After-market spare parts inventory centralization at Sandvik Mining and Rock Technology

Thesis in partial fulfillment of the requirements for the degree of
M.Sc. in Logistics and Supply Chain Management

Faculty of Engineering LTH
Industrial Management and Logistics
Division of Production Management

Mining and Rock Technology
Crushing and Screening

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Abstract

Title: After-market spare parts inventory centralization at Sandvik Mining and Rock Technology.
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Background: In spare parts logistics, customers expect a high availability of spare parts from their providers. It is very critical for spare parts providers to be able to satisfy customers' demands. It acts as a differentiator in the customer's buying decision. Sandvik, an engineering company, is interested in improving their spare parts logistics. The case company is interested in benefits from centralizing their inventory. They target increasing their inventory service levels, while at the same time, having a feasible solution. Inventory centralization is thought of interest because of the risk pooling benefits that lowers the demand uncertainty. Thus, higher service levels can be achieved with lower global safety stocks.
Purpose: The purpose of the thesis is to investigate, model and analyze a centralized spare parts inventory solution for the case company.
Methodology: Mathematical modeling of single-echelon, single item inventory systems using Visual Basic for Applications within Microsoft Excel is a core method for this thesis. All data were collected from the case company. Quantitative data was the dominant type of data to be used. However, qualitative data complemented the quantitative one where necessary. The thesis follows an abductive approach but with an emphasis on deductive methods.
Conclusions: Fully centralizing inventory achieves better service levels with lower safety stocks if compared to a less centralized model. However, the transportation time towards customers increases. Customers experience availability as a performance measure. Availability includes keeping high shelf availability and short delivery times. In this thesis, a fully centralized and a partially centralized inventory solution are further investigated. However, it is recommended to balance the conflicting goals of providing fast delivery speed and lowering inventory. In all investigated models fill-rate is increased by 55% if compared to the current state. In the fully centralized model the company can achieve a higher fill-rate and at the same time lower its inventory (cycle and safety stock) by 28 %. However, to achieve the same fill-rate in the partially centralized model, the company is expected to increase inventory by 40 % on average if compared to the current state. Also, the case company is expected to deliver the spare-parts quicker to the customer in the partially centralized model when compared to the fully centralized model.
Keywords: Inventory Management, Inventory Centralization, Single-Echelon Inventory Models, spare parts Logistics

Preface

This M.Sc. thesis is the result of the project work carried out in cooperation of LTH and Sandvik during the time of February — May 2018. The authors are grateful for the opportunity to conduct this research together with the Division of Production Management and at Sandvik Mining and Rock Technology. We have been supported by numerous people in both the university and the case company. We want to highlight some of them:

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— Ruben Brückner and Jawdat Higab

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Abbreviations and Symbols

	definition
μ'	mean demand during the lead-time [units]
μ_d	mean demand per time unit [units]
μ_L	mean supply lead-time [time unit]
σ'	standard deviation of demand during the lead-time [units]
σ_d	standard deviation of demand per time unit [units]
σ_L	standard deviation of the supply lead-time [time unit]
DOS	days of supply
IL	inventory level [units]
IL^-	back-ordered demand [units]
IL^+	inventory on-hand [units]
$E[IL^+]$	expected inventory on hand [units]
IL^+_{actual}	actual average on-hand inventory level at case company [units]
Q	order quantity [units]
R	reorder point [units]
S_1	service level 1, (probability of no stock-out during replenishment period)
S_2	service level 2, *fill-rate* (fraction of demand satisfied immediately from stock)
S_3	service level 3, *ready-rate* (fraction of time with positive stock on hand)
$\mathrm{S}_{2\ \mathrm{actual}}$	actual service level 2 as measured by the case company
VMR	Variance to Mean Ratio

	definition
AM	After-Market
APAC	Asia Pacific
APICS	American Production and Inventory Control Society
BA	Business Area
DC	Distribution Centre
ERP	Enterprise Resource Planning
IoT	Internet of Things
NA	North America
PA	Product Area
RDC	Regional Distribution Centre
SA	South America
SMCL	Sandvik Mining and Construction Logistics

Chapter 1

Introduction

This introductory chapter describes the background of the study, introduces the case company along with the formulated problem, and finally discusses the delimitations of this thesis project.

1.1 Background

According to the American Production and Inventory Control Society (APICS), inventory is defined as stocks or items that are used to support production (raw material and work-in-process), support activities (maintenance, repair, and operating supplies) and customer service (finished goods and spare parts) (Pittman et al. 2016).

Supply chain management is concerned with planning, controlling and managing the flows of materials from suppliers to customers (Axsäter 2006). Today, a significant amount of capital is tied up in inventory, therefore, it is widely recognized by top management as an area with opportunities for improvement (Axsäter 2006). Inventory can't be isolated from other supply chain management functions as different functions can have a direct influence on inventory, for example, purchasing often tries to buy material in large batches as it is more economical, at the same time, production prefers having stocks on hand immediately to avoid long machine stoppage, also, the marketing function prefers having high finished goods inventory to provide high service levels for customers (Axsäter 2006). Inventory management aims to balance these different inventory goals. Along with the advances in information technology, it is now possible to efficiently manage inventory to lower costs (Axsäter 2006). The two main reasons for keeping inventories are economies of scale and uncertainties. The economies of scale are often generated by the fact that ordering in batches is more economical than ordering a single unit. Uncertainties in demand along with having variable supply lead times create the need for keeping safety stocks (Axsäter 2006).

Spare parts logistics can be defined as a logistical system that includes the planning, design, realization, and control of spare parts supply and distribution. Efficient spare parts logistics with a well-aligned strategy can differentiate a business from its competitors. It can add greater value to the customer beyond the primary product benefits. This can build a long-term customer loyalty and help achieving better profit margins. Manufacturers are expected to meet the customers' high expectations in terms of delivery of service and long-time availability of spare parts (Wagner et al. 2012). Also, providing a high service level will result into very few lost sales (Axsäter 2006).

Through multiple case studies, (Wagner et al. 2012) conclude that companies who are performing well in the field of spare parts logistics most often had a central storage, while keeping fast-moving items available closer to the customer. Long-term contracts are established and selective storage is decided based on spare parts criticality and value. Threats to the after-market spare parts business are identified as direct sales by suppliers and copied parts, especially from the Asian markets (Wagner et al. 2012).

One of Sandvik's sub-companies (*Crushing and Screening*) has perceived the importance of spare parts logistics and the potentials for improving the current logistics system. This master thesis focuses on investigating and analyzing three centralized inventory solutions for Sandvik's *Crushing and Screening* spare parts distribution network.

1.2 Company description

Sandvik is a global engineering company in "mining and rock excavation, metal-cutting and materials technology" (Sandvik 2018).

Sandvik's Product Area (PA) *Crushing and Screening*, part of the Business Area (BA) *Sandvik Mining and Rock Technology* (SMRT), develops, produces and sells equipment for size reduction and sorting of rock material. Different industrial solutions such as excavator-like "breaker" machines, sorting and conveying systems "screens", as well as stationary and mobile crushing units are offered. Their product family of stationary crushers is used in countries around the world. The after-market logistics for PA *Crushing and Screening* is currently being handled by one of the eight other *PAs* in *SMRT* called *Parts and Services*. The PA *Crushing and Screening* is undergoing a strategic alignment project to gain better control over their logistics operations and rely less on the *Parts and Services* organization. This comes aligned with Sandvik's high-level strategy of decentralizing their PAs. *Parts and Services* will then continue to take care of after-market sales and customer service, while inventory control and distribution will be entirely managed by *Crushing and Screening*. More details about Sandvik units and products hierarchy is shown in Figure 1.1. In this master thesis *Sandik Crushing and Screening* and *Parts and Services* will be referred to as the case company and the intermediate organization, respectively.

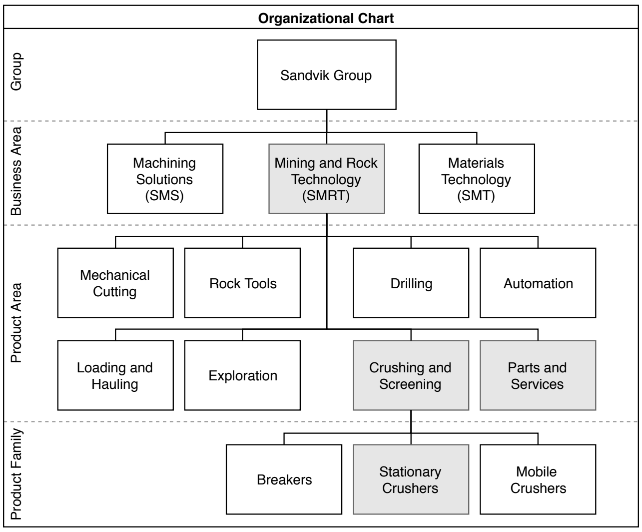


Figure 1.1: Product areas within *Sandvik Mining and Rock Technology*.

1.2.1 Product Area Crushing and Screening

As presented by the president of the Product Area (PA) *Crushing and Screening* (Svensson 2018), they offer advanced and proven solutions for any-size reduction process whether it is stationary or mobile. The equipment is engineered for maximum productivity with comprehensive life cycle services. The product portfolio includes three categories shown in Table 1.1.

Table 1.1: Product portfolio structure of *Sandvik Crushing and Screening*

Type	Use Case
Breakers	Applied in construction units to break rocks.
Mobile Crushers	Mobile unit with crushing and screening equipment mounted on it.
Stationary Crushers	Large non-movable and connected with screens and feeders.

Each category has a wide range of equipment that is used for rock crushing and processing. Figure 1.2 shows an overview of an exemplary mining site with *Sandvik's* solutions. Generally, the purpose and the type of rock define the processing equipment that should be used.

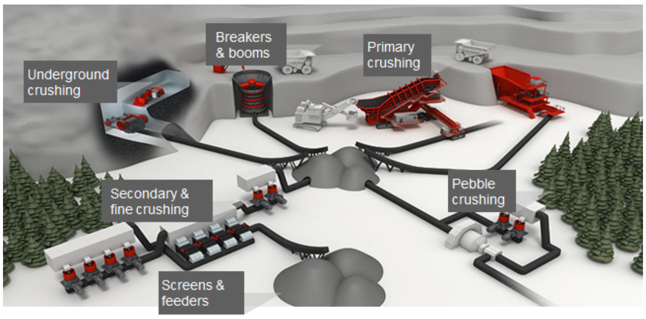


Figure 1.2: *Crushing and Screening* rock solutions (Sandvik Crushing & Screening 2018).

1.2.2 Current distribution network

The distribution network for spare parts (see Figure 1.3) is currently run by two different types of entities, the central network and the sales areas:

- *Central Network.* Central distribution centers in Western Europe and regional distribution centers on every other continent are operated by the logistics function of the intermediate organization. The distribution centers belong partly to the after-market function of the entire business area. Recently, one central distribution center has been transitioned to a new warehousing site managed by the case company.

- *Downstream Organizations.* Entities are most often responsible for the business in one country, where inventory is held in non-standardized ways. Some entities rely on inventory management principles, while others might build stock based on recent sales of new equipment and promises made towards end-customers.

The spare parts are partly produced by the production sites which are also assembling the new equipment, others are supplied externally.

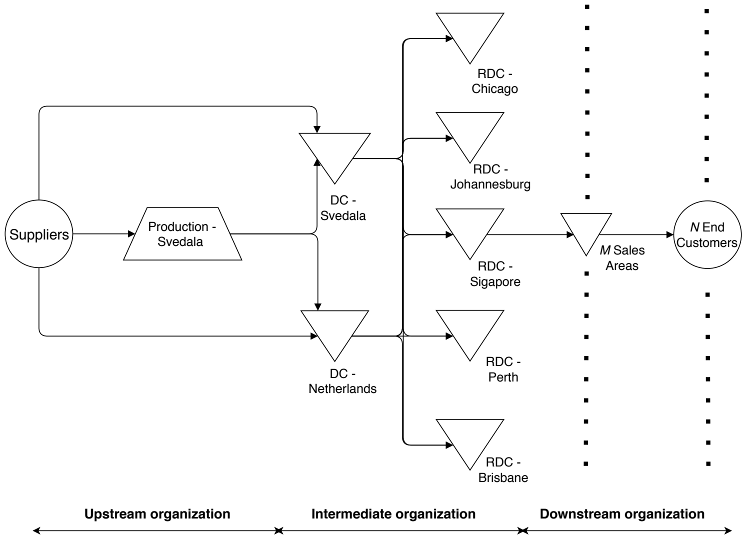


Figure 1.3: Current supply and distribution network.

1.2.3 Benchmark - *Sandvik Coromant*

Sandvik Coromant, another company in the *Sandvik* group, is active in the tools and inserts business for metal cutting applications such as turning and milling. The information in this section is mainly based on a telephone interview with a person responsible for Supply and Production Planning at *Sandvik Coromant* (Israelsson 2018). Inserts are small parts of a cutting tool that are worn off during use. These small yet expensive parts are regularly bought, have a high stock availability target and are shipped to customers over night. Insert holders are sold less often, also have a high stock availability goal but are shipped within 72 hours, often within 24 hours. The distribution network of the benchmark company consists of four distribution centres (DCs) located in four different geographical regions (more exactly in the Netherlands, North America, China and Singapore). The mode of transportation employed between the DCs is air-freight, for which fixed volumes are contracted from carriers serving airports close to the DCs. Supply into the distribution network and deliveries to customers are often road-based, but air freight is used when necessary.

By that, *Sandvik Coromant* offers its customers consistently short lead-times and maintains low inventory levels by pursuing a centralized distribution strategy in conjunction with express freight. Customers do not need to keep significant inventories and can rely on timely deliveries. Because insert holder production is designed for achieving short lead-times even for many customized products, customers can get those specific tools often in less than two weeks.

1.3 Problem definition and the proposed network

The case company is exposed to changing market conditions. Demand has been changing considerably resulting in a need for inventory adjustments. Recently, the demand has been increasing which has depleted inventories in parts of the after-market supply chain. This has resulted in decreased trust in the after-market capabilities of the case company by the downstream organization and end-customers. The main objective of this thesis is to develop a generic inventory model that can help to improve the after-market distribution network. For a sample of items a comparison is made between current and future inventory performances.

In comparison with other business areas inside *Sandvik Group*, the case company offers opportunities for improvement with regards to logistics cost. The company is wondering whether the logistics system for Stationary Crusher spare parts could be organized similar to the logistics system at the benchmark company *Sandvik Coromant* (see Section 1.2.3). Even though the product range is quite different, it is to be evaluated whether there are possible learnings to be transferred.

The after-market business model for the case company is considered to be different than the benchmark company. Spare part logistics differs from the logistics for consumables. The quantity and frequency of spare parts order lines are often low. In contrast, consumables at *Sandvik Coromant* have significant material flows.

Sandvik Crushing and Screening identifies some of their crushers as Core Products (or core machinery equipment). Core equipment are defined based on sales, profit, installed base and life cycle potential. Core equipment are as follows: Cone Crushers, Jaw Crushers and Screens. Each equipment consists of a large amount of components. *Sandvik* categorizes components for Cone crushers into four main types:

1. Wear Parts: Parts that are in direct contact with rocks and wear off during usage. Can be characterized as heavy, bulky and non-stackable.
2. Spare Parts: All nuts, bolts and small parts that have no proprietary drawing.
3. Key components: Strategic and important components that are *Sandvik* specific.
4. Major components: Large and heavy *Sandvik* specific parts that shapes the crusher.

The crushing products are recognized by the case company to have the highest potentials for improvement. Among the crushing products, cone crushers are chosen due to their popularity among customers. They come in different sizes and depending on the customers' requirements slight technical modifications are present. The case company is interested in improving the inventory management for their strategic components, thus, this master thesis will focus on two main categories, *Major components* and *Key components* (see Figure 1.5). According to the case company, strategic items are constantly driving the after-market sales, also, these items form a critical need for the crusher to function. Furthermore, the study will be conducted on an item level.

It has been directed by the management to start by modeling a single location warehouse. This thesis will, as a first option, consider an inventory model that relies on a single DC. The DC will supply end-customers with after-market spare parts (see Figure 1.4).

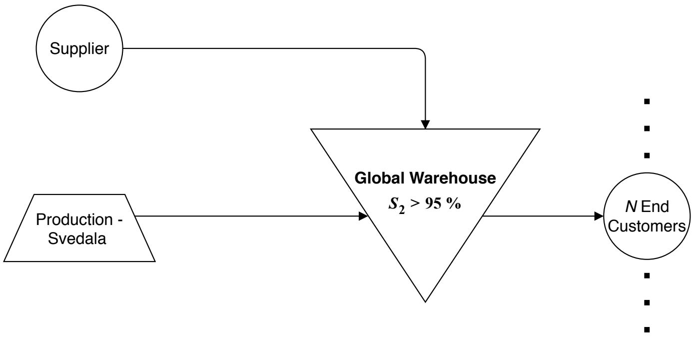


Figure 1.4: Distribution network with a single warehouse (later on referred to as Scenario 1)

Additionally, the company showed concerns regarding the rate of spare part sales per sold capital equipment varying greatly among different sales areas. It is suspected that this is mostly due to a difference in availability of spare parts toward the customer. The role of lost demand in connection with the analysis of the thesis will be discussed separately.

1.4 Purpose and research questions

The purpose of this thesis is to model and analyze a centralized inventory solution for the case company's aftermarket distribution system. Thus, the research questions are:

1. How much stock should be kept in a centralized inventory solution to accommodate a fill rate of 95 %?
2. What are the benefits and trade-offs of having such a system?
3. Can new equipment production use the centralized inventory solution as well?
4. How can lost sales be related to the suspected availability issues?

1.5 Research limitations and company directives

The aim of this section is to specify the the scope and limitations. A number of different limitations were determined together the case company. The following limitations are considered to limit the scope of the research. However, the limitations are thought to be able to deliver generalizable findings. The main limitations are as following:

- Demand data should be based on end customer sales orders only.
- The study should only consider a sample of key and major components for cone crushers.
- Target fill-rate in the virtual warehouse should be 95 %.

1. Not considered
2. Key component
3. Key component
4. Major component
5. Major component
6. Key component
7. Not considered
8. Not considered
9. Not considered
10. Key component
11. Key component
12. Not considered
13. Not considered
14. Not considered
15. Key component
16. Key component
17. Key component
18. Not considered
19. Key component
20. Not considered
21. Not considered
22. Major component
23. Not considered
24. Key component
25. Key component
26. Not considered

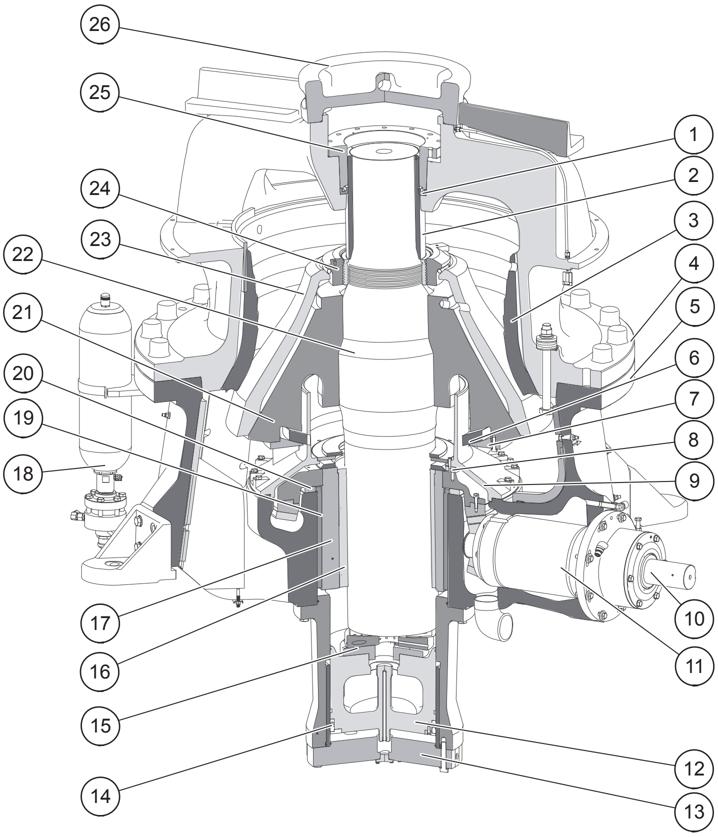


Figure 1.5: Overview of important parts in a
Cone Crusher with major components and key components highlighted as per definition by the case company.

Chapter 2

Methodology

This chapter discusses different types of methodologies used in operations research. It describes the approach that is used in this thesis and the working procedure that is followed. The data collection conducted and the criteria of research credibility are described and reflected upon.

Organizations have become more and more complex since the industrial revolution and along with division of labour and specialization. Along this development, it becomes more difficult to allocate resources for activities in an effective and efficient way for the whole organization. The ambition to find answers to questions of resource allocation builds the basis for Operations Research (Hillier & Lieberman 2001). Different frameworks have been published as attempts to improve the empirical base of operations research in relation to research methodology. One interesting framework has been developed by (Fisher 2007) which presents a two-by-two matrix (Figure 2.1) for empirical research in this field. The author distinguished four kinds of research methodologies depending on the goal of the research (descriptive or prescriptive) and the level of real world interaction (highly structured or less structured). This master thesis is discussing a highly structured data and algorithms that are directly related to the surrounding environment in order to provide a solution for a well defined problem, thus this thesis mainly falls under the Engineering category according to Fisher's matrix.

Also according to (Woodruff 2003), two research approaches, that any research follows when contributing to a field of knowledge, can be categorized. The categories include the inductive approach and the deductive approach (Figure 2.2). The inductive approach tries to generalize from a specific observation such as interviews to describe a phenomenon. On the other hand, the deductive approach relies on logical

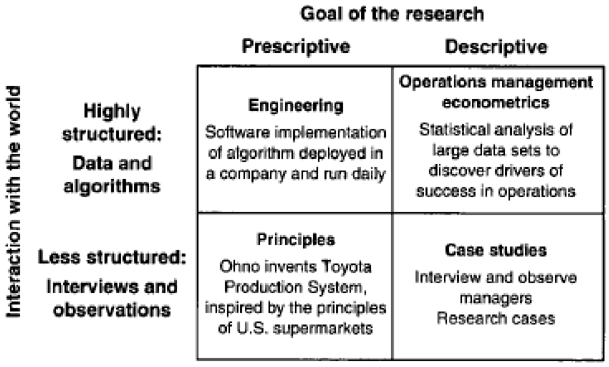


Figure 2.1: Empirical Research of operations research (Fisher 2007) .

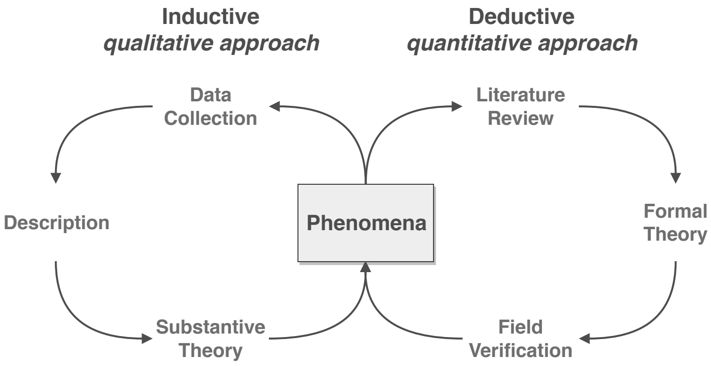


Figure 2.2: Inductive and deductive approaches to research (Woodruff 2003).

structures and certain preconditions in order to make true claims. Most parts of this master thesis rely on logical structures, literature reviews and actual data but also with the presence of some interview to understand the description of specific problems. Thus, this master thesis can be categorized as a mixture of both approaches (also known as abductive approach (Kovács & Spens 2005)), but with an emphasis on the deductive approach.

2.1 Approach

Quantitative research tries to discover solutions for real problems (Mitroff et al. 1974). This theory is established upon being able to separate subsystems through system boundaries, as do most of engineering disciplines. The authors describe the research process in four main elements:

(I) Reality: The origin of ideas and the starting point of research.

(II) Conceptual model: An abstract model that is related to reality.

(III) Scientific model: More formal terms with more formal relations between parameters (e.g. mathematical equations).

(IV) Result: Problem solving is applied to the well structured model in ordered to get the solution (e.g. linear programming).

If the four main elements of the research process result in a solution that is accurate for the problem question, an implementation process will close the loop and connect back to the main element which is reality (Mitroff et al. 1974).

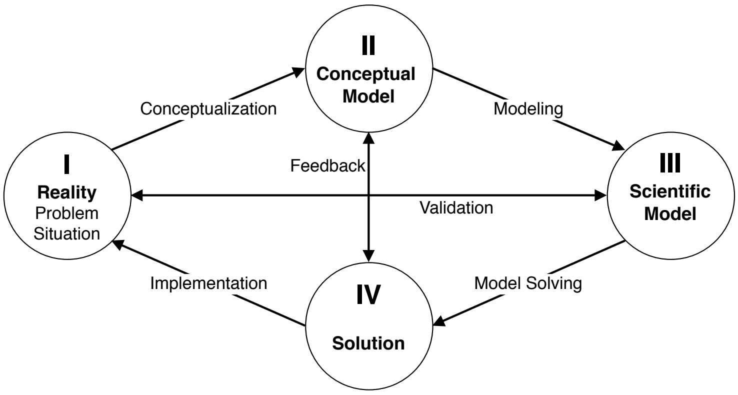


Figure 2.3: Systems view on problem-solving by (Mitroff et al. 1974).

The steps between those four main elements can be more closely (Sagasti & Mitroff 1973): Linking reality to the conceptual model is done by the process *Conceptualization*. This process relies on the idea that a researcher should not tackle a problem with an empty mind, rather with ideas, concepts, anticipations and expectations based on the researcher's background. The *Modeling* process establishes the relation between the conceptual model and the scientific model. In this step the researcher should identify and precisely define the controllable and uncontrollable parameters. The process of determining the "degree of correspondence" of the scientific model with reality is referred to as *Validation*. A very structured and well-defined relation between the scientific model and the solution is called *Model Solving*. In this process, technical skills should be complemented to the appropriate capabilities required in the conceptualization and implementation processes. *Feedback* means comparing the solution with the initial conceptualization. This allows to "test coherence and relevance of solutions", which may require a change in the initial conceptualization of reality. Feeding those results into reality is then considered the *Implementation* of the problem-solving process.

In this master thesis these steps have been put to use as follows:

(a) *Conceptualization:* The current supply chain network is characterized by numerous legal and organizational entities and stocking locations with mostly no standardized decision making. Theory as well as practices at a sister company suggest that there may be benefits from centralization of inventory locations.

(b) *Modeling* As the case company is undergoing a change that affects operations, it is important to construct a basic model for inventory control that utilizes the available data. The model should be adaptable to match reality more closely in the future. Therefore, the investigation first concentrates on a single-echelon, single item model.

(c) *Validation:* The comparison of the current supply chain network with the scientific model chosen leads to the generation of more realistic scenarios including five distribution centres, one per geographic business region.

(d) *Model solving:* An algorithm is designed and implemented in Visual Basic for Applications (Microsoft Excel) to evaluate and optimize the results of the the scientific model.

(e) *Feedback:* Results coherence and alignment with the conceptual model formed the importance of this step.

(f) *Implementation:* Presentation of the visualized model outcome and collection of feedback from practitioners at the case company. Based on this, the ability to implement the solution was discussed.

2.2 Working procedure

The working procedure for this study follows an approach similar to the one by (Mitroff et al. 1974) as described in Section 2.1. Figure 2.4 provides an overview of the working procedure.

Figure 2.4: Overview of thesis working procedure

The first step is to understand the real inventory system situation, formulate the problem and collect initial data to help developing thoughts for a conceptual model. Then a scientific model is built. It relies on data collection as inputs and validation techniques to confirm correspondence with the real system. Then, the scientific model solving offers initial results that are taken into further analysis. The results are then analyzed and reflected into reality in order to understand how the implementation of this model will influence the real situation. The analysis also includes testing of the conceptual model to make sure that it is aligned with theory and results.

2.3 Data collection methods

(Flynn et al. 1990) describe a step-wise approach to Operations Management Research. As a first step, it should be contemplated whether the endeavour entails theory building or theory verification. Afterwards, a research design is to be chosen. Furthermore, a data collection method is to be defined, for which they mention among others "historical archive analysis, observation, interviews, questionnaires and content analysis". Gathering this data is called "implementation" in their terminology, followed by data analysis. Then, a publication is to be produced and published.

Various data collection techniques can be used in logistics. Both quantitative and qualitative data collection methods are present. Quantitative techniques are most likely connected to numerical data and specifically to numerical analysis (Spens & Kovács 2006). On the other hand, qualitative data collection methods gather non-numerical data. The data collection method does not necessarily conclude the research type (quantitative or qualitative) as quantitative data can be used to be analyzed qualitatively and conversely, too (Spens & Kovács 2006).

2.3.1 Quantitative data collection

Archived data has no bias, as the data provider is not aware of the observation process. However, the desired data might be hard to obtain as the environment is not under the control of the observer. Historical archive analysis makes use of physical traces and archives, for example reports that firms are required to file (Flynn et al. 1990). This master thesis relies heavily on the case company data records. Data is documented and published using different software packages. As part of accessing the data, responsible data stakeholders are involved into granting access to the researchers. Data is also fragmented across different software packages and IT systems, therefore, the authors received administrative instructions for this data collection method.

2.3.2 Qualitative data collection

The interview is one of the most popular methods in qualitative research. It often is semi-structured, i.e. there is a predefined set of topics that are planned to be covered. It nevertheless is open and the interviewer can react to previous responses and change the course of the interview. The environment in which the interview is held as well as the briefing before and debriefing after an interview play an important role in creating a successful information exchange. Interview questions should be asked using the language of the interviewee (Kvale 2007). According to (Flynn et al. 1990) there are two main types of interviews; (1) structured interviews and (2) ethnographic interviews. Structured interviews often follow a standard form of questions that is scripted, however, other questions maybe asked based on the direction of the conversation. This type of interview allows for some comparison between the interviewees while keeping the focus on the depth of the personal interview. On the other hand, ethnographic interviews follow a hierarchy of questions that begins with a general question, by then, the questions are framed based on the interviewees answers. The quality of both interview types further improve with transcriptions, because the researcher is not distracted by taking detailed notes (Flynn et al. 1990). In this master thesis, a structured interview is held in order to collect qualitative data regarding the lost demand section. The interviewee was briefed with the interview questions prior to the interview. During the interview, the interviewer was not the one taking notes, rather, focused on the depth of the interview. It is worth noting that a challenging issue regarding this part can be the possibility for holding multiple interviews with similar stakeholders in order to gather more reliable qualitative data.

2.4 Research credibility

Research quality can be assessed through different factors. It has been pointed out that quantitative research is a method of the positivist paradigm (Näslund 2002). Positivists research is formed after mechanisms used in natural science. Research following the positivist method can be described as "good" if the following four criteria apply (Näslund 2002):

1. Internal validity
2. External validity
3. Reliability
4. Objectivity

Internal validity: Internal validity is concerned with the degree of how good the findings are in mapping the phenomena, in other words, how good the model is in presenting reality (Näslund 2002). In this thesis, a well defined theory (single echelon inventory optimization) is being used, therefore the internal model validity has already been tested across many years of previous research. The input data was continuously cross-checked with stakeholders to confirm an accurate representation of reality. Therefore, it is argued that the internal validity is high.

External validity: External validity is concerned with the outer space of the research and how well it is applicable in similar situations (Näslund 2002). As in this master thesis, the inventory being modelled is specifically done for spare parts supply chain distribution and the findings are in line with literature recommendations. The scientific model is general and was implemented in an algorithm without significant constraints. The algorithm can be used in similar settings and does not have to follow the same assumptions that have been used in the project work (e.g. replenishment quantity Q: the calculations in this report are based on $Q = 1$, but the model has been designed to work with any quantity).

Reliability: Research reliability includes the degree of which the finding can be repeated or reproduced (Näslund 2002). Regarding the scientific model in this master thesis it has been further tested manually and produced the same numbers for the same inputs. Furthermore, the inputs are thought to be the main challenge in this thesis as data collection process relied on gathering data, cleaning data from outliers and validating it for usage. The model consistently produces the same output for the same inputs. Thus, the reliability is considered to be high.

Objectivity: Objectivity is concerned with the research bias and how to develop bias-free findings (Näslund 2002). This research relied on mathematical modeling that is well defined in literature, the collected data has no influence over the mathematical model design, rather, the mathematical model objective is to prescribe a solution for the real situation and the results are then analyzed and understood without any directives. For some parts of this thesis, where the researchers discuss the issue of lost sales, qualitative data collection was relied on to gather further understanding that was not acquired from archived data, therefore, a bias toward the interviewee could be possible regarding this part. The statements from the interview have been put into context and it has been made clear that their validity is restricted to the geographical responsibility of the interviewee. As the general recommendation is to further look into this matter, this possibility of a bias is not considered severe.

Closely connected to the question of research credibility is the selection of and reflection on the sources. Source criticism has its roots in the historical sciences. According to (Thurén 2003), source criticism is not possible based on a "recipe" only, but requires (1) knowledge, (2) attention to small things, (3) thoughtfulness, (4) imagination, and (5) awareness of one's own prejudices. Based on those prerequisites, it is possible to attempt an evaluation of a source regarding four dimensions (loosely translated from (Thurén 2003)):

1. Authenticity
2. Time
3. Dependency
4. Tendency

Authenticity means that the source has not been forged. All sources used in this thesis are either based on genuine internal information (company records, personal meetings and conference calls) at the case company or literature from recognized journals and publishers when it comes to theory. Therefore, authenticity is achieved by relying on subject authorities (well reputed scientific journals) and representatives appointed by the principal at the case company.

Time relates to the fact that the human memory changes over time. Company records have been used to provide evidence regarding past developments. Other information related to the current state at the case company, which makes the factor time unproblematic.

Dependency considers rumors and different kinds of influences. Personal sources have been contacted based on directives or multiple referrals from previously established contacts. In some cases, only one source was used, however care was taken not to consider information that might have been influenced by dependency. The main outcomes of the thesis are based on scientific models and archival records, which makes a possible dependency less impactful.

Tendency means that sources that are affected by the research are less trustworthy than impartial sources. Company employees could have been biased to present their performance or the state of a specific part of the organization different from reality. The interests of stakeholders have been reflected upon in order to prevent an adverse effect on the credibility of the research and its conclusions. No potential of significant influence of the research outcome due to tendency has been identified.

Chapter 3

Theoretical Framework

First, a brief introduction to order qualifiers and order winners is provided. Then, a basic inventory system under certainty is described. The influence of supply and demand uncertainty and the role of safety stock are then introduced. Furthermore, the steady-state nature of inventory models and the crucial role of the lead-time demand are touched upon. The general function of the probability distributions of the lead-time demand, inventory levels, and how those are related to basic performance measures of inventory systems are described. After establishing these fundamentals, closed-form expressions and scientific findings based on the popular assumption of Normal distributed demand are recapitulated. Furthermore, implications of using the Normal distribution are compared to using discrete demand distributions, such as the Poisson distribution and the Negative binomial distribution.

3.1 Order winners and qualifiers

Hill & Hill (2009) introduce the concept of distinguishing customer desires into order qualifiers and order winners in their *Framework for linking corporate objectives and operations and marketing strategy development*:

Qualifiers "get a product into a marketplace [...] and keep it there" – should the company not manage to deliver this attribute satisfactorily, this leads to losing customers; some qualifiers are especially order-losing sensitive and should thus be carefully considered. Order-winners then are used to compare different offers that are under consideration due to the fulfillment of the qualifiers.

The importance of one qualifier or order winner might change depending on the time and market as well as growth and new market entry aspirations. Price and delivery speed are two prominent examples, which illustrate that those attributes are not independent but rather often involve trade-off situations.

They furthermore present examples of attributes that often are important qualifiers or order winners, a selection of which will be briefly introduced.

- **price:** most often, price is perceived as a qualifier: potential suppliers are shortlisted based on whether their offer lies in a reasonable price range compared to their competitors. The lowest bidder does usually not get the order without any other factor considered.
- **delivery reliability:** meeting the promised delivery date is often considered an order qualifier. However, it is only experienced once the order is placed. In some businesses, this criterion is classified as being order-losing sensitive.
- **delivery speed:** is often considered an order winner.
- **quality conformance:** is often considered an order qualifier, as customers expect the product to adhere to its specifications.

3.2 Demand categorization

Syntetos et al. (2005) suggest that the use of forecasting methods for spare parts demand should be undertaken using their four-field decision matrix. It employs two dimensions: the average demand interval and squared coefficient of variation (which are denoted here with ADI and CV^2, respectively). Cut-off values have been defined based on goodness-of-fit tests with large data-sets of real demand patterns against different forecasting methods.

Even though this categorization was originally intended for choosing the optimal model to forecast future demands (Syntetos et al. 2005), it will hereafter only be used to present a structured overview of the demand patterns present at the case company (see also limitations regarding forecasting in Section 1.5). The four classes of demand as shown in Figure 3.1 are called (1) smooth, (2) intermittent (but not very erratic), (3) lumpy, (4) erratic (but not very intermittent).

The average demand interval ADI is, different from the proposed forecasting procedure, not updated based on exponential smoothing (also, it was originally denoted with p Syntetos et al. (2005)). Inter-demand intervals are considered if there have been periods with no recorded demand that are followed by a period with non-zero demand. This means that an item with only one demand period recorded can have different values for their ADI. If the only non-zero demand period occurs in the very first period considered, the interval between the zero-th period and the first period is considered as 1. If in the opposite case, the only non-zero demand period is in the

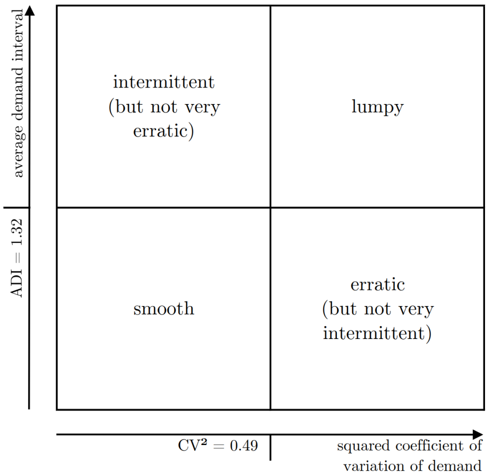


Figure 3.1: Demand categorization model (Syntetos et al. 2005).

most recent period considered, the total number of periods considered is recorded as ADI. Thus, when put into practice, such cases have to be considered carefully. The squared coefficient of variation CV^2 is in this context defined as in (3.1).

$$CV^2 = \left(\frac{\text{standard deviation of demand sum in non-zero demand period}}{\text{arithmetical mean of demand sum in non-zero demand period}} \right)^2 \tag{3.1}$$

The matrix model distinguishes four different demand types with rather ambiguous names. It is intuitive to understand that smooth demand occurs in (nearly) every period and is fairly predictable regarding the number of demanded items. In contrast, lumpy demand exhibits demand not in every period and the amount of demanded items varies considerably. The classes intermittent and erratic might both appear more random to the observer but differ in the source of the demand variability: intermittent demand is mostly characterized by periods of no demand but does not exhibit high variability in the demand sum of a period. This is on the other hand the major source of demand variability of erratic demand, which in turn does not have as many periods with no demand (Ferrari et al. 2006). That being said, it is likely that Normal demand assumption based inventory management systems perform well for smooth demand but are less accurate with erratic, intermittent and lumpy demand.

3.3 Basic Inventory System

The following remarks on inventory management and most of the notation builds on the book *Inventory Control* (Axsäter 2006). Figure 3.2 shows a basic inventory control system.

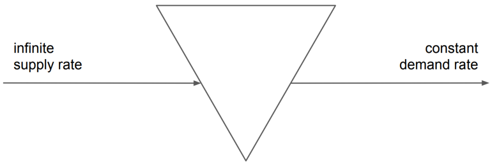


Figure 3.2: Single stage inventory system.

Under constant demand and constant lead-times, orders can be placed so that a replenishment arrives exactly when stock has depleted to zero. This behavior results in the basic sawtooth pattern, which can be observed in Figure 3.3.

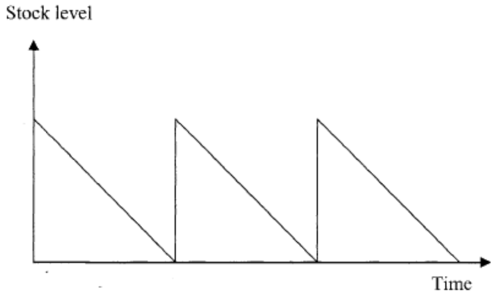


Figure 3.3: Basic inventory graph under constant demand rate and order quantities. Source Axsäter (2006)

In this basic case, all demand is satisfied directly from stock, as replenishments arrive in the time instant when the stock level reduces to zero. It could however be beneficial to let customers wait. In this case, the stock level decreases below zero.

3.4 Supply and Demand Uncertainty

In industrial inventory systems, the underlying assumptions of the aforementioned basic model do not apply: Demand is seldom constant or deterministic; supply uncertainties add on to the complexity of inventory systems in reality. Therefore, inventory is oftentimes held in addition to the turnover stock seen in Figure 3.3. This type of inventory is called safety stock.

More general inventory models consider back-orders: If there is no stock on hand when a customer demand materializes, customers wait to receive the item. In contrast to models in which consequences of back-orders are described by a cost factor, the chosen model considers full back-ordering under an availability constraint.

There are two possible generic states of an inventory when a customer arrives:

either there is stock available or there is not. It is the most intuitive way to think of inventory as physical goods that are available. However, customer demands that have not been satisfied yet (backorders) and replenishments that have not arrived yet have to be considered as well. Those three elements are necessary to define two indicators of an inventory system: The inventory position IP and the inventory level IL.

The inventory position IP is the basis for ordering decisions of the inventory system and defined as in (3.2).

$$IP = \text{physical stock on hand} + \text{replenishments outstanding} - \text{backorders} \tag{3.2}$$

When evaluating the inventory performance (e.g. in terms of holding and backordering costs), the inventory level IL has an important role. It is defined similar to the inventory position IP but does not consider replenishments outstanding, as shown in 3.3.

$$IL = \text{physical stock on hand} - \text{back orders} \tag{3.3}$$

Hence, if there is stock on hand, $IL > 0$ – if customer demand is backordered, $IL < 0$.

From here on, we are using the following notation for simplicity: stock on hand is donated with IL^+, and back orders are denoted with IL^-. More formally, they can be defined as in (3.4) and (3.5).

$$IL^+ = \max(IL, 0) \tag{3.4}$$

$$IL^- = \max(-IL, 0) \tag{3.5}$$

3.5 Continuous and Periodic review of (R, Q)-based inventory systems

When the reorder-quantity Q is fixed, a common inventory management policy is the $(R,\ Q)$-policy. That is, when the inventory position decreases to the reorder point R, a replenishment of Q units should be requested. A special case of this policy is the $(S-1, S)$-policy or base-stock policy, i.e. $Q = 1$ and $R = S - 1$. Every time the inventory position IP falls to or below R, a new replenishment is requested. An exemplary pattern of how the inventory level IL and IP can develop in an (R, Q)-system subject to discrete unit demand can be seen in Figure 3.4.

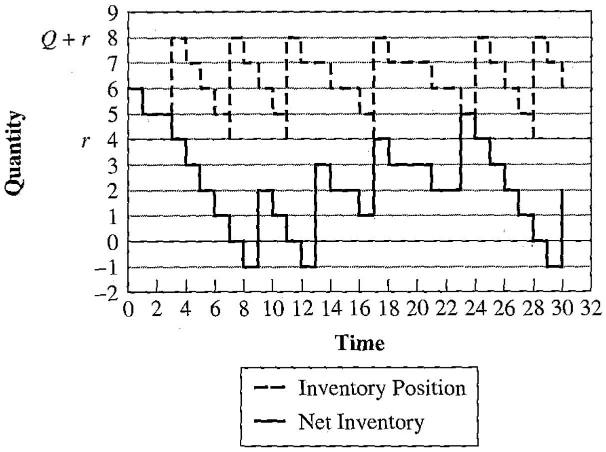


Figure 3.4: IL and IP with $R = 4$ and $Q = 4$ (Hopp & Spearman 2000).

Depending on the frequency of checking the current status of the inventory, review systems can be characterized as either continuous or periodic review.

While in periodic systems, IP is only checked and acted upon at defined time instances, a continuous review system always keeps track of IP in real time (Axsäter 2006). Periodic review systems need to take the review interval into account in determining inventory parameters (see Figure 3.5). In Figure 3.5, R represents the inventory position IP that triggers an order, while Q represents the quantity ordered. Companies with Enterprise Resource Planning software and Electronic Data Interfaces often have very short review intervals as does the case company, thus this thesis will not elaborate on distinctive features of periodic review systems. On the other hand, continuous review systems track the current status of the inventory and issue requests for replenishments at appropriate instances.

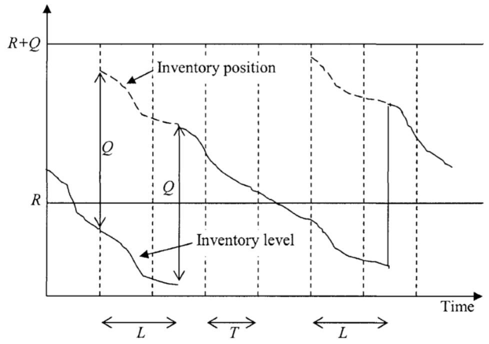


Figure 3.5: Basic inventory graph to illustrate periodic review for a (R, Q)-policy (Axsäter 2006).

3.6 Demand during stochastic lead-times

The demand and supply at an inventory system can be seen as two separate stochastic processes. These empirical processes can be approximated by fitting a probability distribution using the first two central moments of the random variable.

When analyzing empirical data of an inventory system, demand is considered per period (e.g. month). The occurrence of a demand per time units forms the population to determine both the mean and variance. The mean and standard deviation of the demand per time unit are denoted μ_d and ${\sigma_d}^2$, respectively. While these might be determined by forecasting efforts, this report considered an arithmetical average and variance of a sample period (see Section 4.3). The supply lead-time is treated similarly. Here, the distribution of the lead-time duration is of interest. It is the population for determining the mean and variance of the lead-time, which are denoted with μ_{LT} and ${\sigma_{LT}}^2$, respectively. Under the assumption of sequential deliveries and independence of the lead-time from the demand, an approximation may be used. Sequential deliveries refer to the principle of orders not crossing in time. Independence of the lead-time is given if lead-times are not influenced by future demand. Under this assumption, lead-times do not become longer due to unusual demand levels at a supplier (Axsäter 2006). The mean demand during the lead-time μ' and the variance of demand during the lead-time (${\sigma'}^2$) can then be obtainied from (3.6) and (3.7) (Axsäter 2006).

$$\mu' = \mu_d \cdot \mu_{LT} \tag{3.6}$$

$$\sigma' = \sqrt{{\sigma_d}^2 \cdot \mu_{LT} + {\mu_d}^2 \cdot {\sigma_{LT}}^2} \tag{3.7}$$

When determining demand probabilities for a given system, appropriate demand distributions are used to describe a steady state.

3.7 Performance measures of inventory systems

In inventory models, common performance measures are different types of service levels to customers. There are a lot of different definitions of such measures, three popular service level measures are (Axsäter 2006):

- S_1 : service level 1, *cycle service level* – probability of no stock-out per order cycle
- S_2 : service level 2, *fill-rate* – fraction of demand satisfied immediately from stock
- S_3 : service level 3, *ready-rate* – fraction of time with positive stock on hand

In practice, measuring those indicators is done in many ways. Organizations can decide to consider entire orders (of different products) or order-lines (of individual items) in their indicator or instead choose to also consider partly filled orders or order-lines, either based on quantities or item value (Larsen & Thorstenson 2014, Ronen 1983). Alternative performance measures are the customer order waiting time (Tempelmeier 2000) or allowing for a per-customer definition (Zinn et al. 2002). (Cohen & Lee 1990) highlight in their case study that for spare parts, especially the part unit fill rate, part dollar fill rate (by either cost, revenue or contribution), order fill rate, repair order completion rate (repair orders typically need more than one spare part to be executed) as well as customer delay time are relevant indicators to measure.

Furthermore, companies are interested in determining cost factors that can help in the decision making process. It is popular to consider

- cost of placing an order (or: ordering / set-up cost) – the administrative handling of a purchase or production order as well as one-time costs such as handling fees and set-up times in production.
- cost of transportation – depending on the inventory and customer location as well as the desired time to satisfy the customer demand and the physical dimensions of the item, a cost is incurred for physical movement
- cost of holding inventory (or: holding cost) – inventory ties up capital; thus most often an interest rate on the item value is imposed in inventory models. recently, the belief of capital cost being the dominant factor in holding costs has been challenged (see e.g. Berling (2008))
- cost of backorder / lost sales – customers might turn to a different supplier - the loss of customer goodwill when not satisfying their demand can be considered, most often using a factor per unit and time unit

Two important measures; stock on hand $E[IL^+]$ and backorders $E[IL^-]$, are crucial for determining cost-based performances (see Section 3.12). This thesis focuses solely on the minimum inventory level necessary to fulfill a certain service level constraint. More detailed information regarding total cost-based inventory optimization can be obtained e.g. from Axsäter (2006).

One commonly used performance measure of inventory management efficiency is the turnover ratio or inventory turnover (Hopp & Spearman 2000). It is defined as the ratio of throughput to average inventory. The ratio represents the average number of times inventory is replenished.

$$\text{Inventory turnover} = \frac{\text{Throughput of products}}{\text{Average inventory on hand}} \tag{3.8}$$

Days of supply *DOS* is a measure of the inventory on-hand based in relation to estimated future demand (e.g. average demand) (Arnold et al. 2007). It is the inverse of the inventory turnover adjusted for days. If μ_d is based on a period of months, the formula for days of supply becomes (3.9).

$$\text{DOS} = \frac{E[IL^+]}{\mu_d} \cdot 30 \tag{3.9}$$

3.8 Normal demand

It is common to assume that the lead-time demand follows a Normal distribution. We follow the common convention to denote the probability density function of the standardized Normal distribution (mean = 0, variance = 1) with φ and its cumulative distribution function with Φ. Using the simple conversion in (3.10), we can use tabulated values.

$$\underline{\overline{X}} \sim N(\mu, \sigma) \longrightarrow Z = \frac{\underline{\overline{X}} - \mu}{\sigma} \sim N(0, 1) \tag{3.10}$$

It can then be shown that the probability of no stockout per order cycle for a given reorder-point R is available as closed-form expression in (3.11).

$$S_1(R) = \Phi\left(\frac{R - \mu'}{\sigma'}\right) \tag{3.11}$$

It almost as easy to determine the fraction of demand that can be satisfied immediately from stock on hand for a given reorder-point $S_2(R)$ using (3.12) and (3.13).

$$S_2 = 1 - \frac{\sigma'}{Q}\left[G\left(\frac{R - \mu'}{\sigma'}\right) - G\left(\frac{R + Q - \mu'}{\sigma'}\right)\right] \tag{3.12}$$

$$G(x) = \varphi(x) - x(1 - \Phi(x)) \tag{3.13}$$

In industry, the so-called safety factor k (or sometimes z) is often used to determine safety stock levels. For many aspired service-levels S_1, corresponding safety factor values are available in tables. The safety stock is then calculated as the standard deviation of demand during the lead-time σ' times the safety factor k. When determining safety stock levels (or the reorder point) under a fill-rate constraint, i.e. with a certain desired value for S_2, the fill-rate has to be determined for a number of values in a reasonable search range, g. by using a bisection algorithm. Under a fill-rate constraint, the lowest reorder-point R that satisfies the constraint renders the lowest inventory on-hand.

3.9 Normal demand assumption and discrete alternatives

Traditionally, the normal distribution assumption has been used widely in industry. This is beneficial as values of the standardized Normal distribution are available in tables and are easily accessible in enterprise software. In reality, demand occurs most often in non-negative integer values (Axsäter 2006).

When using the Normal distribution assumption, there is a risk of overestimating the availability provided. The Normal distribution is continuous and probabilities for negative demand might be considered due to the left-hand tail of the bell curve. It should therefore only be used when the lead-time demand is relatively high compared to the standard deviation (Axsäter 2006). Alternatively, non-negative distributions can be used in order to avoid negative demand probabilities. Both continuous and discrete distributions exist for this purpose. In case of relatively low demand, discrete demand distributions fit the purpose well. Here the calculation of demand probabilities has to be carried out for all demand sizes. This makes the computational effort relatively high compared to the search strategies possible in the case of normally distributed demand. Computationally, using the Poisson distribution is quite convenient, as the probability mass function is readily available in computer programs. For practical discrete demand distribution fitting, decision rule based on the variance-to-mean ratio, which we denote with VMR, is provided (Axsäter 2006) .

$$VMR = \frac{\sigma'^2}{\mu'} \tag{3.14}$$

For reasons of computational efficiency and convenience it is argued that usage of Poisson distribution is suitable as long as $VMR \approx 1$. By definition, the variance-to-mean ratio VMR of the Poisson distribution is $VMR = 1$.

The proposal is thus to use the Poisson distribution with $0.9 \leq VMR \leq 1.1$. For $VMR > 1.1$, it is recommended to use the negative binomial distribution to model the demand (Axsäter 2006). The probability mass function for the negative binomial distribution is only defined for $VMR > 1$, which becomes clear when looking at (3.17)–(3.19).

For $VMR < 0.9$, the possibility to use appropriate binomial distributions is mentioned (Axsäter 2006), while it could also be argued that the risk of considering negative demand under the normal distribution assumption becomes relatively small for $VMR \ll 0.9$. In practice, using the Poisson distribution is the method of choice, even though it overestimates the variance (Axsäter 2006) .

3.10 Poisson distribution

If assuming Poisson distributed demand during the lead-time, the probability distribution function for k demanded items with an average of μ' items demanded during the lead-time is (3.15).

$$P(D[L] = k) = \frac{e^{-\mu'} \cdot \mu'^{k}}{k!} \tag{3.15}$$

The variance σ'^2 is equal to the mean μ', which renders the variance-to-mean ratio from (3.14) to be $VMR = 1$. The factorial $k!$ is defined by recursion, which has implications regarding the computation of the probability mass function: When determining the value of the factorial separately, very large values have to be processed by the computer program of choice. This problem can be avoided by either using readily available tables of the probability mass function for Poisson distribution or using a recursive calculation.

3.11 Negative binomial distribution

Another discrete, non-negative probability distribution is the Negative binomial distribution. Instead of being defined by mean and variance directly, the notation of the probability mass function used hereafter is based on parameters p and r.

$$P(k) = \binom{k + r - 1}{k} \cdot (1 - p)^r \cdot p^k \tag{3.16}$$

The negative binomial distribution expresses the probability of yielding k times *success* before r times *failure* have taken place in a row of independent and identically distributed Bernoulli trials (Cook 2009). The above definition strictly requires $r \in \mathbb{Z}^+$ due to the binomial coefficient. However, the suggested distribution-fitting equations based on the definition of mean and variance of the negative binomial distribution, (3.17) and (3.18), do not necessarily result in values satisfying this condition.

$$p = 1 - \frac{\mu'}{(\sigma')^2} \tag{3.17}$$

$$r = \mu' \cdot \frac{1 - p}{p} \tag{3.18}$$

In order to allow for $r \in \mathbb{R}$, it is decided to therefore follow the definition by Axsäter (2006). The closed form of the probability mass function is then defined by (3.19).

$$P(D[L] = k) = \frac{r(r + 1)\ \ldots\ (r + k - 1)}{k!} \cdot (1 - p)^r \cdot p^k \qquad k = 1, 2,\ \ldots \tag{3.19}$$

With the probability of no demand during the lead-time being defined as $P(D[L] = 0) = (1-p)^r$, all following probabilities can be computed recursively using (3.20). This way, the computational impediments of using the factorial are avoided.

$$P(D[L] = k) \;\; = \;\; P(D[L] = k-1) \cdot \frac{p}{k} \cdot (r + k - 1) \tag{3.20}$$

3.12 Inventory level probabilities

Using (3.15) – (3.20), the demand probabilities can be calculated with reasonable computational effort and can be stored for later use. In order to limit computation time, an upper bound could be defined – it could for example be deemed sufficient to determine demand probabilities until the sum of all probabilities equals 99.9999%.

It can be shown that the inventory level IL can be determined using the inventory position IP and the lead-time demand $D(L)$: $IL = IP - D(L)$. Based on the distribution of the inventory position and the assumption of steady state conditions, (3.21) can be derived (Axsäter 2006, ch. 5.3.3).

$$P(IL = j) = \frac{1}{Q} \sum_{k=max\{R+1,j\}}^{R+Q} P\left(D[L] = k - j\right) \quad for\ j \leq R+Q \tag{3.21}$$

In determining $P(IL = j)$, computational effort can be reduced by using the relationship in (3.22).

$$P(IL = j \mid R) = P(IL = j + i \mid R + i) \tag{3.22}$$

As the inventory level IL cannot become any higher than $R+Q$, computation of the ready-rate S_3 (fraction of time with positive stock on hand) becomes simple: (3.23).

$$S_3 = P(IL > 0) = \sum_{k=1}^{R+Q} P(IL = k) \tag{3.23}$$

The ready-rate S_3 is defined as the probability of (and, share of time with) positive inventory, which is the prerequisite to serve a customer order. If demand is continuous or if customers always order only one unit, every customer arriving will get his order fulfilled with a probability of S_3. In this case, the ready-rate is exactly the same as the fill-rate S_2, the share of demand being fulfilled directly from stock on hand Axsäter (2006). If demand is not strictly one-for-one, but at least dominant across a sample, it can be used as an approximation.

Similar to the ready-rate, the expected value of inventory on-hand needs to consider all possible positive values of the inventory level and is given by (3.24).

$$E[IL^{+}] = \sum_{k=1}^{R+Q} k \cdot P(IL = k) \tag{3.24}$$

3.13 Centralization in spare parts distribution

Spare parts distribution strategy should be aligned with the spare parts business strategy. If the company's focus is to only decrease costs, then inventory centralization will help in lowering storage costs, avoid excessive stocking and parts obsolescence. If the brand image and customer retention are among the main goals, then high availability and fast delivery of spares are especially important. Spares should be stored locally with the tendency of overstocking if the last goals were considered (Wagner et al. 2012).

Maister has initiated a discussion regarding the effect of a change in inventory locations serving a given demand by publishing his paper on the "square root law of inventories" (Maister 1976). The extreme case of centralization of several inventory locations into a single location would achieve a per cent reduction as shown in (3.25).

$$\text{per cent reduction} = 1 - \frac{\text{centralized inventory}}{\text{decentralized inventory}} = 1 - \frac{1}{\sqrt{n}} \tag{3.25}$$

However, this relationship is based on several assumptions that have been discussed since the topic was brought up the first time. Depending on the set of assumptions, it has been discussed whether the relationship is applicable for the cycle stock and safety stock or only for safety stock. Among others, it is required for the demand to be normally distributed and replenishments need to be carried out based on an economic order quantity (EOQ) model with a constant supply lead-time. Furthermore, the different demands need to be uncorrelated, and be the same at every stocking point (Fleischmann 2016).

However, those savings do not allow conclusions regarding total saving but do only relate to the change in inventory carried. If the above mentioned assumptions do not hold, a different approach has to be chosen in order to determine possible reductions in inventory held by centralization efforts. Examples of alternatives are the numerical approaches that have been used to look into more specific cases (Fleischmann 2016, Nozick & Turnquist 2001).

It is noted by Tallon that adverse effects are to be considered as well. One of these effects is the increase of distance to markets, and hence lowered customer service. This lower service might be remedied through transportation and/or order processing improvements. Thus, product consolidation and transportation performance need to be looked at not as singular matters but as a holistic system. The influence of demand and supply variability (see Section 3.6) on the necessary safety stock needs to be considered and contractual agreements with customers and suppliers can be used to reduce the variability the inventory system has to compensate. By that, safety stock can be reduced in a decentralized set-up or even increase the improvements when changing to a centralized set-up (Tallon 1993).

Centralized and decentralized service supply chain strategies have been compared by Cohen et al. (2000). They postulate that the choice of having a centralized or distributed service strategy should be determined by the service criticality or need urgency of the customer (Cohen et al. 2000). Thus, if service criticality is high, a distributed service strategy should be employed while for low service criticality, a centralized service strategy is a good match. Furthermore, they compare centralized and distributed strategies in terms of four attributes, performance targets, network structure, planning process and fulfillment process, which can be found in Table 3.1.

Table 3.1: Comparison of service supply chain strategies (Cohen et al. 2000).

Attributes	Centralized	Distributed
Performance Targets	Achieving the highest level of inventory turnover at the lowest cost.	Ensuring that customers can rapidly obtain any critical part.
Network Structure	A small number of central warehouses and repair depots.	Inventory and repairs available from locations close to customers.
Planning Process	Visibility of demand at the point of sale.	Inventory and transaction visibility at all levels.
	Statistical forecasting of local demand and lead times.	Forecasting based on estimates of reliability of parts and installed base (customer region).
	Stocking decisions at retail locations made independently of network decisions.	Stocking decisions are made based on what products are required and where they are available for all locations.
Fulfillment Process	Drop-off or mail-in repairs are a viable alternative.	Parts are designed to be easily serviced by the service provider (the manufacturer).
	Little fulfillment coordination needed among stocking locations.	A high level of coordination exists among all stakeholders in the supply chain.
	Both planning of inventory levels and physical fulfillment may be outsourced.	Planning of supply-chain management is rarely outsourced.

Chapter 4

Modeling and Data collection

In this chapter, the steps of conceptualization, modeling and model solving are reflected upon by describing the current way of working with inventory at the case company. Furthermore, this chapter presents the design and execution of the proposed models as well as performance data to put the model outcome into perspective.

4.1 Inventory Management at the case company

Inventory is managed in the intermediate organization, but not necessarily in the downstream organization entities. The following description is based on the current practices of the team that the researchers were associated with (Dahlborg 2018). It concentrates on the processes related to the model discussed in this thesis: The basic review system in use, lead-time determination and setting of reorder-point.

All inventory for the case company's after-market operations is managed based on review systems. Setting the re-order point is done either automatically or manually. Per item, an indicator (flag) is set in order to activate a mode of updating the reorder point. These alternative modes are

- A (R_A): automatic determination using S_1-based safety factor and forecasting
- M (R_M): force usage of manually set re-order point
- G (R_G): use $MAX(R_A,\ R_M)$

In the European DC, these settings for the selected sample are 49.6 % flag G, 47.1 % flag A as well as 1.7 % flag M.

When setting the re-order point manually, the reason for that is supposed to be documented (SMCL 2014*a*). One example for this practice is that inventory is built up before the summer months in order to hedge against longer lead-times during popular vacation periods or during the beginning and end of the product life cycle.

When setting the reorder-point R automatically, it is set based on three different calculations, of which the greatest value is used. One option considers a service level goal S_{goal} which corresponds to safety factors, similar to the determination of safety stock using S_1.

1. safety factor, demand-forecast and its updated forecast error
2. average monthly consumption in last 12 months
3. manually set number of weeks of forecasted consumption

Similarly, the order quantity can be set manually or automatically, rules are defined based on a categorization system further described below. If definitions are not available on a per-item level, default values set on a category level are used. For automatic values, both determination of an economic order quantity and a given number of demand forecast periods can be used for generating an order quantity.

4.1.1 Lead-time

The supply lead-time has an important influence on the need for inventory and is considered in the determination of the demand during lead-time (see Section 3.6). Thus, it is important to describe how the lead-time is measured and managed by the case company. Personal communication with experts at the case company has been conducted to understand this (Dahlborg & Ringsbo 2018).

The company-specific extension of the ERP-system can estimate the average lead-time based on the record of observed lead-times. It can be used to set the system lead-time on initiation by a user (SMCL 2014*b*). However, variability in supply lead-time has historically not been considered. Interviewees in the case company highlight that lead-times that turn out to be longer than planned are critical for parts availability.

There has up to today not been lead time accuracy measurements resulting in consequences for the supplier relationship. Lead-times are discussed with suppliers, but not actively negotiated. The case company however expresses the desire to change towards a more active role in negotiating, measuring and following up lead-times and their accuracy. Results of discussions with suppliers are used as planned lead-times in the inventory control system. On a case-by-case basis, orders are expedited, the effect of emergency shipments should however not result in lower lead-times for inventory determination purposes. In the system, lead-time is managed based on a split of internal lead-time, supplier lead time and transportation lead time. It is expressed as fraction of weeks (SMCL 2014*a*).

4.1.2 Methods of categorization

The company currently uses four different ways to categorize items in addition to their hierarchical classification. The categorizations are based on sales intensity (order occurrences, not quantity), sales profitability (ABC analysis), item criticality and movement (new introduction, slow movement, obsolescence). Item criticality is a manually maintained code which does not impact inventory policies.

4.2 Model design and execution

As a main deliverable to the case company, a decision support tool for determining minimum reorder points under a given fill-rate constraint was agreed upon. Both due to the restrictions in demand data available and the limitation not to look at forecasting as a focus area, the decision support tool expects the mean and variance of the demand during the lead-time as well as the ready-rate constraint as inputs. Note that using this tool when optimizing for a given fill-rate S_2 constraint, it needs to be ascertained that customer demand occurs one-by-one, i.e. every demand consists of exactly one unit of the considered item. Otherwise, the result has to be interpreted strictly as the ready-rate S_3, which is the fraction of time with positive stock on hand. Spreadsheet cell formulas are provided in order to determine those inputs from data extracted from the ERP systems.

The model considers one single stock-location (installation stock) at a time. Table 4.1 summarizes the inputs and outputs of such model.

	Input
S_3	target ready-rate
Q	order quantity
μ'	mean demand during lead-time
σ'	standard deviation of demand during lead-time

	Output
R	recommended reorder point
${S_3}^*$	theoretical ready-rate achieved
$E[IL^+]$	average inventory on hand

Table 4.1: Inputs and outputs of the tool programmed in Visual Basic for Applications (Microsoft Excel).

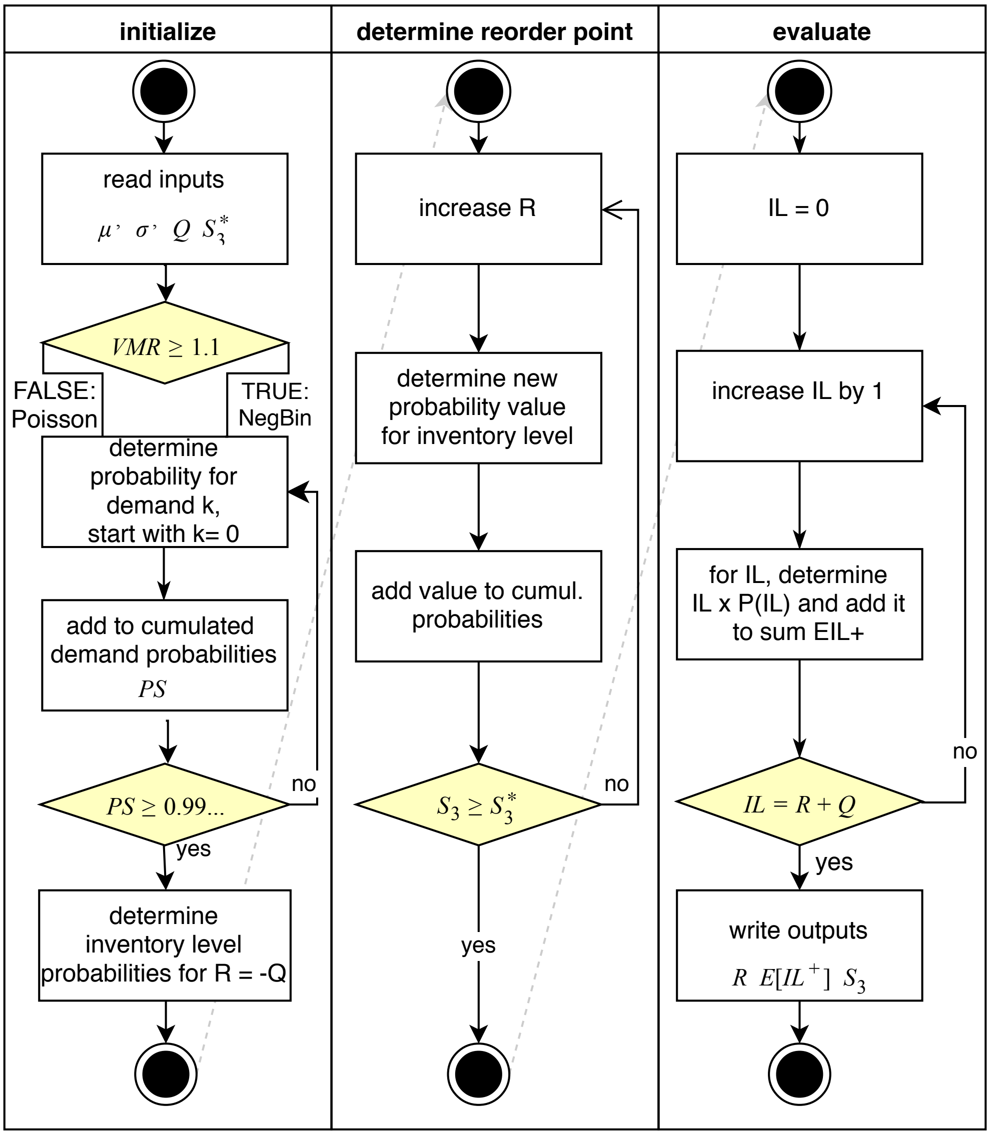


Figure 4.1: Algorithm used in Analysis.

As mentioned in Section 3.12, inventory level probabilities can be re-used leveraging a simple conversion of the argument. In the proposed algorithm, the difference of R and $-Q$ is called *addedR*. This simplifies looking up inventory level probabilities, as it describes the offset of the inventory level probability array index and j, which simplifies using the relationship in (3.22). To enable re-using intermediate results, these are saved in global arrays.

The average stock on hand $E[IL^+]$ can then be calculated using (3.24), which is done once the reorder point has been determined. With this, it is possible to determine

$min\ E[IL^+]$ with $S_2 \geq S_{2goal}$, the algorithm has been visualized in Figure 4.1.

A visualization application is also developed and delivered to the company. The visualization application contains all the results from the decision support tool along with other data. Other data included: item costs, recorded inventory levels and item descriptions. Therefore, the visualization application is used to quickly filter-out items and results which allows for better comparisons. An application overview is presented in the Appendix.

4.3 Data collection

Quantitative data was collected from different systems. The company uses an ERP software, the database of which can be accessed through a visual query-based interface across different countries. Furthermore, aggregated data from different data sources is available through designed-for-purpose applications in a business intelligence software. Throughout the collection process, data was constantly filtered down to match the studied set of items.

4.3.1 Demand

According to Axsäter (2006), in practice, if a demand is not met it often results in a lost sale and is not recorded. Therefore, it is difficult to measure the real demand unless having high service levels where very few lost sales occur.

As per the current distribution network in the case company, there are two main demand types being recorded:

1. Replenishment orders: internal demand within the downstream organization and the intermediate organization.
2. Sales orders: end customer orders within the downstream organization and the customer (also known as invoiced sales).

Axsäter also mentions the systematic error one often needs to accept when using sales data instead of real demand data. When the fill-rate is high, it can be assumed that sales $\approx$ demand, but if this is not the case, it is complicated to estimate the demand. If customers ask for an item that is not in stock, this is not necessarily recorded in the company's sales system.

Each sales entity in Sandvik has data recorded in an enterprise resource planning software (ERP) which can be accessed separately through a visual form-based query interface for each entity. Another software system is being used to compile demand data into a central platform (business intelligence software).

As the proposed model suggests that inventory should be kept in a single centralized location which will serve the end customer directly; the end customer sales data becomes relevant to use as a demand input. The data provided by the responsible manager contains a sales history of for the time period Jan 2016 — Mar 2018. The demand data contained lines for monthly ordered items per customer. Item's mean demand and standard deviation per month can be calculated by taking all demand instances in those 27 months. The received demand data contained few instances of item returns which are excluded when determining the average monthly consumption. From this data set, a loss of information is to be suspected for the case of more than one order-line per customer-item-month combination. Thus, an analysis of the order sizes has been done for a smaller geographic region on an order-line level.

4.3.2 Supplier lead times

Historical data is considered for all materials that are ordered from all suppliers for the period of Jan 2013 — Dec 2017. The data contains lines for item order date and item receiving date in connection with the supplier. The data is filtered down to match the specified studied items and all lines with no dates are excluded. The lead time is calculated as the difference between the ordering date and the date of receiving. Lead times for preferred suppliers [defined as the default supplier by *Sandvik*] are considered as a first choice. Supply lead-time and standard deviation are calculated based on averaging the different transactions for each supplier and item. By that, the data includes instances when material is shipped partially by the supplier against a single order.

For the use of a specific scenario, suppliers are required to deliver items to proposed locations, therefore, transportation time estimates from Europe to four different business regions are also collected (SeaRate 2018). These times are added to the original lead time mean under the assumption that suppliers are located in Europe, not considering any additional variability due to the transportation. It is worth nothing that in the model, items are supplied directly from European suppliers to the different DC locations. Therefore, no transit time is added to the lead-time used for Europe's DC.

From	To	Transit time (d)
Europe	North America	15
	South America	19
	Africa	24
	APAC	30

Table 4.2: Estimate of sea freight transit times (in days) from European suppliers to four different business regions.

4.3.3 Crusher components list and crushers' demand

The parts in focus are also used to produce new machinery [new equipment], therefore, some parts demand is present for production purposes. The production entity for new equipment at the case company uses different item codes and places orders with the suppliers independently. In order to be able to include this demand in the analysis, a component list per machine type is required. The list acts as a map to connect item codes to new equipment. A new demand compilation therefore includes the machine demand along with the after-market demand. In order to create the list, a subject matter expert is consulted and provided with the items in focus in order to be connected with the machine types. Crusher demand was provided by the company for the last nine years. However, demand was considered for the period between 2016 — 2017. This period showed a stable pattern (no trend and little variability) and was also advised by the principal company. Historical new equipment demand per month has been been converted to parts demand using the crusher to parts list. This demand has been merged together with the after-market demand (from Section 4.3.1) to form a new demand mean and standard deviation.

4.3.4 Inventory and stocks on hand

Inventory data is available through the business intelligence software which allowed for data extraction for a past year. Thus, inventory data for the period of Feb 2017 — Mar 2018 was collected. The inventory is collected on a stockroom level, which then is aggregated in two ways:

1. Global inventory levels: All data points are aggregated on a monthly level.
2. Regional inventory levels: All data points are aggregated on a monthly level into 5 different business regions (North America, South America, Europe / Middle East, Africa and APAC)

4.3.5 Service measure: Fill-rate

The principal company records order fulfillment and the status of each order if it was filled directly from stock or not. The data can be retrieved from the business intelligence software. The fulfillment status for each customer order line was extracted for the period of Mar 2017 — Apr 2018. The data show each order-line and whether if it was fulfilled directly from stock or not. The data was used to create an average fill-rate for each item. Therefore, it is worth mentioning that the used fill-rate data do not represent the performance of the downstream organization, rather, it represents the fill-rate performance as perceived by the end customer for the set of studied items only.

4.3.6 Lost demand

A semi-structured interview was carried out with a sales manager in Northern Europe. Because of the poor quantitative data quality (assessed together with company representatives) a further quantitative analysis was not pursued. The quantitative data included information on quotations, the geographical spread of crushers sold and crushers known as active. The interview is the main data input to investigate lost sales. This is further described in Chapter 6.

Chapter 5

Analysis

This chapter is intended to deliver and explain the findings of the thesis in detail. As the results of the mathematical model include a large number of items, main findings are presented in groups and a selection of items that represent a group of findings is taken to a more detailed level of analysis. Furthermore, this chapter discusses advantages and disadvantages of centralizing after-market spare parts inventory.

5.1 Different scenarios

The initial model (Scenario 1) considers the case company's current distribution network a black box. Distribution from the suggested DC to customers currently include stockrooms that are managed by the respective downstream organization. This fully centralized solution is a very idealized model. A comparison of this first model with reality in a step of validation has resulted in the decision of considering a second model that comes closer to the reality (Scenario 2). This adjusted model considers that the customer does not experience shelf availability but rather a waiting time until order fulfillment. In this regards, decentralization of inventory would be considered as positive by the customer. At the same time, a centralized solution offers the case company better control of their inventory. This is due to reducing the safety stocks as demand uncertainty is diminished. However, a centralized solution would require express shipments of parts to customers who are potentially facing a business interruption. To add more complexity, the studied items can mostly be described as large and heavy items which might create additional barriers for express shipping. Thus, Scenario 2 includes five different distribution centres based on the business region. This scenario is thought to provide a middle ground for the mentioned dilemma.

Currently, the inventory management for the production organization at the case company is relatively independent from the inventory management of spare parts. The studied items are required by both; the after-market and the production of new equipment. Therefore, same parts can be ordered, stored and replenished separately. While the software systems are not fully aligned to accommodate a high visibility of similar items used in production and after-market, it was in the management's ambitions to consider both types of demands in the inventory model. Thus, a scenario that includes both types of demands is introduced (Scenario 1P).

From the historical data the conclusion is that order sizes equal to 1 in most cases. Therefore, it is worth noting that for the numerical results in this thesis, the order quantity is assumed to be $Q = 1$, however the decision support tool is designed for variable values of Q. Please see Section 4.2 for a detailed explanation of the decision support tool. A detailed description for the mentioned scenarios will be provided in the following sections.

5.1.1 Scenario 1: Fully centralized after-market demand

The first model looks at the upper bound for inventory level reductions due to centralization efforts by merging all demands on a global level and serving them by direct deliveries from a single warehouse. Therefore, achieving the least variability in the system (see Figure 1.4).

For this model, the main stochastic inputs that are used:

1. Sales consumption (invoiced): After-market collected sales averages (see Section 4.3.1) are represented by two statistical measures for each studied item (μ_d and σ_d).
2. Supply lead times: Collected lead times of supplies (see Section 4.3.2) are also represented by the statistical measures (μ_{LT} and σ_{LT}) for each item.

Both data inputs are subject to a data cleaning process (see Section 4.3) mainly by filtering and excluding data with missing order lines. Both inputs are compiled together following (3.6) and (3.7) forming μ' and σ', respectively. Entering these inputs, along with the targeted service level (fill-rate = 95%), into the decision support tool returns the following inventory parameters:

1. Re-order point
2. Achieved service level (fill-rate)
3. Expected inventory level

Furthermore, Figure 5.1 visualizes the steps for this model.

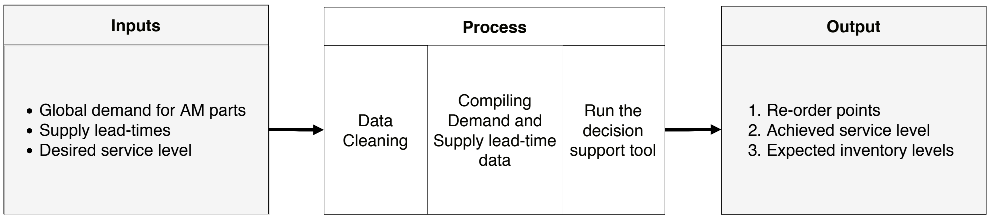
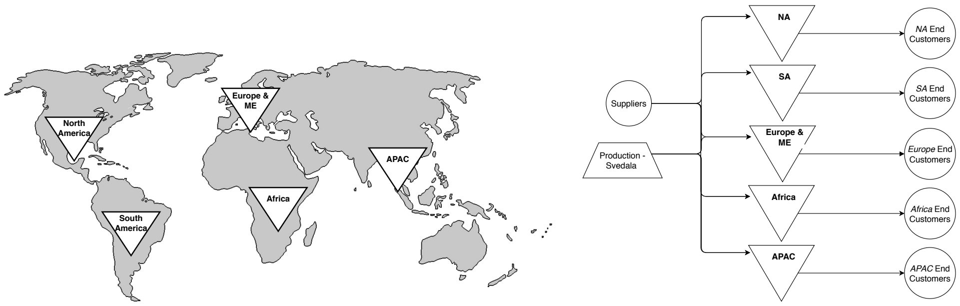


Figure 5.1: Data modeling for Scenario 1

5.1.2 Scenario 2: Partially centralized after-market

A more realistic scenario that considers the customer's willingness to wait and considers the fact that items are very heavy (and costly to ship by air), has been set up by modelling one inventory location per geographic business area. For this scenario the same sales data is used as in Scenario 1 (Section 5.1.1) but now divided into five models; Europe and Middle East, Africa, North America, South America and APAC. Figure 5.2 shows these inventory locations in different business regions (5.2a) along with the distribution network (5.2b) for this scenario. Scenario 2 assumes that the five regional DCs are independent from each other and that each DC represents a single echelon optimization problem with infinite supply and variability in supply lead-time.



(a) Scenario 2 geographical DCs spread (b) Scenario 2 distribution network

Figure 5.2: Scenario 2 distribution network

The suppliers data base for the case company showed that the vast majority of all suppliers of the studied items are based in Europe. Therefore, it was assumed for this scenario that items to be shipped to other locations than Europe will experience a delay caused by shipping the items using sea freight (see Table 4.2). Uncertainty related to transit times was not taken into consideration. Thus, the supply lead time considered differs based on storage location. Combining demand, supply lead-times and transit times produced the statistical measures μ' and σ'. Figure 5.3 shows the steps for modeling Scenario 2.

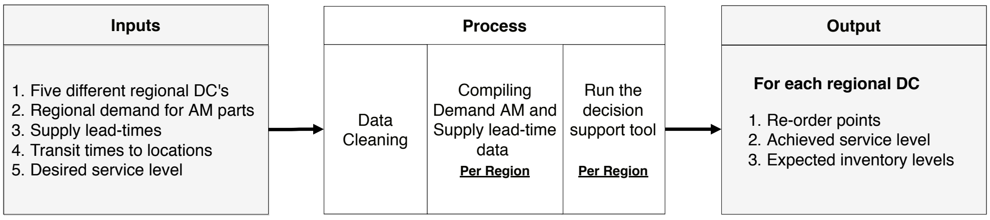


Figure 5.3: Data modeling for Scenario 2

5.1.3 Scenario 1P: Centralized after-market and production demand

It was hypothesized whether a combination of after-market demand and the demand for parts in new equipment production would help in setting up a combined inventory system. This would allow to reduce new equipment production lead-times (see Figure 5.4).

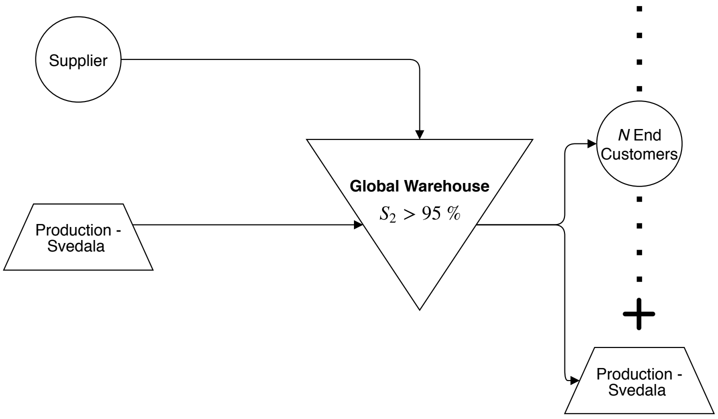


Figure 5.4: Distribution network featuring a high fill-rate global warehouse for parts that can be used as after-market spare parts or in new equipment production.

For this scenario, the model is similar to the model in Scenario 1, but, with a demand aggregation to include the following two types:

1. Sales consumption (invoiced), as in Scenario 1 (see Section 5.1.1)
2. Combination of crushing equipment sub-assembly information and equipment sales into new production parts requirements as described in Section 4.3.3.

Both demands were compiled in a single data set and the statistical measures μ_d and σ_d were calculated. Then, the scenario followed the same procedure as in

Scenario 1 by combining the stochastic lead times of supplies to finally end up with μ' and σ'. Figure 5.5 shows the steps for modeling Scenario 1P.

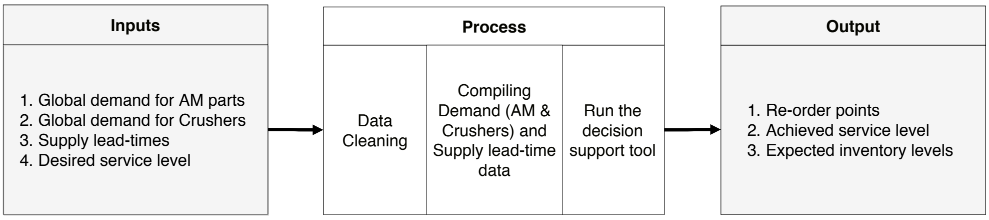
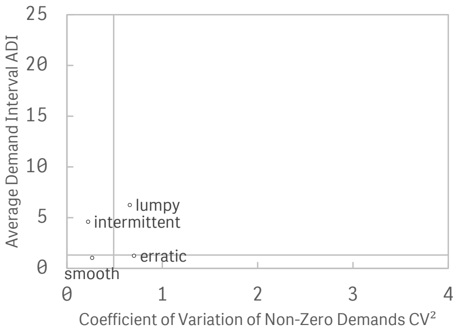


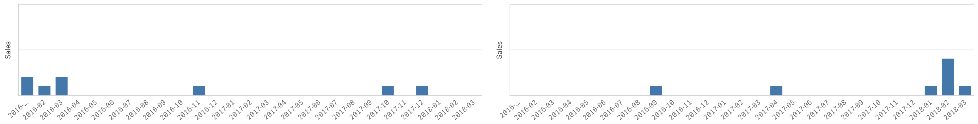
Figure 5.5: Data modeling for Scenario 1P

5.2 Identifying demand patterns

In order to provide an overview of the different types of demand, the four-field matrix introduced in Section 3.2 is used to categorize the sample into the classes of intermittent, lumpy, smooth and erratic demand. Examples of demand time series for the four different categories can be seen in Figure 5.6.

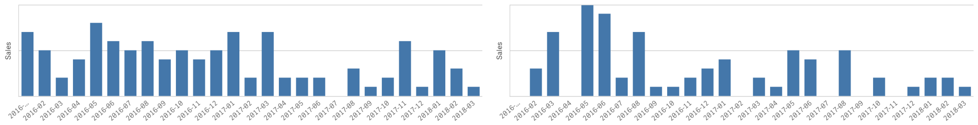


(a) overview of example items



(b) intermittent demand

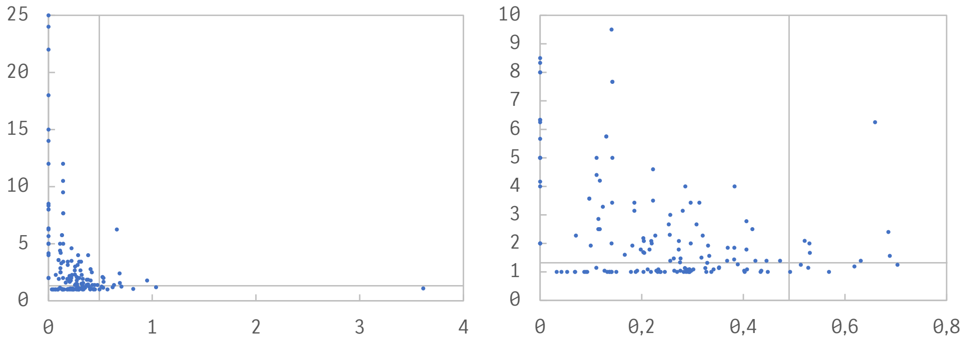
(c) lumpy demand



(d) smooth demand

(e) erratic demand

Figure 5.6: Demand graphs over time of example items.



(a) all items (b) detail view

Figure 5.7: Investigated items in the four-field matrix by Syntetos et al. (2005): variability of non-zero demand periods CV^2 on horizontal axes, average demand interval ADI on vertical axes.

Figure 5.7 gives an overview of the result of our investigation using the four-field matrix suggested by (Syntetos et al. 2005). The considered item population splits up in the four categories as shown in Table 5.1. Note the difference in fill-rate $S_{2\text{ actual}}$ for smooth demand items, which indicates that current methods work better with smooth demand patterns.

Table 5.1: Overview of items in demand categories

	# of items	share	$S_{2\text{ actual}}$
intermittent	90	55 %	36.6 %
smooth	56	34 %	65.4 %
erratic	9	6 %	43.5 %
lumpy	8	5 %	32.6 %

The analysis has been carried out on a global demand level, i.e. on the highest possible level of aggregation. The review period used in the analysis is one month and there has been no advanced forecasting applied, instead the whole population of 26 months is used with equal weighting for all periods in determining ADI and CV^2. Of the investigated item sample, 35 items are demanded every month, i.e. $ADI = 1$. 13 items only have one recorded demand during the period investigated, which results in very high levels of ADI (depending on the time instance of the recorded demand, as only non-demand periods that occurred before a recorded demand are considered).

Table 5.2 illustrates the relationship of the popularity of a machine type (column) and their corresponding spare parts' demand by component type (row). The four

Table 5.2: Overview of machine types and their respective spare-parts' demand pattern, abbreviated by their initials: **S**mooth, **E**rratic, **I**ntermittent, **L**umpy.

	MT1	MT2	MT3	MT4	MT5	MT6	MT7
sale	.18	.21	.21	.06	.05	.06	.03
fleet	.13	.28	.27	.02	.03	.06	.02
Major	I	I	I	I	I	I	I
Major	S	S	I	I	I	I	I
Major	S	I	I	I	I	I	I
Key	S	S	S	E	I	L	I
Key	S	L	E	I	L	I	I
Key	S	S	S	S	E	I	I
Key	E	S	I	I	I	I	I
Key	S	E	S	S	S	I	–
Key	I	I	I	I	–	I	I
Key	S	S	S	S	S	I	I
Key	S	S	–	E	–	S	–
Key	S	S	S	S	S	S	S
Key	S	S	S	S	S	S	I
Key	S	S	S	S	S	S	S
Key	S	S	S	S	S	I	S

demand types introduced in Section 3.2 are abbreviated with their initials. It is interesting to highlight that especially the very popular machine types $MT1$ and $MT2$ generate a lot of smooth demand patterns on a global level. Furthermore, the different component types (rows) generate different kinds of demand patterns across the machine types (columns): The very large, heavy and expensive major components in rows 1–3 most often exhibit a rather intermittent demand, while some key components generate a rather smooth demand pattern across machine types (last four rows).

5.3 Expected inventory levels $E[IL^+]$

The inventory optimization (see Section 4.2) resulted into providing two main parameters: the reorder point R and the expected inventory level $E[IL^+]$. While the reorder point R is the controllable measure that the company can further implement in order to apply the inventory policy, the expected inventory level $E[IL^+]$ is considered as the key measure for analysis. $E[IL^+]$ acts as a comparable measure for the current situation at the case company.

Actual inventory levels (IL_{actual}) and actual fill-rate ($S_{2\ actual}$) are representatives for the current performance of the case company. Data collection for these measures is explained in the previous chapter (see Sections 4.3.4 and 4.3.5).

Recall that Scenario 1 considers a single after-market inventory location, Scenario 1P also includes demand from new equipment production and Scenario 2 looks at five different geographic regions with dedicated stocking location. Each scenario produced a number of items that $E[IL^+]$ either need to be increased or decreased if compared to the current inventory levels (IL_{actual}). An overview for the results is presented in Figure 5.8. It shows average numbers for the whole sample.

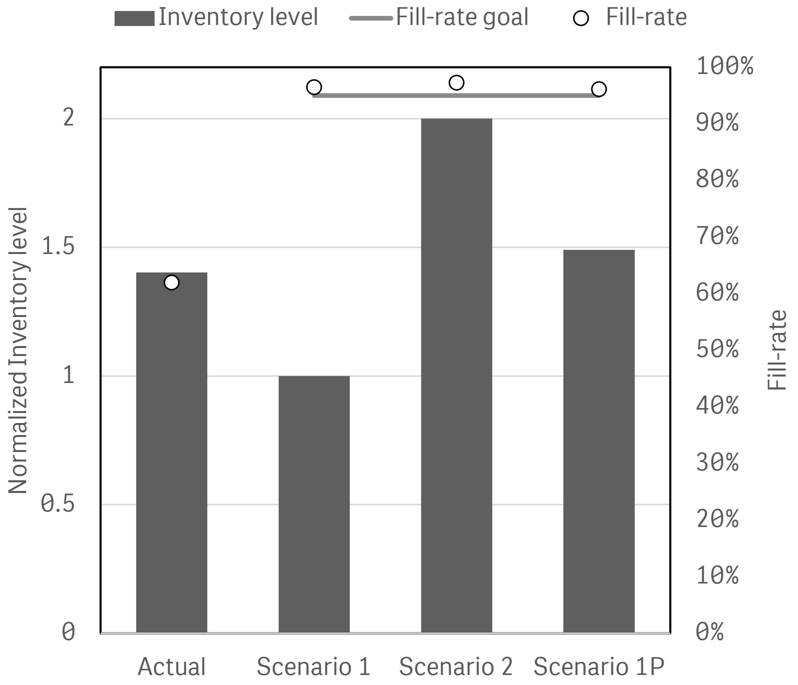


Figure 5.8: Overview of the results for the expected inventory levels (Normalized inventory levels)

Under the current actual inventory system, the case company is not achieving the desired fill-rate constraint (95%). Generally, all three scenarios increase the average fill-rate by 55% if compared to current situation. Fully centralizing inventory (Scenario 1) will reduce the average $E[IL^+]$ by 28 % from current levels, while meeting the fill-rate constraint at 95%. On the other hand, the partially centralized model (Scenario 2) will increase $E[IL^+]$ on average by 40 % if compared to the current actual, however, it will provide much higher fill-rate (55% increase in fill-rate to meet the constraint at 95%). If Compared to Scenario 1, Scenario 2 is expected to double the $E[IL^+]$. Scenario 2 provides higher availability for customers because items have high fill-rate (shelf availability) and generally much shorter transportation times to customers compared to Scenario 1.

Adding the production consumption to Scenario 1 will result into a 50 % increase in $E[IL^+]$ while meeting the fill-rate constraint at 95%. Moreover, this increase is a result mainly driven by the major components. The major components are currently made to order, therefore, a significant increase in $E[IL^+]$ is reasonable when considering an R,Q policy instead.

More specific analysis is conducted. The items are further analyzed regarding their inventory performance in different scenarios. Each item belongs to an "increase" group or a "decrease" group. However, for some items the relative inventory difference (Δ) is small (± 10 %), and thus, worth analyzing separately. Table 5.3 illustrates the number of items found in each scenario and categorizes them into the three defined groups. Items that did not have any demand over the course of the collected period (see Section 4.3.1) or did not have any supply lead time data (see Section 4.3.2) resulted into not including the item in the study. Therefore, Table 5.3 also shows the number items with missing data.

Table 5.3: High-level comparison of actual inventory levels

	increase $\Delta > 10\%$	decrease $\Delta < -10$ %	$\sim$ same -10 % $< \Delta < 10$ %	missing data
Scenario 1	49	100	16	41
Scenario 2	106	32	27	41
Scenario 1P	86	67	25	28

In order to examine all cases ("increase", "decrease" and "same") shown in Table 5.3, a selection of items that represent these cases are taken into further analysis, these items are shown in Table 5.4. Item A represents an inventory increase across all scenarios. Item B represents an inventory decrease across all scenarios. Item C represents a roughly similar inventory performance required for Scenario 1 and 1P, and finally, Item D represents a roughly similar inventory performance required for Scenario 2. Scenarios 1 and 1P can be considered equal for the upcoming analysis and will be differentiated by the end of this section.

Table 5.4: Item group representatives

	increase	decrease	$\sim$ same
Scenario 1	Item A	Item B	Item C
Scenario 2			Item D

5.3.1 Category "increase"

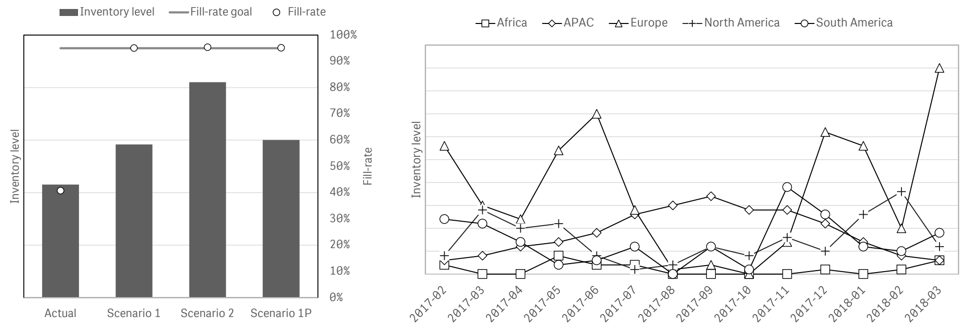
Item A represents the set of items that have a lower current inventory level than what the model suggests to achieve (the desired fill-rate S_2). Figure 5.9a shows the expected inventory level $E[IL^+]$ and the fill-rate S_2 for all scenarios versus the IL_{actual} and $\mathrm{S}_{2\ \mathrm{actual}}$. Scenario 1 and 1P suggest increasing the inventory to achieve a 95 % fill-rate. This shows two main effects:

1. The effect of increasing inventory in order to meet the demand and thus achieve a higher fill-rate.
2. The effect of centralizing inventory; by keeping lower safety stocks in a fully centralized network (Scenario 1 or 1P) versus a less centralized network (Scenario 2) where the amount of required safety stock is higher to cover more uncertainty.

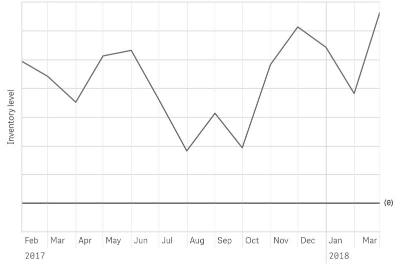
Globally, an item might have an adequate amount of stocks but in a location that is different than where the demand occurs. This results in missing customer order lines and obtaining a lower service level. This can be shown by comparing the actual inventory development over time on a regional level with the global inventory level (Figures 5.9c and 5.9b, respectively). It is worth noting that both levels consist of the same inventory records from all stockrooms but are aggregated on two different levels. In these figures, the global inventory pattern shows no stock-out cases for Item A, however, the recorded fill-rate is approximately 40 % (Figure 5.9a). A closer look into the regional level shows that the item has stock-out instances in Africa, Europe and South America, explaining the low fill-rate. This specific finding is applicable across all categories and not only here.

5.3.2 Category "decrease"

On the other hand, Item B represents the case of having a high amount of inventory (IL_{actual}) which exceeds the suggested levels of all scenarios (Figure 5.10a). Despite



(a) IL^+ & S_2 performance (b) IL_{actual} development on a regional level

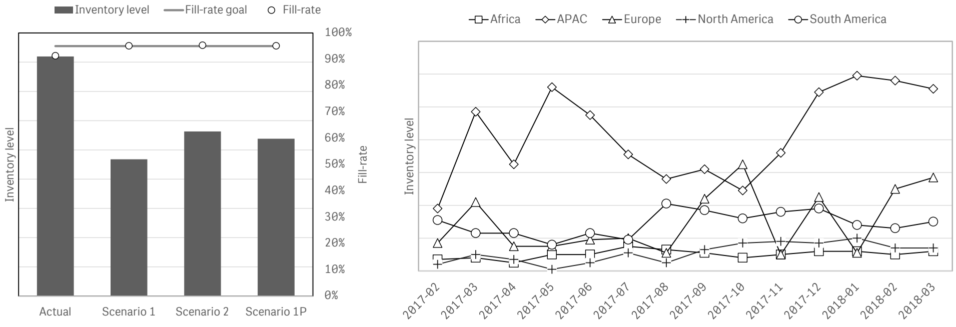


(c) IL_{actual} development on a global level

Figure 5.9: Item A: category increase

having high amount of inventory, item B still doesn't satisfy the 95% fill-rate target. For this particular item the current fill-rate is approximately 90 %. All modeled scenarios suggest lower inventory levels to achieve the desired fill-rate. Similar to Item A, the centralization effect is present (lower inventory levels satisfy a higher fill-rate) as the actual case fill-rate is relying on having the item in stock at the stock room level (including country level). Even if no stock-outs are present on the regional level (Figure 5.10b), an order line can be missed on a country stockroom level therefore having a 90 % fill-rate instead of a 100 %. It is also worth noting that in this category items with very low fill-rates (lower than Item B) are observed and the same justification is applicable, as having the stocks in the wrong location will result in having high inventory levels and low fill-rates. This group can also be identified as the group of items that has the potential of lowering tied up capital, as lower inventory levels would suffice to achieve better fill-rates compared to the actual situation.

One can argue that Scenario 1 (or 1P) fill-rate is comparable to Scenario 2 only if the difference in transportation time is considered. Customers experience a longer transportation time in a highly centralized distribution network (Scenario 1) when compared to a less centralized network (Scenario 2). Thus, the waiting time experienced by the customer will vary between those two scenarios. Even if both achieve the desired fill-rate of 95 %, Scenario 1 only equals Scenario 2 in availability performance if the customer accepts the additional transportation delay for every order placed.



(a) IL^{+} & S_2 performance

(b) IL_{actual} development on a regional level

Figure 5.10: Item B: category decrease

5.3.3 Category “same”

For a smaller group of items, the suggested inventory decrease or increase (Δ) is relatively low (± 10 %). This group is thought to be relevant to analyze as achieving the targeted fill-rate has mainly resulted from centralizing stocks. Two items represent this range, Item C and D. Item C is chosen as it falls in the (± 10 %) change range for both Scenario 1 and 1P. Item D is chosen to cover the (± 10 %) change for Scenario 2 as no single item was found to cover the whole (± 10 %) category across all scenarios.

Figure 5.11 shows the inventory performance in terms of average inventory on-hand level IL^{+}_{actual} and fill-rate $S_{2\ \text{actual}}$ along with $E[IL^{+}]$ and S_2 for Item C. It is shown that Scenario 1 or 1P can achieve a considerably higher fill-rate with roughly the same amount of inventory due to the centralization effect.

Item D represents the small set of items where Scenario 2 suggests about the same amount of total inventory. As can be seen in Figure 5.12a, similar inventory level achieved a better fill-rate in Scenario 2. Furthermore, the actual regional inventory pattern as shown in Figure 5.12b exhibits how different regions are managing their inventory. For example in North America (+ sign in the chart), the company managed to keep low inventory levels with nearly no stock-outs, while APAC (Diamond sign in the chart) kept much higher inventory. This can be explained by the erratic demand pattern that is experienced in that region. For item D centralization has arranged the current stock level in different regions and achieved the fill-rate goal.

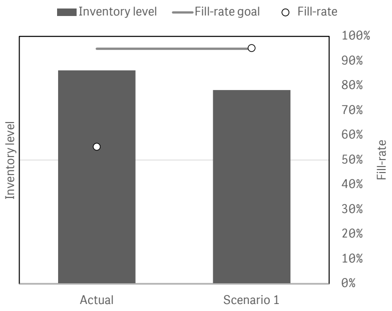
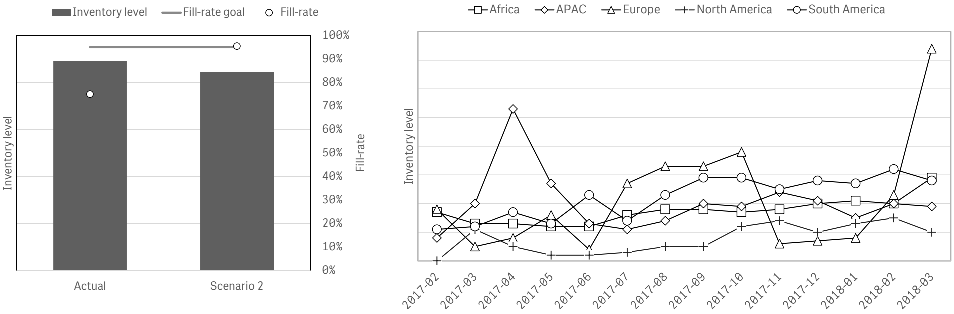


Figure 5.11: Item C: $\Delta = \pm 10$ % for Scenario 1 and Scenario 1P



(a) IL^+ and S_2 performance

(b) IL^+ development on a regional level

Figure 5.12: Item D: $\Delta = \pm 10$ % for Scenario 2

5.3.4 Integrating production

Scenario 1P was motivated by case company's interest in the possibility of utilizing the high fill-rate DC for production as well. This model would prove to be beneficial if the production consumption does not form a high disturbance in variability. The effect on the expected inventory level depends on the correlation between the two demand types. An initial evaluation based on the relative change in the value-to-mean ratio of all items reveals that the inventory system would experience mostly small changes in this regard. In total, 174 of the items under investigation were considered in Scenario 1P. 50 % of these items exhibit a relative change of ±10 % in VMR. 21 % of the items show a more significant relative decrease, while another 21 % show a more significant relative increase of up to 60 %.

However, when looking at the resulting average inventory on-hand, the comparison of Scenario 1 and Scenario 1P shows significant increases in expected level of inventory on-hand resulting from the optimization under the fill-rate constraint of 95 %, which is

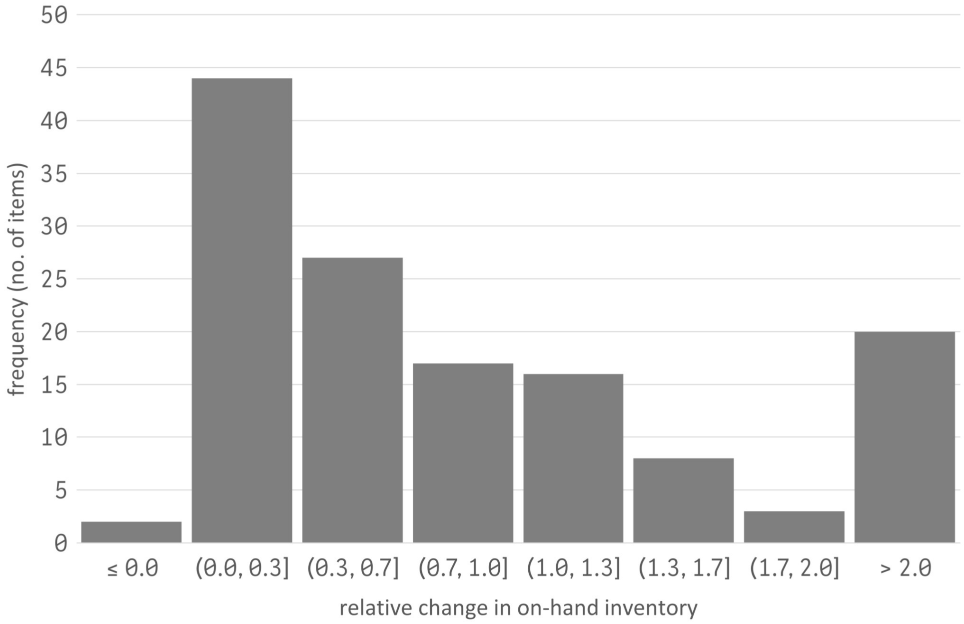


Figure 5.13: Overview of change in on-hand inventory level when integrating production demands with the fully centralized aftermarket inventory.

illustrated in Figure 5.13: While 25 % of the items only exhibit an on-hand inventory increase of 30 % or less compared to Scenario 1, 11 % of the items in Scenario 1P exhibit an expected inventory level that is more than three times as high as their result in Scenario 1. A general benefit from merging the two demand types can thus not be deduced.

5.3.5 Summary of scenario analysis

Currently, the inventory system of the / is highly decentralized across their geographical markets. One option to increase the efficiency of inventory management is centralization. But as motivated earlier, Scenario 2 resembles the most feasible solution for the case company. Logistics costs for this type of spare parts are very high if one warehouse needs to cover the entire global demand. Spare parts are often ordered with urgency (i.e. as a result from machine stoppage), thus, need to be delivered within an acceptable time frame. In addition, some parts are not applicable for express shipping. For example it is almost impossible to ship a major component using air freight because of it's weight and shape. Having five warehouses across the world could act as a variability buffer for the upstream supply chain, while at the same time, increase speed of delivery to the end customer.

Scenario 2 can be further analyzed by conducting a two-way categorization in terms of demand pattern and expected inventory levels. Table 5.5 shows the breakup of items in Scenario 2 with the corresponding demand pattern (see Section 5.2). It is worth mentioning that some items with missing data from both sides (demand pattern or inventory level analysis) could not be reflected in this table.

Table 5.5: demand shape vs performance (actual versus Scenario 2)

	increase	decrease	same	$S_{2\ \text{actual}}$
intermittent	64	12	12	36.6 %
smooth	27	17	12	65.4 %
erratic	5	3	1	43.5 %
lumpy	6	1	1	32.6 %

As can be seen in Table 5.5, the largest number of items that need for inventory increase belong to the intermittent demand (64 items). Furthermore, looking at the current fill-rates ($S_{2\ \text{actual}}$) recorded for items with intermittent demand, it is as low as 36 %. The low fill-rate explains the need of inventory increase in Scenario 2. Also, intermittent demand is difficult to manage and can explain the current low fill-rate fulfillment by the case company. On the other hand, smooth demand is relatively easy to manage and therefore achieves a better fill-rate (65 %). However, 27 items still need an inventory increase to achieve the desired fill-rate. This relationship (an increase in on-hand inventory is required to increase the fill-rate) is expected.

It is also worth noting that the low fill-rate numbers (shown in Table 5.5) might show critical business situation for the case company. Low spare parts order fulfillment can create significant issues for customers. However, the case company still provide its customers with the spare parts from a nearby location even if the demand was not met from the first instance. So these fill-rates do not directly represent the service level that the customer is experiencing.

5.4 Centralization: Factors and Performance

Performance regarding inventory centralization and decentralization will be further discussed. Certain attributes are important to analyze in order to get a better holistic understanding of the model. These attributes are formulated in Table 5.6. The table is based on the literature that can be found in Table 3.1, however, not all attributes are discussed as this thesis focuses on inventory management.

Waiting times for customers are often higher in a centralized solution as the warehouse is located further away if compared to a decentralized solution. The only

Table 5.6: Overview of implications of centralization decisions.

Attribute		**Centralized**	**Decentralized**
Performance Target	Customer waiting time	Generally longer, but only due to transportation	shorter when item available
	Inventory level at the same S_2	Lower	Higher
	Time in inventory	Lower	Higher
Network structure	Number of DCs needed	Lower	Higher
Planning Process	Demand variability	Lower, as individual and regional demand patterns merge into one global demand pattern that is easier to forecast	Higher, as the demand is forecasted on a lower level of aggregation
	Supply variability	Controlled by buffering stocks in a single location	Less controllable, as smaller demand is ordered from suppliers

difference between those two solutions is believed to be the delivery delay caused by the transportation time to the customer.

As shown in Section 5.3, expected inventory levels in a fully centralized solution is lower than in a partially centralized solution for the same targeted fill-rate (Scenario 1 and 2, respectively). All under the assumption that demand is independent.

The inventory performance measure (inventory turnover) can help in determining the expected number of replenishments needed. Companies can not store materials for very long period of time as the held materials need to be converted into sales in order to have a healthy cash flow. Furthermore, inventory turnover measure is often expressed in terms of average days needed for a stocked item to be converted into sales (Days of Supply DOS, see Section 3.7). DOS for Scenario 1 is estimated to be 65 days, while in Scenario 2 the average DOS for all regions is 92 days. A higher DOS indicates that the inventory is kept for a longer time and thus tying up capital for longer periods.

Section 3.13 introduced the “square root law”, the percent reduction when cen-

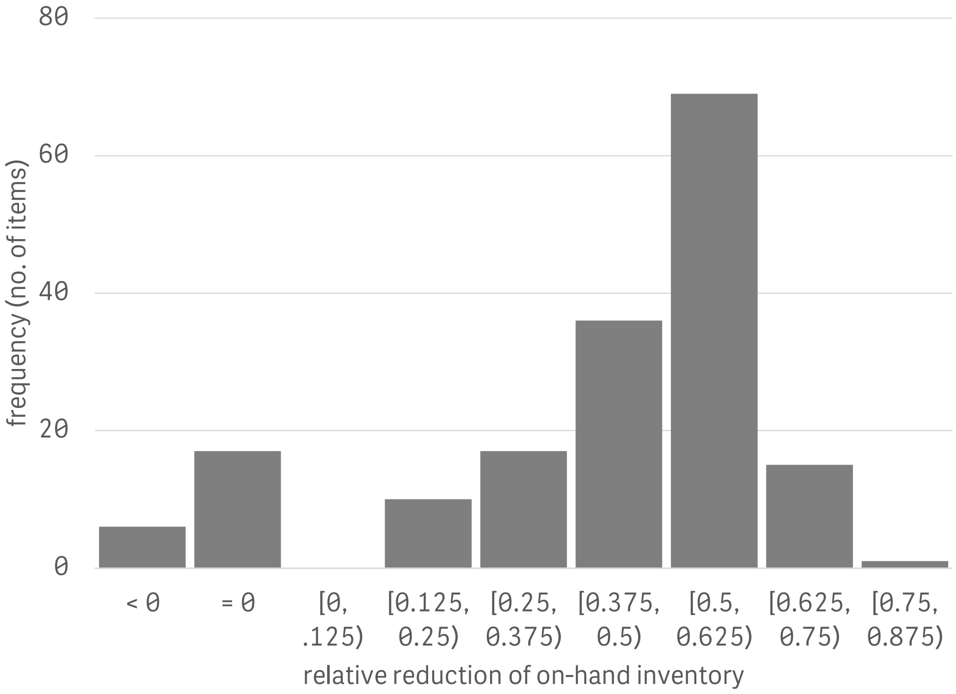


Figure 5.14: Reduction in on-hand inventory histogram

tralizing inventory given certain assumptions. It is interesting to highlight that in contrast to the simplifying expectation of the percent reduction from five inventory locations to one (Scenario 2 versus Scenario 1) being $1 - \frac{1}{\sqrt{5}} \approx 55$ %, the numerical modeling shows that for the items under investigation, the average per cent reduction is rather about 38 %. However, for a large group of items, the change in on-hand inventory when changing from five inventory locations to one inventory location is about $50 - 62.5$ %, which is in line with the claim made by the aforementioned "square root law" (see Figure 5.14).

5.4.1 Determining item centralization level

The question of whether to centralize the after-market distribution network for the case company can not be answered on a global level using the results from the analyzed model. It is necessary to consider additional information and thus, the analysis is providing a support tool for such a decision. Among the factors to consider are the end-customer location, resulting transportation time to the customer, their installed base and promises towards them. An item-by-item procedure is suggested. In which, the demand patterns along with actual and optimized data are considered both globally and on a regional basis. This process can be done using the delivered visualization application (Appendix page 74).

Scenario 2 considers five geographic regions. It is suggested (on an item level) to compare these regions, and determine whether there are any outliers with regards to the inventory level suggested (for example in days of supply DOS) and the demand type identified (the demand variability per period with demand CV^2 and the average demand interval ADI). Regions that exhibit relatively smooth demand patterns could be allowed to continue keeping stocks in a regional inventory, while regions with more difficult demand patterns can be considered for centralization. In the same way items with a significant difference in expected inventory on hand in Scenario 1 and Scenario 2 can be considered for centralization.

Chapter 6

Discussion about the impact of lost sales

The research question *"How can lost sales be related to the suspected availability issues?"* has not been taken up in the Chapter 5 due to a lack of reliable data. The preliminary findings and possible further actions are thus discussed in this chapter.

6.1 Approaches

Different kinds of data were gathered in order to shed light on the questions (1) whether there have been lost sales, (2) what the reasons for the phenomenon are, and (3) how the impact on demand patterns and thus expected inventory levels can be quantified. Information relevant to those questions that have been collected as part of the main study are after-market parts demand information (see Section 4.3.1) and the crusher-to-parts relationships (see Section 4.3.3). In order to investigate the above questions, data has been collected regarding quotations, the equipment fleet and customer decision making.

In order to answer the question of the general existence of such a problem, after-market sales can be compared to quotation data for after-market parts. Quotation data is compared to order lines using an analysis tool of the ERP used at the company. An initial analysis of the data record shows that reasons not to order based on a quotation are often either not known or not recorded in the system, which is why this data is not further considered. Furthermore, customer requests that do not turn into quotations are not available for analysis as the data is not recorded in this specific system.

Alternatively, sales of spare-parts per group of crushers (either on a region, country, customer or site level) can be considered relative to the number of crushers. As the equipment sales history does not necessarily represent the active machine population, such a list of active equipment was acquired from the company. Sales managers of the respective geographic regions are responsible for the data management. The business intelligence tool is still in the process of being built during the time of the study.

Thus, a preliminary data set was used as a preview of what kind of analysis will be possible in the future. Initial data analysis regarding sold crushers and active machine population leads to suspicions of discrepancy between machine population and sales of after-market spare parts. Some countries show much stronger after-market sales when compared to others. For example, two countries can have a similar machine population (both in terms of sales and recorded active crushers) but have a compelling gap in after-market sales.

Due to the general lack of reliable information for an approximation of the magnitude of lost sales, the question for an adjustment of the demand forecast or inventory levels for lost sales can not be answered properly.

6.2 Lost sales and inventory centralization

A semi-structured interview with a sales manager was carried out in order to get a better understanding of the underlying factors of lost sales at the case company (Carlqvist 2018). The collected information focuses on exploring factors affecting lost sales and the relationships it induces.

Parts failures at customer sites depend on unpredictable factors such as machine utilization, machine setup, rock type, maintenance procedures and many more. Therefore, a qualitative understanding of the end customer perspective for spare parts purchasing is to be analyzed here.

The interviewee deems the market share in Sandvik cone crusher spare parts business satisfactory regarding their geographic scope of responsibility (Northern Europe). Customers in this region enjoy a high fill-rate due to the proximity to the distribution network. It is explained that endeavours to further increase the market share would not necessarily have a positive impact on the overall company profitability e.g. due to investments or price reductions (Carlqvist 2018).

The business intelligence tool for comparing after-market sales performance with potential sales is based on average spare parts consumption as well as proactive maintenance workshops (Norden & Svennelid 2018). It is yet under development but deemed a welcome aid for sales work, however doubts are raised regarding the necessary data. It is argued that customers behave differently from each others and that even two sites for the same customer may have very different spare part consumption patterns (Carlqvist 2018).

During the research, it was hypothesized whether an increased availability could have a positive effect on sales. The interviewee highlighted that this might be true for customer retention, but not regarding the initial after-market buying decision. According to the subject matter expert, the customer assumes that the case company is able to offer a high availability in line with the premium brand image established (Carlqvist 2018).

However, to observe the relation and quantify it, lost sales should be investigated more deeply. This could be done by collecting both more direct and indirect data. Direct data about customers, their crushers and specific parts consumed on a regular basis would strengthen the ability to analyze the spare parts demand share for a specific customer. One possibility for the company to collect relevant direct data is to use technologies related to the Internet of Things (IoT) for live data collection, e.g. it would be possible to let the equipment report its status and the condition of different parts through the internet to the case company data centers. On the other hand, indirect data could also be helpful, e.g. sales performance and overall market share for the purpose of benchmarking. Today, the case company might not be interested in providing machine up-time as an after-market service (Carlqvist 2018) but when having enough information about how crushers are being operated at customer sites, it might become an attractive opportunity. The business intelligence tool is a starting point for collecting this data and might have a major impact on forecasting for after-market parts. The data might be required to be customer and country specific.

It is known that there is a general causality of low availability and lost sales (Axsäter 2006). However, it is not the only reason for lost sales, which makes it difficult to estimate the volume of sales lost because of a lack of availability. Accommodating additional expected demand (that is expected to be gained because of raising service levels) in the centralized model is considered not to be as challenging as determining the magnitude of the lost sales due to availability. Should more information on lost sales become available in the future (e.g. due to more insights from the business intelligence tool and other market research endeavours), it can be considered using manual forecasting (or an adjustment of the automatic forecast). If there in fact is an increase in sales due to an increase in availability, this can be taken care of from an inventory control point of view by regularly updating the demand forecast and thereby the inventory parameters.

When introducing the idea of express distribution from few inventory stocking locations to the customer, a note of caution is raised: Transportation of large parts would pose a problem, as air freight is considered impractical from the interviewee's perspective and road transport might take a considerable amount of time depending on the distance to the end-customer (Carlqvist 2018). Furthermore, the interviewee highlighted that a static logistics solution would not help solve the lost sales issue. Rather, a solution should be sought that is tailored around customer base characteristics. For the distribution network, examples for relevant characteristics are:

- Sales channel: direct sales or sales through a distributor.
- Customer stock keeping: inventory is kept or not.
- Uptime criticality: mining customers lose valuable production time if a crusher is not operating, while many construction customers have some flexibility with regards to machine uptime.
- Customer's stance on preventive maintenance, utilization and material properties.

Depending e.g. the above criteria, customers might consider delivery speed as an order winner or qualifier (see Section 3.1). In combination, these factors define the impact of inventory keeping on the end-customer. This will help to better estimate the trade-off magnitude between costs, service levels and inventory turns.

Chapter 7

Conclusion

This conclusion chapter reflects back on the main findings for this thesis. The findings described in the previous chapter are connected and used to answer the research questions. Limitations and future research are then highlighted.

It was hypothesized that centralizing inventory should in general lower the amount of safety stock necessary in the distribution network. The case company's main issue is related to availability. Therefore, it was also expected that an inventory model that targets a higher fill-rate will increase the amount of inventory kept, disregarding if the inventory is centralized or not. The findings in this thesis are aligned with this. The main findings for the modeled scenarios are as follow (based on average numbers for all studied items):

- Fully centralizing the inventory (Scenario 1) will result into lowering the total inventory by 28 % (on average) if compared to the current situation while increasing the fill-rate by 55 %.
- Partially centralizing the inventory (Scenario 2) will increase the total inventory by 40 % (on average) if compared to the current situation while increasing the fill-rate by 55%.
- Partially centralizing inventory is expected to double the amount of inventory (on average) if compared to the centralized model (Scenario 2 vs Scenario 1) while both are achieving the fill-rate constraint at 95 %. However, Scenario 2 has a quicker delivery to the customer if compared to Scenario 1.
- Including the production demand into the fully centralized model (Scenario 1P) will induce an increase of 50 % (on average) for the total inventory if compared to Scenario 1 to achieve the same fill-rate constrain at 95 %.

It is recommended to consider centralization on an item-by-item basis. Scenario 1 and Scenario 2 both represent more centralized models if compared to the currently used distribution system and thus can only provide an indication of the potential of centralization. The delivery speed towards the customer and centralizing inventory are two conflicting goals. Therefore, an Item-by-item decision to centralize has been presented in this thesis. It is recommended to use the provided tools to identify other possible combinations of regions and also even less centralized models. In the next sections, the research questions will be answered in detail.

7.1 How much stock should be kept in a centralized inventory solution to accommodate a fill rate of 95 %?

The first question aims at providing the case company with numerical values that they can use as comparison in current strategic decisions. Furthermore, it generated information that was used to answer the second research question. As highlighted in Section 5.1, three different scenarios were considered: Scenario 1 considers a fully centralized inventory system serving global after-market demand, Scenario 1P additionally considers new equipment demand and Scenario 2 considers only after-market demand served from five different regional DCs.

The current fill-rate for the distributed system that the company follows, does not achieve the desired service level (95 %). For many items inventory needs to be increased in order to meet this constraint.

Scenario 1 and 1P represent an ideal case where the service level is defined as shelf-availability only. However, customers experience service levels differently, as a combination of shelf-availability and delivery speed. Also, for such large and heavy equipment the spare parts can pose a challenge for express shipping due to their physical dimensions. This is especially problematic for the major components due to their weight and volume. Thus, Scenario 2 was considered to include a more comparable model to the current distribution network (see Section 5.1.2). After-market spare parts demand was aggregated on a monthly basis for five regions. Expected inventory on hand is strictly larger across all items compared to Scenario 1 due to increasing inventory locations. For those items that exhibited the need for increased inventory levels in Scenario 1, this is accelerated in Scenario 2.

Under the current distribution network, inventory levels have to be increased in order to achieve the set fill-rate constraint. In more centralized distribution networks, as modeled in this thesis, this has to be done to a lesser extent. For a subset of items, centralization is sufficient to achieve the set fill-rate constraint with the same amount of inventory in the system. For some of those, inventories can even be depleted while still meeting the fill-rate constraint. In *Scenario 2*, inventory levels need to be increased for more items of demand categories that are “harder” to manage, i.e. erratic, lumpy and intermittent demand. For about half of the items that belong to the category of smooth demand, the average inventory on-hand was already more than what the optimization suggested.

The optimization has resulted into providing quantitative figures (R, $E[IL^+]$) which can be used to implement this model and answer this question.

7.2 What are the benefits/trade offs of having such a system?

It was motivated by the goal to strategically evaluate the distribution network.

Instead of a general recommendation to either fully or partly centralize the inventory, this report has highlighted aspects to consider when making item-by-item decisions. This recommendation aims to form a combination between the proximity to customers and centralization in order to acquire the most benefits out of the two. It is observed that centralizing stocks produces smoother patterns (demand and inventory) to manage. On the other hand, decentralizing stocks is more challenging to manage as it adds more uncertainty in the system. Inventory is kept in less locations and turns faster in a centralized solution ,however, it raises logistical challenges such as increased transportation time and costs. Items can be evaluated in terms of their benefits to centralize based on the measures on-hand inventory level, demand patterns, logistics costs and inventory turnover. The benefit of using a centralized distribution strategy for an item can be determined by evaluating the interaction of these measures. Items that exhibit a smooth demand pattern can be considered for a more decentralized approach, while items exhibiting “difficult” demand patterns on a local and regional level are candidates for a centralization effort.

7.3 Can new equipment production use the centralized inventory solution as well?

Similar to Scenario 1, *Scenario 1P* is restricted by a fill-rate constraint that results into increasing the overall expected inventory on-hand. However, this scenario merges production and after-market demand together. Those two types of demand have different planning and forecasting horizons, which in turn means that different statistical distributions are being mixed under the same statistical measure.

As explored in more detail in Section 5.3.4, Scenario 1P does not exhibit a consistent benefit across all items, but for some of the investigated items, the increase in expected inventory levels is relatively low. This makes it possible to consider on an item-by-item basis whether production should be allowed to use this common inventory in order to shorten the production lead-time for new equipment, as this could allow the company to compete on markets with shorter accepted lead-times for new equipment. However as mentioned before, Scenario 1 and 1P are thought to be idealized models and difficult to achieve practically.

7.4 How can lost sales be related to the suspected availability issues?

The fourth research question is based mostly on observed discrepancies of the average consumption per crusher.

While lost sales and availability are related on a very basic level, in this master thesis a direct connection could not be formed. Rather, it was discussed that different factors can affect lost sales. Further data is needed to form a deep understanding of the dilemma. Such data consist of crushers population and working environment for each customer, reasons behind unsuccessful quotations and spare part criticality to the customer.

At this stage, it is recommended for the case company to observe demand under improved fill-rate performance and continuously update their forecast based on demand realization.

7.5 Generalizability of the models and research results

A general and well tested model of single-echelon inventory optimization with a fill-rate constraint has been applied. It is used to evaluate the effects of two different levels of centralization of the inventory system, as well as, the integration of production requirements into the after-market inventory system. The thesis has used the demand classification by (Syntetos et al. 2005) as relevant criterion to be considered in evaluating the level of centralization of spare parts. No verification of the effectiveness of this categorization for the mentioned purpose has been provided.

The model and its results can be used by the case company to evaluate their current inventory policies. If conditions change or more accurate information is acquired, the model can be executed again by the case company using different input values. The model can be easily extended to consider a continuous distribution for smooth, low variability demands in order to be more general.

Inventory centralization is a decision that cannot be made relying only on changes in inventory levels but must consider a more holistic view on the entire supply chain. This includes different types of costs (warehousing, transportation, order processing) and effects on performance (fill-rate and customer waiting times).

7.6 Limitations and further research

Limitations of this research were identified earlier in Section 1.5. However, one important limitation for the results is the order quantity when replenishing the DCs. This thesis has assumed continuous review with one-for-one replenishment, however when using sea freight as suggested in Scenario 2, this type of replenishment might not be preferable. With long shipment times, a longer review period or larger reorder quantity are more likely to be employed. Actions like this would lead to an increased average level of inventory on-hand compared to the results of the model presented.

Lead-times used in the inventory control model have been based on the past performance of supplier deliveries, both regular and emergency shipments.

The inventory control model used in this thesis treated all demands with a very low variance compared to the mean ($VMR < 0.9$) as if they follow a pure Poisson arrival process; thus the variability might have been slightly overestimated, and therefore, overestimating the necessary average inventory on-hand.

One important part of managing "difficult" demand patterns is forecasting the demand. This topic has not been treated in the thesis due to the limited scope. It is however worth looking into a differentiation of the forecasting method based on the demand categories that have been used in this thesis. Using a good method for forecasting in combination with manual adjustments can help phasing out products at the end of their product life cycle, thus reducing the risk for obsolete items.

This thesis is part of an end to end logistics study at the case company. Other studies regarding the network upstream, specifically supplier lead times and efficient order quantities are conducted. It is expected that the insights from the supply-side study will be a valuable input to the model introduced in this thesis.

The thesis model assumed direct supplier deliveries to inventory locations. This does not reflect reality very accurately. In a more advanced model, replenishments from a central warehouse can be considered.

In order to determine a suitable strategy, the findings from this research could be combined with cost assumptions. This would allow for a comparison of different distribution scenarios in a total cost analysis.

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Appendix: Visualization Application

Figure 1: The Dashboard for the visualization application that is delivered to the company in order to allow for quick analysis

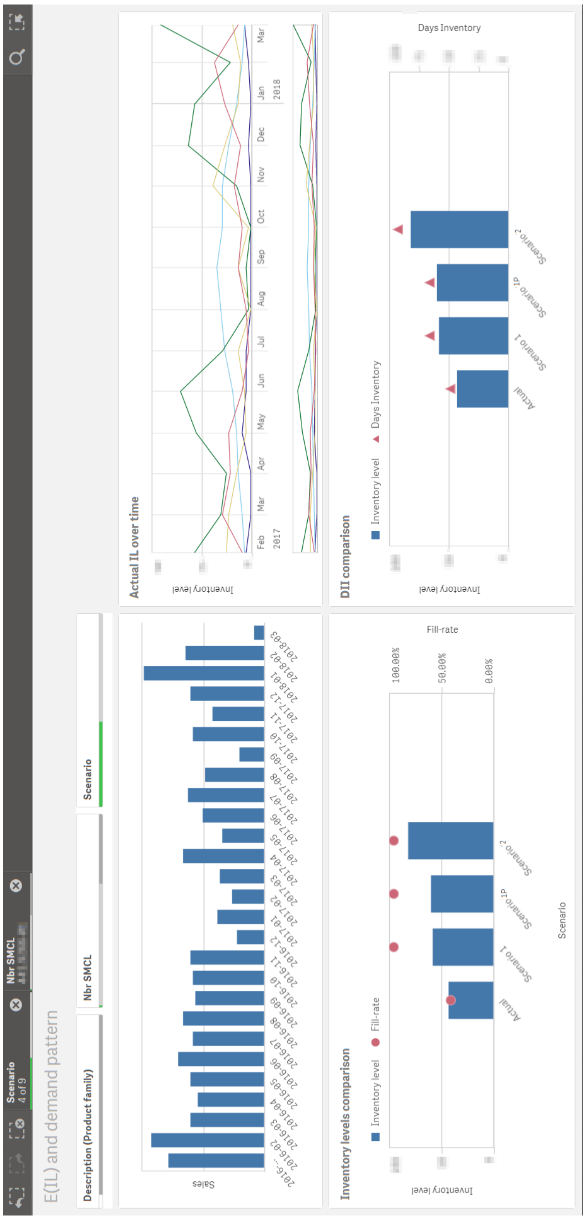

Figure 2: Another view in the visualization application that shows a drill-down analysis