this case, when the opening inventory position is enough for the incoming customer order at time t for spare part i , order is considered finished whereas if the opening inventory position even short by one unit as compared to the incoming customer order, the order is considered missed. The ending inventory position and backorders are updated accordingly.

$$IP_{it}^{gy} = \begin{cases} S_i^{gy},\ if\ t = 1 \\ EIP_{it}^{gy}\ +\ Q +\ BO_i^{gy}, if\ x_{it}^{g} > 0 \\ EIP_{it}^{gy}\ +\ OP_i^{gy} * Q +\ BO_i^{gy}, otherwise \end{cases}$$

The inventory position variable IP_{it}^{gy} for spare part i at time t is set at order upto level S_i^{gy} at the start of the simulation period. Thereafter, inventory position is calculated as the sum of the ending inventory position at time t and the pipeline inventory Q minus the backorder.

$$OP_i^{gy} = \begin{cases} OP_i^{gy} + 1,\ if\ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ OP_i^{gy} - 1\ ,\ if\ OR_{it}^{gy} = 1 \\ OP_i^{gy}, otherwise \end{cases}$$

A replenishment order is placed whenever at time t (a multiple of Tm_i^{gy}), the inventory position is lesser than or equal to the re-order point s_i^{gy}. In such a case, the order placed counter variable OP_i^{gy} goes up by one unit. Whereas, whenever a replenishment order is received by the company, OP_i^{gy} goes down by one unit.

$$BO_i^{gy} = \begin{cases} 0\ , \quad if\ \ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ OIP_{it}^{gy} - x_{it}^{g}\ ,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ BO_i^{gy}, otherwise \end{cases}$$

As explained earlier, a backorder is registered whenever the stocks are unable to fulfill the incoming customer order. The backorder variable BO_i^{gy} records the ongoing number of units short for spare part i .

$$OR_{i\ t+LT_i^g}^{gy} = \begin{cases} 1,\ if\ t = n * Tm_i^{gy} and\ IP_{it}^{gy} \leq s_i^{gy} \\ 0, otherwise \end{cases}$$

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1,\ if\ t = n * Tm_i^{gy} and\ IP_{it}^{gy} \leq s_i^{gy} \\ TOP_i^{gy}, otherwise \end{cases}$$

While order received variable $OR^{gy}_{i\,t+LT^g_i}$ makes sure that a replenishment order is placed whenever the inventory position is observed to be less than or equal to the reorder point s^{gy}_i after every Tm^{gy}_i units of time, the variable TOP^{gy}_i goes up by one unit whenever an order received is logged.

$$HC^{gy}_{it} = h * UC^g_i * EIP^{gy}_{it}, if\ EIP^{gy}_{it} \geq 0$$

Similar to the other cases, the holding cost records the cost of holding spare part i at time t in the inventory.

An *(S-1,S)* inventory policy is defined for $y = 4$. This is considered as a special case of *(s,S)* policy where *s* is set to *S-1*. The model and variable definitions go as follows:

$$OQR^{gy}_{it} = \begin{cases} OQ^{gy}_{it},\ if\ OR^{gy}_{it} = 1 \\ 0,\ otherwise \end{cases}$$

The order quantity variable OQR^{gy}_{it} works exactly the same way as the above three inventory models.

$$OQ^{gy}_{i\,t+LT^g_i} = \begin{cases} x^g_{it}, & if\ x^g_{it} > 0\ and\ IP^{gy}_{it} < S^{gy}_i \\ 0,\ otherwise \end{cases}$$

In the case of an *(S-1,S)* inventory policy, a replenishment order quantity is received for spare part i at time $t + LT^g_i$ whenever a customer order has been placed and the inventory position in the current time period is less than order upto level S^{gy}_i.

$$Q = \begin{cases} Q - OQ^{gy}_{it},\ if\ OR^{gy}_{it} = 1 \\ Q + OQ^{gy}_{it}, if\ x^g_{it} > 0\ and\ IP^{gy}_{it} < S^{gy}_i \\ Q,\ otherwise \end{cases}$$

Similar to the *(T, s, S)* inventory policy, variable Q calculates the pipeline inventory. These are number of units of spare part i that have been ordered for replenishment but have still not been received.

$$OIP_{it}^{gy} = \begin{cases} S_i^{gy},\ if\ t = 1 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy} + BO_i^{gy},\ if\ t \neq 1\ and\ BO_{it}^{gy} < 0 \\ EIP_{i\,t-1}^{gy} + OQR_{it}^{gy},\ otherwise \end{cases}$$

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} - x_{it}^{g}, & if\ \ OIP_{it}^{gy} \geq x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ 0, & if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ OIP_{it}^{gy}, & if\ x_{it}^{g} = 0 \end{cases}$$

The opening and ending inventory position variables calculate the exact units of spare part i at the start and end of time t. As an assumption, the opening inventory position is set to the order upto level at the start of the simulation period.

$$OF_i^{gy} = \begin{cases} OF_i^{gy} + 1, & if\ \ OIP_{it}^{gy} \geq x_{it}^{g} and\ x_{it}^{g} > 0 \\ OF_i^{gy} & otherwise \end{cases}$$

$$OM_i^{gy} = \begin{cases} OM_i^{gy} + 1, & if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ OM_i^{gy} & otherwise \end{cases}$$

An order is considered finished only when the entire customer order size can be fulfilled using the current stock of spare part i at time t. Otherwise, an order is considered as missed and number of units short are recorded as backorder.

$$IP_{it}^{gy} = \begin{cases} S_i^{gy},\ if\ t = 1 \\ EIP_{it}^{gy} + Q + BO_i^{gy}, if\ x_{it}^{g} > 0 \\ EIP_{it}^{gy} + OP_i^{gy} * Q + BO_i^{gy}, otherwise \end{cases}$$

The variable IP_{it}^{gy} calculates the inventory position for spare part i at time t as the sum of the ending inventory position and the pipeline inventory minus backorder. Replenishment decisions are taken based on the value of inventory position.

$$OP_i^{gy} = \begin{cases} OP_i^{gy} + 1\ , if\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} < S_i^{gy} \\ OP_i^{gy} - 1, if\ OR_{it}^{gy} = 1 \\ OP_i^{gy}, otherwise \end{cases}$$

Whenever a customer order is placed and therefore, inventory position drops down below the order upto level, an order is placed and the variable OP_i^{gy} goes up by 1. As soon as a replenishment order is received, OP_i^{gy} goes down again by 1.

$$BO_i^{gy} = \begin{cases} 0\,, & if\ \ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq s_i^{gy} \\ OIP_{it}^{gy} - x_{it}^{g}\ , & if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ BO_i^{gy}, & otherwise \end{cases}$$

A backorder is registered whenever the current stock of spare part i cannot fulfil the incoming customer order at time t.

$$OR_{i\,t+LT_i^g}^{gy} = \begin{cases} 1, & if\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} < S_i^{gy} \\ 0\,, & otherwise \end{cases}$$

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1, & if\ x_{it}^{g} > 0\ and\ IP_{it}^{gy} < S_i^{gy} \\ TOP_i^{gy}, & otherwise \end{cases}$$

The order received and total order placed variables make sure that a replenishment order is received at time $t + LT_i^g$ and that in such a case the count of the total orders placed goes up by 1 unit, whenever a customer order is placed and the inventory position goes below the order upto level.

$$HC_{it}^{gy} = h * UC_i^{g} * \ EIP_{it}^{gy}, if\ EIP_{it}^{gy} \geq 0$$

The holding cost is calculated based on the inventory level at the end of each time period t.

For $y = 5$, a *(T,S)* inventory policy is modelled. The variable definitions are as follows:

$$OQR_{it}^{gy} = \begin{cases} OQ_{it}^{gy}, & if\ OR_{it}^{gy} = 1 \\ 0, & otherwise \end{cases}$$

$$OQ_{i\,t+LT_i^g}^{gy} = \begin{cases} S_i^{gy} - \ EIP_{it}^{gy}, & if\ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} < S_i^{gy} \\ 0, & otherwise \end{cases}$$

$$Q = \begin{cases} Q - OQ_{it}^{gy}, \ if \ OR_{it}^{gy} = 1 \\ Q + \ OQ_{it}^{gy}, if \ t = n * Tm_i^{gy} \ and \ IP_{it}^{gy} < S_i^{gy} \\ Q, \ otherwise \end{cases}$$

The order quantity received OQR_{it}^{gy}, order quantity $OQ_{i\,t+LT_i^g}^{gy}$ and pipeline inventory Q follow the exact same formulations as that for the *(T,s,S)* inventory model with the exception that the inventory position this case is compared to order upto level S_i^{gy} instead of the re-order point.

$$OIP_{it}^{gy} = \begin{cases} S_i^{gy}, \ if \ t = 1 \\ EIP_{i\,t-1}^{gy} + \ OQR_{it}^{gy} + \ BO_i^{gy}, \ if \ t \neq 1 \ and \ BO_{it}^{gy} < 0 \\ EIP_{i\,t-1}^{gy} + \ OQR_{it}^{gy}, \ otherwise \end{cases}$$

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} \ - \ x_{it}^{g}, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g} \ and \ x_{it}^{g} > 0 \\ 0, \qquad if \quad OIP_{it}^{gy} < x_{it}^{g} \ and \ x_{it}^{g} > 0 \\ OIP_{it}^{gy}, \qquad if \ x_{it}^{g} = 0 \end{cases}$$

The opening inventory position OIP_{it}^{gy} and ending inventory position EIP_{it}^{gy} indicate the actual stock levels at the start and end of time t. In the case of *(T,s,S)* inventory model it is assumed that the opening inventory position is equal to order upto level at the start of the simulation period. Any replenishment order whatsoever is received at the start of time period t and backorders are addressed as a priority.

$$OF_i^{gy} = \begin{cases} OF_i^{gy} + 1, \quad if \quad OIP_{it}^{gy} \geq x_{it}^{g} and \ x_{it}^{g} > 0 \\ OF_i^{gy} \qquad otherwise \end{cases}$$

$$OM_i^{gy} = \begin{cases} OM_i^{gy} + 1, \qquad if \ \ OIP_{it}^{gy} < x_{it}^{g} \ and \ x_{it}^{g} > 0 \\ OM_i^{gy} \qquad otherwise \end{cases}$$

The orders finished and missed variables, OF_i^{gy} and OM_i^{gy} respectively, count the total number of customer order completely fulfilled or missed by even one unit during the entire simulation period. These variables contribute to calculating the target service level for spare part i .

$$IP_{it}^{gy} = \begin{cases} S_i^{gy},\ if\ t = 1 \\ EIP_{it}^{gy} + Q + BO_i^{gy}, if\ x_{it}^{g} > 0 \\ EIP_{it}^{gy} + OP_i^{gy} * Q + BO_i^{gy}, otherwise \end{cases}$$

The inventory position is assumed to be equal to the order upto level at the start of the simulation period. Eventually, for the other time periods, IP_{it}^{gy} is calculated by summing the ending inventory position for spare part i at time t and the pipeline inventory Q and subtracting the backorder BO_i^{gy}.

$$OP_i^{gy} = \begin{cases} OP_i^{gy} + 1,\ if\ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} < S_i^{gy} \\ OP_i^{gy} - 1\ ,\ if\ OR_{it}^{gy} = 1 \\ OP_i^{gy}, otherwise \end{cases}$$

In this case, a replenishment order is placed when after every time period Tm_i^{gy}, the inventory position is observed to be lesser than the order upto level S_i^{gy} for spare part i at time t. As soon as a replenishment order is received by the company, the variable OP_i^{gy} goes down by one. Hence, it keeps a count of the replenishment orders in pipeline.

$$BO_i^{gy} = \begin{cases} 0\ , \quad if\ \ t = n * Tm_i^{gy}\ and\ IP_{it}^{gy} \leq S_i^{gy} \\ OIP_{it}^{gy} - x_{it}^{g}\ ,\ if\ \ OIP_{it}^{gy} < x_{it}^{g}\ and\ x_{it}^{g} > 0 \\ BO_i^{gy}, otherwise \end{cases}$$

The backorder variable BO_i^{gy} keeps a track of any backordered units of spare part i . As discussed earlier, a backorder is registered when the available stock OIP_{it}^{gy} is unable to address the incoming customer order.

$$OR_{i\ t+LT_i^g}^{gy} = \begin{cases} 1,\ if\ t = n * Tm_i^{gy} and\ IP_{it}^{gy} < S_i^{gy} \\ 0, otherwise \end{cases}$$

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1,\ if\ t = n * Tm_i^{gy} and\ IP_{it}^{gy} < S_i^{gy} \\ TOP_i^{gy}, otherwise \end{cases}$$

The order received and total order placed variables, $OR^{gy}_{i\,t+LT^g_i}$ and TOP^{gy}_i, keep a track of the replenishment orders that are to be received by the company at time $t + LT^g_i$ and a count of the total number of replenishment orders placed throughout the simulation period.

$$HC^{gy}_{it} = h * UC^g_i * EIP^{gy}_{it}, if\ EIP^{gy}_{it} \geq 0$$

Similar to the other inventory models, the holding cost for spare part i at time t is determined using the unit cost of spare part i , the holding cost factor h and the ending inventory position EIP^{gy}_{it}.

For $y = 6$, an *(s,S)* model is defined, as follows:

$$OQR^{gy}_{it} = \begin{cases} OQ^{gy}_{it},\ if\ OR^{gy}_{it} = 1 \\ 0,\ otherwise \end{cases}$$

$$OQ^{gy}_{i\,t+LT^g_i} = \begin{cases} S^{gy}_i - EIP^{gy}_{it}, & if\ x^g_{it} > 0\ and\ IP^{gy}_{it} \leq s^{gy}_i \\ & 0, otherwise \end{cases}$$

$$Q = \begin{cases} Q - OQ^{gy}_{it},\ if\ OR^{gy}_{it} = 1 \\ Q + OQ^{gy}_{it}, \quad if\ x^g_{it} > 0\ and\ IP^{gy}_{it} \leq s^{gy}_i \\ Q,\ otherwise \end{cases}$$

The order quantity received OQR^{gy}_{it}, order quantity $OQ^{gy}_{i\,t+LT^g_i}$ and pipeline inventory Q follow the same formulations as that for the *(T,s,S)* inventory model with the exception that the order quantity is registered and pipeline inventory is incremented when an customer order is placed and the inventory position is observed to be less than or equal to the re-order point.

$$OIP^{gy}_{it} = \begin{cases} S^{gy}_i,\ if\ t = 1 \\ EIP^{gy}_{i\,t-1} + OQR^{gy}_{it} + BO^{gy}_i,\ if\ t \neq 1\ and\ BO^{gy}_{it} < 0 \\ EIP^{gy}_{i\,t-1} + OQR^{gy}_{it},\ otherwise \end{cases}$$

$$EIP_{it}^{gy} = \begin{cases} OIP_{it}^{gy} - x_{it}^{g}, & if \quad OIP_{it}^{gy} \geq x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ 0, & if \quad OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ OIP_{it}^{gy}, & if \; x_{it}^{g} = 0 \end{cases}$$

The opening and ending inventory positions, OIP_{it}^{gy} and EIP_{it}^{gy} respectively, follow exactly the same definitions and formulations as that for *(T,s,S)* inventory model. So do the order finished OF_{i}^{gy}, order missed OM_{i}^{gy} and inventory position IP_{it}^{gy} variables.

$$OF_{i}^{gy} = \begin{cases} OF_{i}^{gy} + 1, & if \quad OIP_{it}^{gy} \geq x_{it}^{g} and \; x_{it}^{g} > 0 \\ OF_{i}^{gy} & otherwise \end{cases}$$

$$OM_{i}^{gy} = \begin{cases} OM_{i}^{gy} + 1, & if \; OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ OM_{i}^{gy} & otherwise \end{cases}$$

$$IP_{it}^{gy} = \begin{cases} S_{i}^{gy}, \; if \; t = 1 \\ EIP_{it}^{gy} + Q + BO_{i}^{gy}, if \; x_{it}^{g} > 0 \\ EIP_{it}^{gy} + OP_{i}^{gy} * Q + BO_{i}^{gy}, otherwise \end{cases}$$

$$OP_{i}^{gy} = \begin{cases} OP_{i}^{gy} + 1, \; if \; x_{it}^{g} > 0 \; and \; IP_{it}^{gy} \leq s_{i}^{gy} \\ OP_{i}^{gy} - 1, \; if \; OR_{it}^{gy} = 1 \\ OP_{i}^{gy}, otherwise \end{cases}$$

The order placed variable OP_{i}^{gy} keeps a track of the replenishment orders in pipeline. The OP_{i}^{gy} increases by 1 whenever a customer order is received at time t and the inventory position post addressing the order is lesser than or equal to the re-order point s_{i}^{gy}. Whereas, when an order in pipeline is received by the company, OP_{i}^{gy} decreases by 1.

$$BO_{i}^{gy} = \begin{cases} 0, & if \;\; t = n * Tm_{i}^{gy} \; and \; IP_{it}^{gy} \leq s_{i}^{gy} \\ OIP_{it}^{gy} - x_{it}^{g}, & if \; OIP_{it}^{gy} < x_{it}^{g} \; and \; x_{it}^{g} > 0 \\ BO_{i}^{gy}, otherwise \end{cases}$$

Backorders occur whenever the current stock levels are unable to satisfy the incoming customer demand. In such a case, variable BO_i^{gy} records the backorder quantity which is equal to the opening inventory position OIP_{it}^{gy} minus the quantity demanded by the customer x_{it}^{g}. Please note that BO_i^{gy} has a negative value whenever backorders take place.

$$OR_{i\,t+LT_i^g}^{gy} = \begin{cases} 1, \; if \; x_{it}^{g} > 0 \; and \; IP_{it}^{gy} \leq s_i^{gy} \\ 0, otherwise \end{cases}$$

$$TOP_i^{gy} = \begin{cases} TOP_i^{gy} + 1, \; if \; OIP_{it}^{gy} \geq x_{it}^{g} \; and \; x_{it}^{g} > 0 \; and \; IP_{it}^{gy} \leq s_i^{gy} \\ TOP_i^{gy}, otherwise \end{cases}$$

The order received variable $OR_{i\,t+LT_i^g}^{gy}$ ensures that after time $t + LT_i^g$, a replenishment order is received. TOP_i^{gy} keeps a count of the total replenishment orders placed by the company till time t.

$$HC_{it}^{gy} = h * UC_i^g * \; EIP_{it}^{gy}, if \; EIP_{it}^{gy} \geq 0$$

The holding cost variable HC_{it}^{gy} computes the inventory holding cost of EIP_{it}^{gy} units of spare part i after each unit of time.

6.4 Optimization model

The simulation-optimization procedure, as explained in *Section 3.5*, requires that the simulation model provides the necessary inputs for the objective function within the optimization engine. It is not only the objective function, but also the constraints that require the results from simulation model. The optimization model aims at minimising the total cost which is the sum of the inventory holding cost, order cost and unit cost. Each of these three components are computed over the simulation time period and are ultimately fed into the optimization engine. The constraint of the achieved service level being at least equal to the target service level is computed using the orders finished and orders missed variables in the simulation model. All these variables - HC_{it}^{gy}, TOP_i^{gy}, Q_i^{gy}, OF_i^{gy}, OM_i^{gy} are ultimately functions of inventory policy parameters and therefore, the decision variables can be either s_i^{gy}, S_i^{gy}, T_i^{gy}, Q_i^{gy} depending upto the inventory model y. The optimization model can be formulated as follows:

$$Min\ TC_i^{gy}$$

$$SL_i^{gy} \geq TSL^g$$

$$\text{where, } TC_i^{gy} = THC_i^{gy} + TUC_i^{gy} + TOC_i^{gy}$$

$$THC_i^{gy} = \sum_t HC_{it}^{gy}$$

$$TUC_i^{gy} = UC_i^g * TOP_i^{gy} * Q_i^{gy} \text{ or } TUC_i^{gy} = \sum_t UC_{it}^{gy}$$

$$TOC_i^{gy} = OC * TOP_i^{gy}$$

$$SL_i^{gy} = \frac{OF_i^{gy}}{OF_i^{gy} + OM_i^{gy}}$$

Please note that in case of *(s,Q)* and *(T,Q)* models, the total unit cost can be easily computed at the end of the simulation period for each spare part since the lot-size is pre-defined and stays constant in every time period t. However, for the other 4 inventory models, unit cost needs to be computed separately in each time period and then summed up in the end of the simulation as the replenishment order sizes can vary from time to time or order to order.

6.5 Operational process flowchart

The variables for the simulation optimization model have been defined in the previous section. The operational process flowchart provides an overview of how the simulation optimization model is actually structured. Each spare part in each group goes through the steps described below to ultimately look for the inventory policy parameters that result in adhering to the target service level defined while pushing the total costs down.

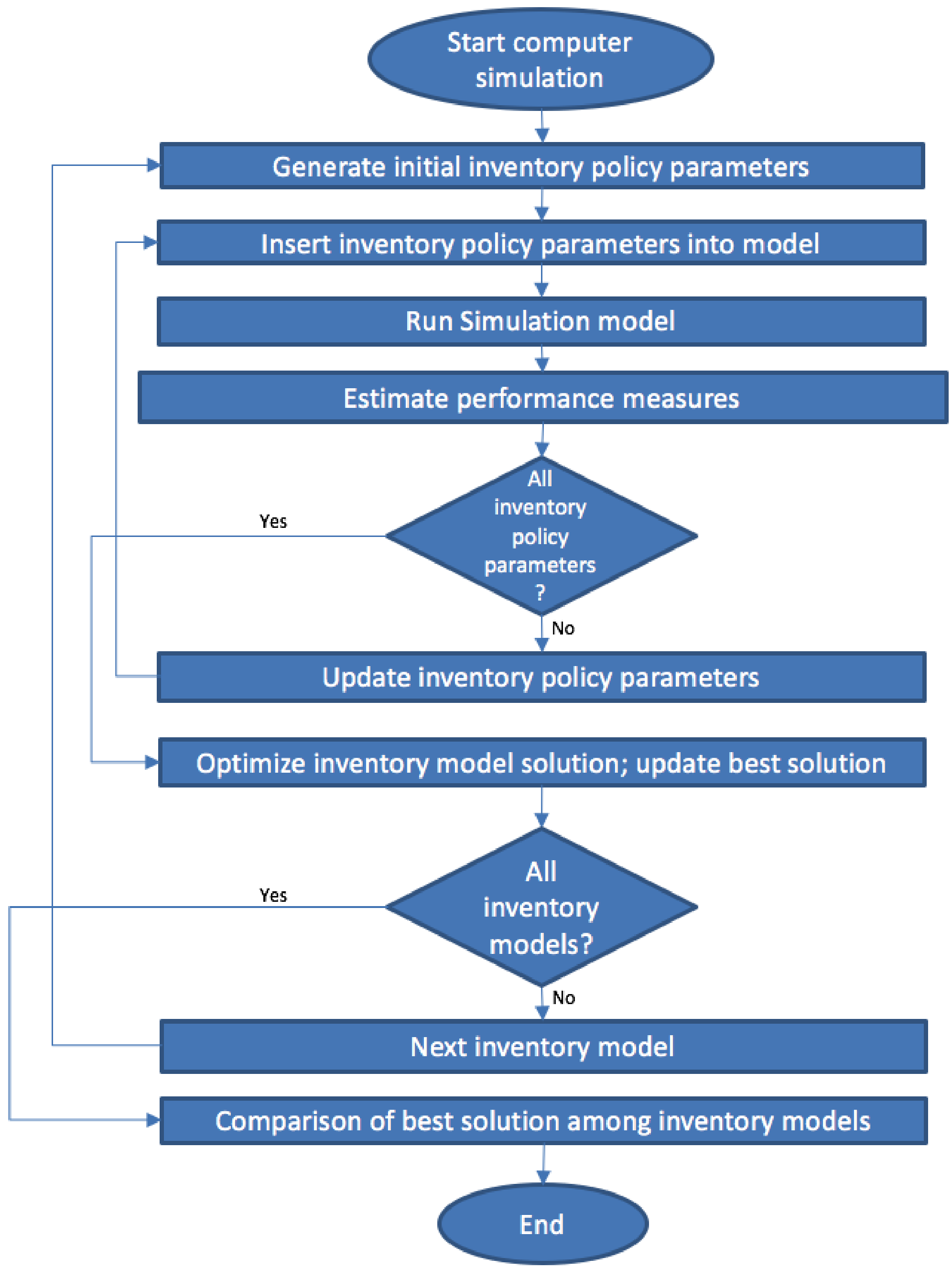

Figure 27: Operational process flowchart - Simulation optimization model

With the start of the simulation, the selected inventory model's policy parameters are generated. This means that for *(s,Q)* model, the parameters s_i^g and Q_i^g are set to 1 and 1 respectively (at the start of the simulation period). Now, with these values of inventory policy parameters, the *(s,Q)* model is run from time 1 to T. The performance measures are calculated using the variables updated after the simulation model is finished with the run. The performance measures include total cost TC_i^g and service level achieved SL_i^g. These values are recorded after which a check is made if all the inventory policy parameter values have been tested with. This means that in the case of *(s,Q)* model, all combinations of s_i^g and Q_i^g ranging from 1 to s_{max}^g and Q_{max}^g respectively (pre-defined by the user) have to be tested one by one. If there is a combination of s_i^g and Q_i^gstill remaining, then the inventory policy parameters are updated and the simulation model is run again. For each s_i^g-Q_i^g combination, the performance measures are recorded. As soon as all the possible combinations are exhausted, the best solution among all is recorded. This essentially means that the combination of s_i^g and Q_i^g that resulted in at least the target service level to be realized at minimum total cost is the solution for this spare part for the particular inventory policy. This process is carried out not only for the individual spare part, but for all the parts in the group.

After one inventory policy is tested, the program moves on to the next one and the same procedure is repeated. The iteration goes on until all the six inventory models have been tested for the group. Based on the total group cost for each inventory model, it can be directly inferred which inventory policy returned the best results.

All the groups can be tested in this manner and for each group, the inventory policy that results in the lowest total cost while achieving the target service level is considered as the policy to follow. Not only this, the program also returns the inventory policy parameter for each spare part in that group that resulted in the optimal solution. This, in turn, provides a straight solution to the spare parts manager as to which inventory policy to follow in the future and which policy parameters to use for each spare part type.

CHAPTER 7 – VALIDATION OF MODEL

This chapter explains how the simulation optimization model is validated and tested with some numerical data. Since contacting and coordinating with companies is a time-taking and exhaustive process, it was decided that self-generated data will be used for demand of spare parts, their lead-times and unit costs. There are three main data tables required to proceed with the simulation optimization model validation exercise:

1. Spare parts demand data: This table contains the demand instances and sizes for each spare part. In this numerical example, past 52 weeks of demand data is considered. An example of such a data-table is below:

Time (t)	x_1	x_2	x_3
1	0	0	10
2	5	0	15
3	0	1	0
4	0	0	0
5	4	0	3
6	0	0	0
7	0	2	0
8	10	1	5
9	11	0	0
10	0	0	0
11	4	0	1
12	7	7	0
…	…	…	…
…..	….	….	….
52	0	8	6

Table 7: Spare parts demand data

2. Spare parts properties data: For each spare part, it is assumed that the replenishment lead time and the unit costs are known beforehand. This data is managed in the form of a table that can directly act as an input to the

simulation optimization model. A typical spare parts properties data table can look as follows:

x_i	LT_i	UC_i
x_1	2	1000
x_2	7	30
x_3	8	500
x_4	1	20
x_5	10	100
x_6	12	2000
…	…	…
….	…	…
x_n	8	750

Table 8: Spare part properties data

3. Spare part to group mapping: After each spare part has been categorized into one of the 12 groups, a table is created that clearly indicates the mapping of spare part to the group it belongs to. Such a table looks as follows:

x_i	g
x_1	1
x_2	7
x_3	8
x_4	1
x_5	2
x_6	12
…	…
….	…
x_n	6

Table 9: Spare part-Group mapping table

7.1 Testing the simulation optimization model

Please note that at this stage, the exercise of AHP for VED analysis is assumed to have already taken place. Therefore, each part has been assigned to a group based on their properties through the procedure explained in *Section 5.3*. For the current numerical example, Microsoft Excel function 'Random' is used to generate demand data for each spare part. The corresponding squared coefficient of variation and *ADI* are calculated and checked and demand data is adjusted based on which group the spare part belongs to. Each group contains 10 sets of 10 spare parts each. Multiple sets are used with the purpose of finding a 'rule of thumb' and observe any repetition or patterns in inventory behavior for different spare part sets belonging to the same group.

Unit cost and lead time is assigned to each spare part based on the group it belongs to. Unit costs range from 3 EUR to 180 EUR whereas lead times can be anywhere from 1 week to 16 weeks. AHP for VED analysis has been used to find the cut-off values for vital, essential and desirable groups and spare parts have been segregated accordingly. The vital group has been set at 95% target service level, while essential and desirable groups are set at 80% and 65% target service levels respectively.

Since there are 12 groups, each with 10 sets of 10 spare parts, a total of 120 simulation runs are carried out. Each run took approximately 2 hours on a 2.7 GHz Intel Core i5 processor. This implies that each run went through all the 6 inventory models and resulted in the minimum total costs possible for the 6 models while at least reaching the target service level defined for that group. The results are tabulated in the next section.

7.2 Result analysis

The simulation optimization model is run for each set of spare parts within each group and the results are collected in Microsoft Excel tables. As an example, for the group Lumpy-Vital, the first set of 10 spare parts provides the following results:

Total Costs (TC_i^{1y})	$\boldsymbol{Total}$	$(\boldsymbol{T},\boldsymbol{Q})$	$(\boldsymbol{T},\boldsymbol{s},\boldsymbol{S})$	$(\boldsymbol{S}-\mathbf{1},\boldsymbol{S})$	$(\boldsymbol{T},\boldsymbol{S})$	$(\boldsymbol{s},\boldsymbol{S})$
$\boldsymbol{x_1}$	6700	10720	5380	7600	6300	7240
$\boldsymbol{x_2}$	10690	10880	10070	12020	10850	10180
$\boldsymbol{x_3}$	6622	7928	7064	9086	7218	8956

x_4	9087	10251	8067	8809	8753	8441
x_5	2840	3460	2950	3570	3460	2950
x_6	7070	15215	6870	7220	7585	6805
x_7	9688	10926	8512	9540	8512	10116
x_8	17850	58010	15740	18070	19270	16030
x_9	19930	42390	15606	21542	18938	16212
x_{10}	4101	5945	4440	4444	4648	4465
Total Group Costs	**94578**	**175725**	**84699**	**101901**	**95534**	**91395**

Table 10: Total cost results for Lumpy-Vital group (Set 1)

The target service level for this set was 95% since it is a vital group. The service levels achieved at the costs mentioned above are depicted in the table below:

Service Level (SL_i^{1y})	(s, Q)	(T, Q)	(T, s, S)	$(S-1, S)$	(T, S)	(s, S)
x_1	1.00	1.00	1.00	1.00	1.00	1.00
x_2	1.00	1.00	1.00	1.00	1.00	1.00
x_3	1.00	1.00	1.00	1.00	1.00	1.00
x_4	1.00	1.00	1.00	1.00	1.00	1.00
x_5	1.00	1.00	1.00	1.00	1.00	1.00
x_6	0.96	0.96	0.96	0.96	0.96	1.00
x_7	1.00	1.00	1.00	1.00	1.00	1.00
x_8	1.00	1.00	1.00	1.00	1.00	1.00
x_9	1.00	1.00	1.00	1.00	1.00	1.00
x_{10}	1.00	1.00	1.00	1.00	1.00	1.00
Average Group SL	**99.6%**	**99.6%**	**99.6%**	**99.6%**	**99.6%**	**100.0%**

Table 11: Service level achieved by Lumpy-Vital group (Set 1)

It can be observed that many parts achieve 100% service level while only x_6, in a few cases, achieves slightly lesser although all the service levels achieved are greater than the targeted 95%. The average service level achieved for the group is therefore at least 95%. It can also be seen that for the group, the inventory model (T, s, S) reaches the target service level at the minimum cost, which is 84,699 EUR for the entire 52-week period. Although it must be noted that the (s, S) inventory model also reaches the target service level but with slightly higher total cost, only 8% more, than

(T, s, S). Hence, it can be inferred that for this set of spare parts, the (T, s, S) inventory policy offers the best results. The inventory policy parameters in this case for the 10 spare parts are:

x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}
5,1,5	11,4,11	9,10,12	5,7,10	4,1,7	2,2,9	11,10,11	5,14,2	6,13,25	11,9,13

Table 12: Inventory policy parameters for Lumpy-Vital parts (Set 1) in case of (T,s,S) model

A small side analysis is also carried out to observe the difference between the 6 inventory models and the traditionally used EOQ model. The following results were obtained with EOQ model:

	EOQ	**Orders Finished**	**Orders Missed**	**Total Cost**	**Service Level**
x_1	2	8	8	3760	50%
x_2	2	1	3	4490	25%
x_3	2	2	9	1716	18%
x_4	2	4	15	3084	21%
x_5	3	10	6	2150	63%
x_6	3	10	13	4565	43%
x_7	2	1	17	4370	6%
x_8	3	1	16	5270	6%
x_9	3	1	17	5868	6%
x_{10}	3	7	9	2218	44%
Group				**37491**	**28%**

Table 13: EOQ model results for Lumpy-Vital group (Set 1)

Although the EOQ model results in lower cost as compared to the best result of the proposed method, the service level achieved is a mere 28% which is unacceptable for such critical parts that constitute this group. It can be clearly seen how ineffective the traditional methods are in such case where demand pattern is not constant and part availability requirement is extremely high. Similar analyses were also carried out for other sets of Lumpy-Vital group and the results are summarized in the following table:

		(s,Q)	(T,Q)	(T,s,S)	$(S-1,S)$	(T,S)	(s,S)
Set 1	TC	94578	175725	**84699**	101901	95534	91395
	SL	99.6%	99.6%	99.6%	99.6%	99.6%	100.0%
Set 2	TC	119515	152310	**105212**	122988	113683	118981
	SL	99.5%	99.5%	99.5%	99.5%	99.5%	99.5%
Set 3	TC	104425	198511	**88386**	102298	103335	100881
	SL	99.0%	99.0%	99.0%	99.5%	99.0%	99.0%
Set 4	TC	92396	107618	**81910**	99480	88772	92094
	SL	97.9%	98.7%	97.9%	97.9%	98.4%	97.9%
Set 5	TC	87761	92293	**86331**	105213	92922	95085
	SL	99.2%	99.2%	99.2%	99.2%	99.2%	99.2%
Set 6	TC	103810	109121	**92953**	109675	100575	98433
	SL	98.7%	98.7%	99.1%	98.7%	99.1%	99.1%
Set 7	TC	124833	150471	**112338**	127700	122782	122779
	SL	98.5%	98.5%	98.5%	98.8%	98.5%	98.5%
Set 8	TC	152283	188308	**145421**	164378	153328	151038
	SL	97.2%	97.7%	97.2%	98.6%	97.2%	97.2%
Set 9	TC	98360	113666	**93314**	108098	99341	95567
	SL	97.4%	97.4%	97.8%	97.8%	97.8%	97.9%
Set 10	TC	121633	161456	**108470**	125849	118730	111995
	SL	98.7%	98.0%	98.3%	98.8%	98.3%	98.4%

Table 14: Total cost and Service level results for Lumpy-Vital group

For all the 10 sets tested under the Lumpy-Vital group, (T, s, S) inventory model provides the best results. It can be safely inferred that for Lumpy-Vital group parts, the (T, s, S) inventory policy can be implemented to keep the total costs down while achieving a high service level. Although it must be agreed that statistical tests are required to apply this statement as a ‘rule’.

Similarly, simulation optimization results from other groups were also summarize and the following results were obtained:

		Optimal Inventory Policy
Lumpy	Vital	(T, s, S)
	Essential	(T, s, S)
	Desirable	(T, Q)
Intermittent	Vital	(T, s, S)
	Essential	(T, s, S)
	Desirable	(T, s, S)
Erratic	Vital	$(S - 1, S)$
	Essential	(T, s, S)
	Desirable	(T, Q)
Smooth	Vital	(T, s, S)
	Essential	(T, Q)
	Desirable	(s, Q)

Table 15: Summary of the optimal inventory policy for each group

It must be noted that to ensure the successful and correct back-end run of the MATLAB program, each step was randomly checked using step-by-step manual calculation using a calculator. This made sure that parameter results from manual calculation match exactly with the results of the MATLAB program. It must also be noted that the above numerical example is only for validation purposed and the results communicated should not be, in any case, used as a representative for other spare parts inventory management examples.

CHAPTER 8 – CONCLUSIONS

Managing spare parts can be an intimidating task especially because of their sheer number and the associated inherent complexities. This research work has highlighted the following major points that can be stated as conclusions:

1. Spare parts management is a comparatively newer focus area for organisations. Considerable attention is now being directed towards utilizing this field as a strategy to gain competitive advantage in the market since it directly influences customer service. Recent years have seen a spotlight on effectively managing spare parts and large organisations are willing to deploy extra resources to make sure that customer service levels are either increased or maintained.
2. The challenges associated with managing spare parts have received considerable attention both, within the research community as well as in the industry. Till now, focus has mostly been on either theoretical understanding of spare parts management or finding a solution to the forecasting issues for spare parts demand. There has been a lack of dedicated studies to manage spare parts from a practical standpoint and, unfortunately, most of such implemented research has been case-based in nature.
3. The suggested 'spare parts supply chain' provides a structured and single view of the various activities that constitute spare parts management. It is in no way a 100% complete picture, but what this framework offers is a way of visualising the numerous stakeholders and processes possibly involved in managing spare parts and the various processes that interact with each other. Any organisation willing to initiate a spare parts management exercise can benefit from this framework and recognise activities to focus on, related time horizons and process owners.
4. The suggested methodology for classifying spare parts into 12 groups using AHP methodology provides a systematic approach to managing large number of spare parts. Having a limited number of groups based on carefully chosen

characteristics not only helps in handling a complex spare parts portfolio, but also helps in identifying similarities and predict managing strategies for new spare parts. Whenever a new spare part is included in the portfolio, with no previous demand data whatsoever, hypotheses can be generated based on the AHP analysis and the already existing groups. Based on the first few demand instances, the hypotheses can be verified. Therefore, the classification methodology proposed also provides a robust and data-backed starting point for a new spare part.

5. Even though it could prove to be more beneficial to divide parts based on the product in which they are used (to define criticality better), but reducing lumpiness benefits the system much more than the disintegration of the part into part per product. Martin et al. (2010) explained how product design and selection decisions primarily influence spare parts demand and that part standardisation can assist demand aggregation and therefore mitigate lumpiness[138]. This feature has been suggested during the AHP analysis so that practitioners can benefit from parts that are inter-changeable and focus has been to utilising the features of a part irrespective of which product or machine it originally belongs to.
6. The Verma-Leisten model offers an industry-independent tool that provides guidance to carry out preventive maintenance by suggesting the inventory model that makes sure that all the parts in a group reach the pre-defined realistic target service level at minimum total costs. The total cost in this case is measured as the sum of the ordering, inventory holding and unit costs. This way, replenishment contracts with suppliers can be renegotiated to make sure that parts are ordered in correct amounts when needed. This is an effort to reach closer to the utopia of ‘no inventory’ and a ‘happy customer’.

[138] Martin et al. (2010), p. 233.

Similar to every research work, there are limitations to this study as well. These limitations are listed as follows:

1. The activity of scoring and rating each spare part to define part criticality can be exhausting. It is a long process considering that, on an average, an organisation handles thousands of spare parts. Assessing each one separately can prove to be a daunting task and can require days of work to receive an approval from all the relevant stakeholders to be categorised correctly.
2. Although efforts have been made to make sure that classification criteria used for AHP analysis are sufficient such that all the spare parts are duly classified, it is still possible that some part does not satisfy any of the criteria. Such parts have been considered out of scope for this research. However, these special parts can be treated as exception cases and should be dealt with carefully. Some examples can be dangerous goods, parts with gradient prices, parts with high seasonality, marketing efforts leading to unnatural demand etc. Also parts that are difficult to specify in terms of number of units, for example cables, chains, foils and glass can also prove to be a challenge for the classification technique proposed.
3. The Verma-Leisten model has been built for a single echelon system. This means that as soon as the inventory system starts growing and more warehouses are added, the model starts getting complicated. Even though each warehouse can then carry out its own simulation optimization, but the AHP for VED analysis will stay the same for all the warehouses.
4. The computation times might prove to be a hindrance. Currently, for 10 spare parts with low demand usage (<30 units per time unit), the computation time is ~2 hours. This can be reduced by using computers with stronger processors. Though as the number of parts in each group increases, the computation time also increases, sometimes even at an exponential rate. The usage of 52 weeks

of demand data might also raise questions since the seasonality affect is completely ignored this way.

5. Even though it has been stated that new parts with no previous demand data can also be analysed using AHP analysis results for parts with similar characteristics, it can still prove to be a challenge. There are cases where new parts are completely different from the parts already existing in the portfolio and therefore, sufficient demand data needs to be collected for such parts such parts before AHP analysis followed by simulation optimisation model.

During the course of this study, many interesting scopes for future work have been identified. Some of them are listed below:

1. The model can be expanded for multi-echelon systems. The storage locations in an echelon can determine its own, best functioning inventory policy for each spare part and this can be used as a demand function for the warehouse in the higher echelon. This way, the inventory policies in each warehouse will influence that of each interacting warehouses. The lower echelons facing the customer will receive the highest variations and irregularities in demand whereas the upper echelons, in most cases, will receive a 'smoothened' demand pattern from the lower echelons because of the implemented inventory management policies. On the other hand, bullwhip effect results in higher echelons storing more units of parts as compared to lower echelons resulting in higher inventory holding costs and eventually scrapping costs.
2. It can be observed that while optimal inventory policy has been assigned to each group based on the minimum sum of the total cost across all the parts where the target service level has been achieved, there are cases where a part (or a set of parts) have a different best inventory policy as compared to the group it belongs to. This property can be utilized to, as a suggestion, classifying parts based on their individual 'best' inventory policy, resulting in this case 6 groups. This does not consider the properties of a part to classify it, rather the best performing inventory policy. Therefore, target service levels

would have to be defined at a part level and the Verma-Leisten model would have to be run first and based on the results, part classification follows.

3. Integration of a repair center can make the model interesting. It results in a closed loop structure of the supply chain and is therefore closer to real-life situations. Additional information regarding the repair time for each part, degree of damage of a part, repair costs etc. would be required, which in most cases are difficult to pre-determine. Similar to many research studies, the repair time can be assumed to be normally distributed and repair costs can be assumed to be proportional to the part unit costs. Such added conditions can add complexities to the model but they would certainly enrich the study.

The above mentioned limitations and scope can form a basis for future work. It would be interesting to see how spare parts management evolves especially in light of Industry 4.0.

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List of annexures

Indicators / Literature	Criticality	Demand Pattern	Stock out penalty	Commonality	Substitutability	Lead time	Fuctionality /Essentiality	Consequence of failure	Specificity / degree of standardization	Unit costs/ Value	Holding costs	Stage of life cycle	Failure rate	Repairability	Consumption / Annual Usage	Supplier characteristics
Bacchetti et al. (2013)	X	X					X			X		X			X	X
Heinecke et al. (2013)		X														
Huiskonen (2001)	X						X		X	X					X	
Gajpal et al. (1994)						X			X							
Fuller et al. (1993)										X					X	
Duchessi et al. (1988)	X		X			X					X		X			
Braglia et al (2004)				X	X								X			
Celebi et al . (2008)	X	X	X	X	X	X				X					X	
Jingjiang and Zhendong (2012)					X	X									X	
Roda et al (2014)			X			X			X	X						
Van Haperen (2013)	X			X	X	X		X	X	X			X	X		X
Cavalieri et al. (2008)						X			X							
Stoll et al. (2015)	X					X	X						X			
Persson and Saccani (2009)																X
Wang and Kang (2007)	X									X			X			
Molenaers et al. (2012)						X							X			X
Flores and Whybark (1987)	X		X		X	X									X	
Petrovic and Petrovic (1992)							X			X				X		X
Partovi and Burton (1993)						X	X			X					X	
Lolli et al (2014)	X					X		X							X	
Sharaf and Helmy (2001)						X			X	X					X	
Schuh and Wienholdt (2011)	X							X								
Rossetti and Achlerkar(2011)	X	X				X	X		X	X						
Teunter et al. (2010)	X		X			X				X					X	
Diallo et al. (2009)																
Winter (2007)	X					X				X						
Shangguan (2013)*	X					X		X							X	
Geertjes (2014)*										X						
Williams (1984)		X														

Annexure 1: Spare Parts Classification- Literature Review

Annexure 2: Sensitivity analysis graph for lumpy-vital group – an illustrative example

The Verma-Leisten model has been run and results have been evaluated for all the 12 groups. The above graph depicts the results for each model run through varying target service levels ranging from 10% to 100% for the lumpy-vital group. The resulting total costs are plotted on the graph and the best fit exponential curve has been generated using the Microsoft Excel feature for formatting a trendline. Several options like linear, logarithmic, polynomial etc. were evaluated and subsequently exponential was chosen due to its best performance with respect to the R^2 value of the trendline for all the series. As depicted on the graph, the (T,s,S) model returns the lowest total costs for all target service levels ranging from 68% to 100%. This implies that for achieving the same target service level, implementing the (T,Q) inventory policy will incur higher cost as compared to the other inventory policies whereas the (T,s,S) can achieve the same target service level at lower costs as compared to the other 5 inventory policies. The total cost variance between the two extremes - (T,s,S) and (T,Q) inventory policies continues to increase as one moves from the 68% target service level to the 100% mark.

The graph shows that at the 68% target service level mark, there is a cut-off point. This implies that the (T,s,S) policy is not the ‘best’ solution for all the cases. It is now the (T,Q) inventory policy that returns the lowest costs for target service levels lower that 68%. This clearly explains why organisations that use (T,Q) policies for managing spare parts often achieve low service levels, since the lumpy-vital nature of spare parts (in this example) can be managed effectively with the (T,s,S) policy to achieve high service levels.

Such a sensitivity analysis is easy to carry out for each group with the Verma-Leisten model. Not only can the resulting data be plotted easily, but the graph shows in a single glance which inventory policy to use for the target service level needs. The graph also clearly depicts how sensitive the best inventory policy is, which means to which extent in what range does the best solution hold.