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An Investigation into the Possibilities for Cost Saving in a Distribution Network with Demand Dependencies

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Abstract

Inventory control is a subject that impacts more or less every section of most businesses, hence companies today view it as a crucial problem of strategic importance (Axsäter, 2015). Managing inventory is a complex task which can be made even more complex by considering multiple items interacting with each other throughout the supply network. This master thesis attempts to show, through a case study how the supply chain can be made more efficient by doing this in a supply chain of large spare parts for heavy machinery.

In order to address the purpose, *"investigate how companies can coordinate dependent demand in their inventory management and distribution network and to determine the associated benefits of doing this.* A simulation tool has been developed in which a regular (S, s) policy has been compared to a new model in which the inventory positions of the products that are likely to be co-ordered are considered. Another attempt to make the supply chain more efficient was to stack products on the pallets rather than sending them one product on each pallet.

The proposed model outperforms the (S, s) policy, mostly through savings in inventory costs and fewer pallets in the warehouse. However, the behaviour of the model is hard to predict, it requires a large amount of data and is also difficult to alter. The model performs very well when implemented in supply chains which have a good flow of information and coordination amongst supply chain partners,since it is reliant on the adequate availability of sales, production, warehousing and products data. Therefore, it is the authors' recommendation that companies that do not have seamless information flows and high level of cooperation between supply chain players do not adopt the model in its current state, since the benefits relative to the additional complexity is small. It is also not recommended for companies that have short product life cycles since they will likely not have the long term data needed to run the model well. Stacking the products resulted in savings in labour and other costs and a reduction in the amounts of pallets in the flow. However, while trying to keep the same service level, the tied up capital increased significantly.

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Acronym List

ATO	Assemble to Order
CDF	Cumulative Distribution Function
EOQ	Economic Ordering Quantity
IL	Inventory Level
IP	Inventory Position
LT	Lead-Time
JR	Joint Replenishment
OQ	Order Quantity
PDF	Probability distribution function
PWH	Production Warehouse
SKU	Stock Keeping Unit
RP	Reorder Point
RWH	Regional Warehouse

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1 Introduction

In this section of the report, the theoretical background to this research will be presented. This will be followed up by a description of the project and an introduction to the case. After which,this report's intended contribution to the present body of literature will be presented, together with the delimitation of this research.

1.1 Background

Inventory control is a subject that impacts more or less every section of most businesses, hence companies today view it as a crucial problem of strategic importance (Axsäter, 2015). Today thousands of spare parts are stored throughout supply chains, which is a major contributor to the overall inventory cost (Moharana and Sarmah, 2016). Inventory management becomes even more complex when several product combinations and dependencies in demand are present, in order to satisfy a customer's order (Lu et al., 2003). During maintenance operations, there are often dependencies in spare part demand, where, when one part of a machinery is exchanged, another is exchanged at the same time to reduce downtime. This phenomenon will in this report be refereed to as demand dependencies. These demand dependencies will lead to situations where the Inventory Level (IL) of one product affects the sales or distribution of another product (Moharana and Sarmah, 2016).

An area of manufacturing that shares the same dependencies as spare parts for maintenance is Assemble to Order (ATO), hence some of the models used for ATO can be of assistance when studying spare parts. To increase a company´s responsiveness towards uncertain product demand, and to avoid frequent stock-outs, many companies are turning towards ATO systems, where components are stored instead of the final product (Akçay and Xu, 2004). ATO systems are characterised by problems of product combinations and dependencies in inventory management theory (Reiman et al., 2018). This also leads to, highly stochastic and dependent demand. This can mean a prolonged Lead-Time (LT) for the customer due to stock-outs and thereby a low service level (Swaminathan and Tayur, 1998). In this report service level is defined as a company´s ability to fulfil deliveries and will be measured as fill-rate and component availability.

A major characteristics of ATO systems is product postponement. This strategy influences business profits by combining the benefits of make to order and make to stock policies. It stabilises demand and supply for markets whose products have characteristic high-option mix and volatile demand. Usually, such products result in large amounts of inventory (Yang and Burns, 2003). Postponement can either be time based or form based (Bowersox et al., 1999). Form postponement includes assembly, packaging, labelling and manufacturing by maintaining products in a rather open-format until a customer order is received (Cottrill, 2004). Analysis of variance for historical order data can be used to derive Stock Keeping Unit (SKU) categories (Kumar et al., 2009).

A low service level can negatively affect customer satisfaction which is immensely important to enterprises and it can be crucial for the long term profitability of companies (Rãdãşanu, 2016). Service levels can be analysed at three levels; order fill-rate, order line fill-rate and component fill-rate (Lu et al., 2003). Each of these measures is useful in its own way and a company may decide to use either one or all of them. By managing to keep adequate inventory companies can then make the business case to fulfil customer demand (Axäster, 2015). Due to the demand dependencies being investigated in this master thesis, service level will be analysed as order fill-rate.

In ATO situations where multiple end products are sold, there is, according to the authors' knowledge no documented optimal solution for inventory management of the system (Reiman et al., 2018). Akçay and Xu (2004) states that, even though the problem of product allocation is NP hard, there are many algorithms that propose approximate solutions. Agrawal and Cohen (2001) states that since, the problems are hard to solve, in practice sub optimal solutions are used. Often, to approach these types of problems, independent base stock policies are used (Song and Zipkin, 2003). This disregards the dependencies, however, Moharana and Sarmah (2016) shows through numerical examples how stock levels can be reduced by considering the dependencies, while keeping the service level. They also claim that keeping the major spare parts at a higher service level, will reduce the overall inventory cost. This report, will extend on the work of Moharana and Sarmah (2016), by seeking to improve the performance of a more complex the inventory system, in comparison to what they have considered in their research.

1.2 Project Description & Problem definition

Currently, the case company is struggling with relatively high distribution costs, as well as a low fill rate of customer orders, around five percent lower than their target. To address this challenge, this project is an effort to, within the given distribution network, raise the fill rate as well as reducing the distribution and warehousing costs.

The project will focus on the inventory management of two different product families which are dependent on each other to meet customer requirements. Both product families are required for an order to be distributed to the customer .i.e for product family A and B, the customer's order is only satisfied if the specific products from both families are in stock. Within the family groups varieties are based on sizes and performance based parameters. For the customer, a product is not interchangeable for another product in the same family of different size. Products of the same size are technically interchangeable, but due to different performance parameters, the products are in practice not interchanged. Figure 1 illustrates the ordering structure. Showing the three options of orders; *only A, only B* or *the combination A and B*. The larger the portion of the orders that are in the combination A and B the larger, the dependencies within these groups are. Now, let $A = \{a_1 + a_2 + ... + a_i\}$ and $B = \{b_1 + b_2 + ... + b_j\}$, there also exist dependencies between the products, that is, between product a_k and b_m where: $0 \leq k \leq i$ and $0 \leq m \leq j$. The dependencies between the products makes the inventory management more complex, since it disrupts simple inventory management models.

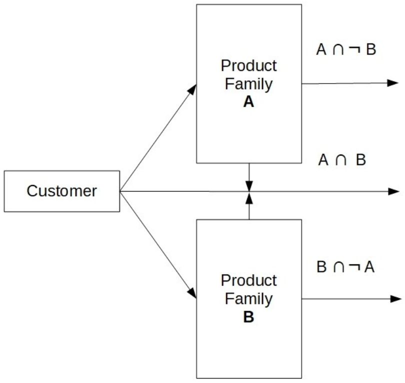

Figure 1: The ordering Process

Due to the characteristics of the products and the way maintenance is normally carried out, when placing an order, customers are unlikely to order from only one of the product families. Both family groups are produced at the same site in Sweden and distributed on the regional warehouse,within Europe. The projects first aim is to leverage on the dependencies between A and B products to optimise the inventory management, and thereby decrease the overall inventory costs of the network. The study will be carried out with data from the European supply chain. The results will then be generalised to other existing and future supply chains.

The products are sold as spare parts, both for routine maintenance and rushed orders which occur as a result of breakdowns. The majority of the flow can, however, still be attributed to maintenance which will be the focal point of this study. The products are made from steel, which means that they are heavy. At present the European supply chain is not stacking the products. However, the Asian suppliers of the same product have, with extra packaging made the products stackable, reducing the space occupied by the products during transportation and in storage.

Deciding what to order, when to order , how to best transport and how many to order of each product has become a complex issue for the case company, resulting in low order fill rates and relatively high distribution and inventory costs. This project aims to provide a systematic approach to the inventory management of the products with respect to, among other things, deciding on Reorder Point (RP) and Order Quantity (OQ). In the project, the possibilities for stacking with the assistance of extra packaging will also be considered. The focus of the project is the physical flow between the manufacturing and the regional warehouse.

1.3 The Purpose and Research Questions

The purpose of this project is to, *Investigate how companies can coordinate dependent demand in their inventory management and distribution network and to determine the associated benefits of doing this.*

To address the purpose, the following research questions will be pursued.

- Determine how the case company should make decisions with regards to their replenishment policy, taking into consideration the dependency of the demand.
- Investigate possible benefits that can be achieved by considering dependencies in the demand and any possibilities in coordinating orders (or parts thereof), when conducting inventory management.
- Investigate the possibility of increasing the inbound logistics fill rate and identify cost benefit possibilities in the distribution network, including any savings in warehousing and transportation.

Benefits will be evaluated on two parameters, fill-rate and cost. The two parameters will, for practical purposes be determined theoretically, no implementation will be taken into consideration.

1.4 Focus & Delimitations

The focus of this project will be a quantitative analysis of inventory management within a specific part of focal company's given supply network. This will be limited to the physical forward flow of two product categories and the market of the Swedish production unit, restricted to the current network. The study will concentrate on the product flow from the production warehouse to the regional distribution centres. The delimitations are illustrated in figure 2. Since the production stage is outside the limitations of this project, the production LT will be approximated as constant.

The last mile distribution, from the regional warehouses to the customers will not be considered. From an operational standpoint, the coordinating of products to meet customer orders will be a necessary consideration in order to achieve the target fillrate of 95% . The operations of the warehouse will be omitted, with the exception of; order consolidation from the production warehouse and at the regional warehouses, investments needed to support the recommendations of the inventory management strategies that will be suggested in this report and the space restrictions of regional warehouses.

Furthermore only one of the regional warehouses will be considered, with this case used as an example for possible implementations thought the supply network.

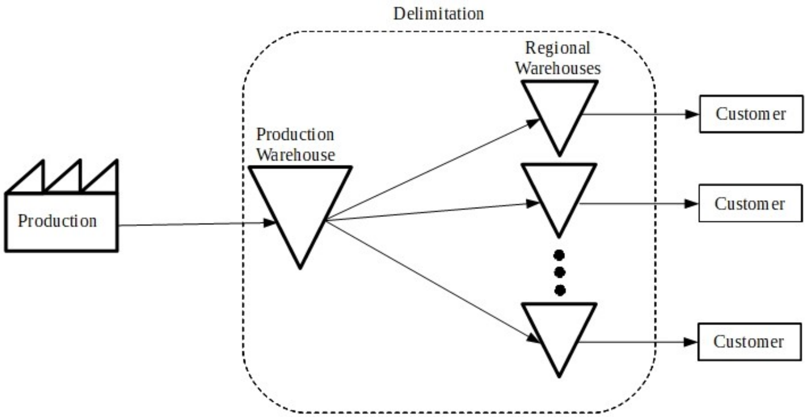

Figure 2: Project delimitation

2 Method

In this section the methods for approaching the research is explained, as well as the project plan. The methods include; case study, simulation and literature review.

2.1 Research Outline

This research starts with the case study that has previously been introduced in chapter 1.2. The project seeks to determine a feasible solution on how to organise and manage the existing flow and storage of goods at the case company. To solve this problem the different aspects of the case together with relevant theories was merged into a model, that has some additions to the existing theories. The model is then to be tested through a simulation and an evaluation from the supply chain professionals at the case company. This process is illustrated in figure 3.

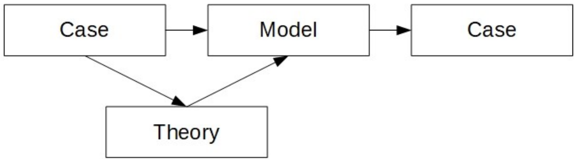

Figure 3: Research Process

According to Singhal and Singhal (2012), operations management should embrace qualitative exploration research including case study, theory development, validity checking, model testing and real world verification. This master thesis has been conducted as a case study approach incorporating model testing by way of simulation. The researched phenomenon is not new and therefore, the research can be said to be mature enough to accommodate and use existing theory. This is further supported by Sadhi and Tang (2014), who claim that, employing a quantitative case approach enhances research integrity and connects research to reality, when compared to adopting just a case research or a quantitative approach independently. Choi et al (2015), discuss single and multiple case studies and how these can also be quantitative or qualitative. Based on the classification of case research, the problem being faced by the focal company is particular to this company's supply chain and can be solved using optimisation mathematical algorithms. Choi et al. (2015), further mention that quantitative case study is a good way to show relevance to the real world practises. As highlighted in the research questions, besides contributing to the present academic literature, this master thesis is being undertaken with the aim to advance industrial knowledge and practises. According to Bergen (1997) operations research cases are motivated by "industrial stories", hence a quantitative case study approach fits well to the purpose.

In most cases, the proposed solution from case studies research is derived under particular conditions that are not entirely generalisable. This reduces the validity of the results (Choi et al. 2015). In order to solve this, Simchi-Levi (2014), proposes that researchers should first collect empirical real world data, then formulate analytic models and finally derive real world applicable solutions. This kind of real world, data driven research has been adopted in this master thesis. Raw data has been collected form the focal company's ERP, thereafter, analytic models have then been developed based on the existing literature and finally the models are applied in a simulation model and also presented to the industrial experts so as to check the applicability of the approach used. Meighen (2015), states that the benefits of quantitative case are a rigorous and rewarding research with real world relevance. Finally, Tang (2014), in his discussion on quantitative case studies adds on and says that quantitative cases can be complimented by other actions including engaging practitioners in the operations management profession.

2.1.1 Time Line

This Master thesis will be undertaken during the Spring of 2019. The time-line spans between 10^{th} of January until 18^{th} June. January was spent on literature study. In February, the modelling will begin and it will carry on throughout March. The Literature study will continue throughout the first three to four months, although it will be on a decreasing scale as the project progresses. In the early stages of the project, the literature search will be focused on previous modelling of similar problems such as Hernandez-Ruiz et al. (2016) and Moharana and Sarmah (2016). As the project draws to and end, the literature study will be focused towards managerial insights and qualitative aspects.

In March the connection to the project and the case will be made, where the literature will be connected to the case. The case will be studied though-out March and April.

In April the focus of the project will be the results analysis, which will run until early May, leaving enough room for the final part of the project which is the round up phase where conclusions are drawn and the final report compiled. This work process is illustrated in figure 4.

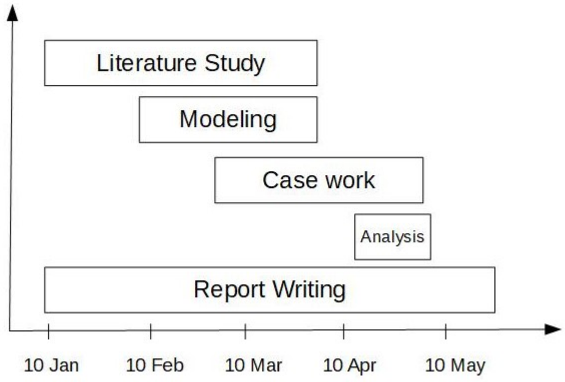

Figure 4: Work Process

2.1.2 Research Approach

Research can be divided into three different categories, depending on the relationship between the theories and the empirics. These categories are deductive, inductive and abductive. In deductive research the researcher starts in existing theory, while trying to explain an existing phenomenon. Thereby trying to test the existing theories. The existing theory then helps the researcher in designing an experiment, such as, which data should be collected and which types of analysis should be performed. This means that the research process gets less effected by the individual researcher but also that the existing research might affect the end result, so that new theories may not get discovered (Patel and Davidsson, 2011).

In an inductive approach the researcher is starting from one or several cases, collecting empirics, and from these empirics trying to create a new, general theory for similar cases. Here the participating researcher will be able to affect the end result in a way that is not as likely in deductive approach. In inductive research another risk is that it can be hard to separate general rules from special circumstances, meaning that the theories will need to be tested to be reliable, which will be done from deductive research. The third option for research is adjunctive, which is a combination of the two previous research methods. Starting form a point of inductive research, and then trying to verify the theories. The risk is that the researchers' choice of phenomenon may affect the theory testing, creating an echochamper where, a theory gets tested under same circumstances that it was developed, thereby reducing the quality of the testing (Patel and Davidsson, 2011).

The current report is based on deductive research, taking strong influence from works such as Axsäter (2015), Lu et al. (2003) as well as Moharana and Sarmah (2016), to mention a few. Meaning that the research approach will be highly affected by these authors.

2.1.3 Research Credibility

According to Bronson (2008), research studies can be assessed on three criterion; the quality of the research method´s internal validity, the external validity in conjunction with relevance of the research and finally, the credibility of the researchers. Internal validity is the extent to which changes may be attributed to the introduction of an intervention whilst external validity is the extent to which the research results can be generalised to other settings. In this regard external validity is related to the contribution that the research has to the academic and managerial domain. Cook and Campbell (1979), suggest more considerations and effort should be directed towards conducting research in real world settings, whilst maintaining the rigorous structures of academic research. According to Bronson and Davis (2012), studies that are conducted in the real world are likely to address practice and or policy challenges in a way beneficial for managerial insights.

Single cases have limitations which include, the risk of misjudging a single event since the study is carried out in a particular context, exaggerating easily available data because one has easy access to it and the generalisability of the results of the case study may be difficult to prove. On the other hand, multiple cases may reduce the depth of the study when resources are constrained but can also augment external validity and help guard against observer bias. In light if this, this research project has been carried out as a real time case employing longitudinal data collection through interviews from operational and strategic staff at the focal company, alongside observations at the production warehouse(Production Warehouse (PWH)) and production sites. This has helped to guard against retrospective sense making and impression management (Eisenhardt and Graebner, 2007). Based on the above discussion, and supported by Eisenhardt and Graebner (2007), who state that, single case researches can accommodate theory exactly to the different parts of that particular case study, a single case study has been deemed sufficient for the purpose of this research.

2.2 Case Study

According to Stake (1995) a case is a bounded system, which, according to Graham (2000), must be a unit of activity studied in its natural setting. According to David (2009), the case can be selected as an example of a general category that can be used to compare similar and/or different examples within the same category to assist with explanations of certain phenomenon.

Yin (1995), describes the case study research as a method of researching complex situations. He further adds on that, case study requires the use of several methods and triangulation in a more quantitative approach. According to him, the researcher may study complex interactions by means of various data collection techniques. Case study research also gives the researcher a chance to collect objective data with greater accuracy and reliability since the researcher has direct access to the original data sources (Voss et al., 2002).

According to David (2009), there are three uses of case study research. The first is organisation and improvement. The second is intrinsic exploration and description of the unique and the particular. The last one is the explanation of complex historical events. This master thesis seeks to delve into the organisation and improvement of the focal company's supply chain network and to do this a case study will be an adequate approach. Case studies are particularly useful when phenomenon and context are not easily separable, since the main objective of using the case study method is to capture the real life event by addressing complexities. This is also complimented by the use of several empirical tools to answer how and why questions about real life events to identify causes. The results of case study research can have a huge impact for managerial use, since the case study is not limited to the scope of questionnaires and models, when compared to surveys ad strictly mathematical modelling research. In situations where there is uncertainty in the definitions of the constructs, case study have proven to be useful too (Mukherjee et al., 2000).

2.2.1 Case Study Procedure

According to (Voss et al., 2002) there are five major steps that have to be followed when conducting case research. The research question has to be asked before any actual work begins on the research. Having a research question also assists in setting up the framework and boundaries for the case study. Once the research question has been asked, instruments for conducting the case study have to be selected alongside with sites for conducting the study. Once the instruments and site have been chosen, data can be collected using the chosen research instruments and from the chosen sites. Data analysis and data collection are usually carried out concurrently and iteratively. The results of the data analysis may then be recorded, tested or simulated before being disseminated to the relevant audience.

In this research of the focal company's inventory and distribution system, a European Supply chain with its starting point in Sweden has been chosen as the domain of the case research. According to Miles and Hubernman (1994), using polar types is one way of identifying the number of case studies. The supply chain that is under study in this research has been identified by the company to be under performing in comparison to the twin network in Asia, hence making it a suitable unit of study in this research. In pursuance of this project, an informal research protocol was developed. Although not entirely strict, this research protocol provided general rules and guidelines as to which data that was to be collected and also the direction that the interviews should take. Bearing in mind that the amount of data that can be collected in case study research is vast (Voss et al., 2002), effort was put towards sticking to the protocol so as to make the project scale-able. In the case research protocol were developed, the research objectives and purpose, which provided a guide to the type of data to be collected (Miles and Hubberman, 1994). The focal company has been chosen, so that the study is conducted in the most natural setting of the supply chain, with the aim of describing the current inventory management systems and distribution network of the chosen supply chain. The research will attempt to use a mixture of quantitative and qualitative analysis. Data will be requested from the company and this will be analysed.

2.2.2 Strategies for Achieving Credibility and Validity

In this study, several methods were used to enhance the validity, reliability and credibility of the data analysis and interpretation processes. Face to face interviews have been conducted with the logistics experts at the focal company and these have been triangulated with follow up interview questions by email or phone call.

In order to enhance the reliability of the case study results, according to (Voss et al., 2002) there must be a good and accurate method of transcribing data. During this case research there was an overlapping of data collection and analysis as earlier alluded to in the Timeline. However, various methods of coding were employed with field notes playing an important role in recording the data and also pushing our lines of thought (Eisenhagrdt, 1989). Throughout the project, effort was made into seeking convergence of ideas from theory, interview responses, data processing and site visits with the aim of triangulating all information and enhancing the construct validity of the data.

One challenge that was identified in the early stages of the project was that of observer bias.This was however overcome by having both project researchers taking up the role of interviewer and then cross reading each others' notes at the end of the day. In order to enhance triangulation of information, consultations have been done with the management at the focal company with regards to selecting the case. The main source of data for the case were structured interviews with key informants. These were often backed by unstructured interviews and interactions. Other sources of data included personal observation, informal conversations and historical sales data. To augment the on site and off-site interviews a tour to the main warehouse was undertaken, as recommended by Boyer and McDermot (1999). Due to the nature of the case study, it was adequate to use a single key informant in all the interviews as they could answer all the questions in the research framework, reliably.

2.2.3 Approach for Data Collection

The data required for this project is mostly quantitative. Sales data, parameters of the supply chain, such as LT, inspection intervals, warehousing and transportation costs as well as data on how changes in the network may affect the parameters. Sales data has been extracted from the ERP system of the case company. Due to the nature of the project, large amounts of data are required. Extracting data that displays the product dependency is crucial for the project, hence a long period of time is required when extracting the data. Systematic corruption of the data may be also be present, due to the dependencies, the distribution and the parameters of the distribution might vary over time.

The parameters of the logistics network are on the other hand fewer and mostly not directly present in the ERP system. The knowledge of the parameters can be found among the experts in the case company. This data does not pose a significant threat for the academic purposes, since the generalisability of the result will not be dependent on minor inaccuracies in the parameters. Similarly the parameters of the changed network can be extracted from the experts. The experts will be consulted through structured interviews in these areas. The interviews will take place in the beginning of the case work phase according to figure 4 and be structured to avoid subjectivity in the parameters.

Lastly, the model verification will be conducted in the end of the case work, to verify that the model sufficiently represents reality. The verification is in two parts, firstly there will be an attempt to simulate reality with the model, trying to achieve a similar result to reality. Consulting the high ranking experts in the company to check if the results are representative of the reality, this will be done through semi-structured interviews.

2.3 Simulation

In situations where business processes are too complex to solve using mathematics, simulation is a useful tool. Simulation is the practice of mimicking reality through models. It is effective for process modelling and performance analysis and prediction of systems. It is important that the model has sufficient complexity so that it can depict what would happen in practice. Being able to illustrate problem solving using simulation, has the capacity to gain management support for decision making. The model can be verified by being built in increments or making the model predictable by removing variability or other simplifications. To determine if the model is valid its output can be compared with the case, through historical data (Laguna and Marklund, 2013).In this master thesis,simulation will be used to test the models that will have been developed to analyse the focal company's supply chain.

2.3.1 Simulation Analysis

In simulation, data analysis is key. Since business processes often have a certain degree of randomness, it is important to reflect this randomness in the simulation. To simulate randomness real data can be used, this however has the shortcoming of potentially missing data, unrepresentative extreme values or lack of history saved. Instead, what can be used is distribution fitting so that the real data set can be approximated with a theoretical distribution. If data is completely missing it might even be necessary to ask experts in the field to approximate the process (Laguna and Marklund, 2013). The demand data which will be the input to the simulation has been collected from the ERP. Simulation analysis for this data has been conducted by trying several distribution fitting and analysis the goodness of fit, this procedure will be explained in detail in the following chapters.

A system is made up of inputs, which are processed to outputs. Since there is randomness in the input data, it is also to be expected that there will be randomness in the output data. This can be analysed both with respect to mean values, variation and other statistical indicators. By comparing which parameters are important it is than possible to determine which settings are preferable (Laguna and Marklund, 2013).

2.3.2 Input and Output Data Analysis

According to Laguna and Marklund (2013), input and output data analysis is key in order for a simulation model to be of any use. The real data that the simulation model tries to mimic is usually non deterministic and hence some statistical analysis to determine the correct distribution that fits the field data needs to be carried out. Once the distribution fitting has been identified, this can be used to generate random varieties in the simulation model. These random varieties are then the input to the simulation model to give some output data. This output data, also has to be analysed as it contains the performance measures under investigation resulting in understanding for a current process or a prediction for a future process. In order for the model to be trustworthy, it can be validated and this may be done by using actual data as input to the simulation model and comparing the results with those of using a statistical distribution fit as input to the simulation. The most critical steps in the input and data analysis is selecting the most appropriate statistical distribution that represents reality.The distribution fitting of the customer orders occurrences was conducted for several distribution systems. The goodness of fit test was done using the Chi -square test which was deemed appropriate for the data available. The Chi square test will be further explained in the coming sections.

For simulation of business processes the parameters that are of most concern are the randomness of processing times and inter arrival times. Since time is a continuous variable, theoretical Probability distribution function (PDF)s are of major concern in business process simulations. A probability density function is a mathematical function that assigns a probability value to a given value or range of values for random variables like processing times and inter arrival times. The most fitting PDF can be determined by trying several PDFs whilst using the goodness of fit test to determine how well the PDF represents data.

2.4 Distribution Fitting

In section 2.4 the methods used for distribution fitting used in the process will be explained. When fitting data to a distribution, it is advised to try several distributions before selecting the best fit. If too much data is taken into consideration, an incorrect distribution can easily be chosen, as it may still fit the data. However, using limited parameters to define a distribution and fit given data reduces the amount of variability in the data, using of parametric approaches usually gives much better results (Cousineau, 2004).

2.4.1 Maximum Likelihood Method

According to Van Zandt (2000), the maximum likelihood method can be used for distribution fitting. Cousineau (2004) describes the maximum likelihood method in the following way:

The method searches for a set of parameters, θ, of a model which has been hypothesised to represent the distribution of some observed data set. The likelihood of a data set T, is the joint probability of the sample for a given model and set of parameters. For a given parameter set θ and a PDF f and assuming the sample to contain independent deviates from this distribution. The assumptions of the model are that the observed data are independent and measured with infinite precision.

$$Pr((RT) = T) = Pr(RT_1 = t_1 \cap RT_2 = t_2 \cap RT_3 = t_3 .... \cap RT_n = t_n = P(RT_i = t_i) \qquad (1)$$

The function L, called the maximum likelihood function is a measure of how likely the data set is, given θ. The larger L is the more likely θ is to the true θ.

To implement the Maximum Likelihood Method, there has to be a distribution function to be fitted, an optimisation routine and the starting values of θ. The choice of the distribution provides the PDF equation f, that is inserted into the function to be minimised. The optimisation procedure to minimise the objective function is usually chosen from a set of algorithms. Analytic derivatives of the objective function using gradient methods and use of numerical approximations by direct search methods to the derivative, are usually employed. However it is more common to use the gradient methods.

2.4.2 χ^2-Test

A χ^2 test is used to determine weather or not a hypothesised null distribution holds for a given data set. In a χ^2 test, observations are split into k mutually exclusive classes where O_i is the number of observations found in class i, and E_i is the expected number of observations in class i. The test criterion used in the test χ^2 is given by equation 2 (Cochran, 1952).

$$\chi^2 = \sum_{t=1}^{k} \frac{(E_i - O_i)^2}{E_i} \tag{2}$$

The value from equation 2 is then compared to equation 3, for the significance level s, greater than 0 and the degrees of freedom, K.

$$f(s,K) = \frac{s^{\frac{K}{2}-1} e^{-\frac{s}{2}}}{2^{\frac{K}{2}} \Gamma(\frac{k}{2})} \tag{3}$$

Where Γ is given by equation 4 for natural numbers, n or 5 for numbers given by n+1/2.

$$\Gamma(n) = (n-1)! \tag{4}$$

$$\Gamma(\frac{n}{2}) = \sqrt{\pi} \frac{(n-2)!!}{2^{\frac{n-1}{2}}} \tag{5}$$

2.4.3 Considered Distributions

Discrete distributions are separated from continuous. In this project the distributions chosen are those that are more common than others, Axsäter (2015), together with other distributions that are usually used in the context of logistics. A list of the considered distributions is given in table 1

Table 1: Considered distributions

Discrete
Poisson distribution
Binomial distribution
Negative binomial distribution
Geometric distribution

3 Theoretical Framework

This chapter will discuss the theories that will be used in this report, the second level chapter will give a brief introduction to each subject while the third level goes more in depth on each field that will be covered. These sections will focus on the methods that could be useful and also look into managerial insights. For step-by-step mathematical illustrations of complex models the reader will be referred to the appendix.

3.1 Inventory control

The two most common ordering policies are the (R, Q) and the (s, S) policies. In a (R, Q) policy the OQ always ns the same, whilst it can vary in a (s, S) policy (Axsäter, 2015). One way of determining the OQ is the Economic Ordering Quantity (EOQ), the EOQ has several simplifications, which means that is not a strictly an optimisation but, it is rather a sufficient tool for decision-making due to the differences in OQ often having marginal difference on the total cost (Jonsson and Mattson, 2005). The formula for EOQ can be derived from the total cost function and then setting the derivative to zero according to formula 6.

$$0 = \frac{\partial C}{\partial Q} = \frac{\partial}{\partial Q}\left(\frac{A \cdot D}{Q} + \frac{h \cdot Q}{2}\right) \implies EOQ = \sqrt{\frac{2AD}{h}} \tag{6}$$

Where:
C is the cost per time unit
A is the ordering cost
h is the holding cost per unit and time
D is the demand during the time
Q is the ordering Quantity

To determine when to order companies are usually using either continuous or periodic review systems. The key difference between these two systems are that in a continuous review system, products are ordered was soon as the Inventory Position (IP) becomes less than or equal to the RP, whilst in a periodic review system,the IP is inspected at predetermined intervals and if at the time of inspection there are products whose IP is less than or equal to the RP. This means that, the time of ordering will always be later in a periodic review system, resulting in a lower service level for identical RP (Singha et al., 2017).

Another important subject in inventory management is how production should be planned. Hill and Hill (2018) suggests five generic settings for where the customer order decoupling point should be placed. The five steps are design to order, engineer to order, make to order, ATO and make to stock. In general, when the the decoupling point is further away from the customer the LT increases but a larger portion of the demand is known, this means that the first mentioned steps allow for more planning, while the later steps are dependent on forecasts to a higher degree.

According to Axsäter (2015), a deterministic model is one which always performs the same way for a given set of parameters. Random variations are disregarded and therefore the lead times can be disregarded as long as they are constant i.e they are the same for all items.On the other hand, a stochastic model is one that displays random variability and will not always display the same results for a given set of parameters. The demands are therefore independent and stationery and due to the variability, the lead times can therefore not be disregarded. In both cases, deterministic or stochastic . back orders may be allowed for.

In determining lot sizes,it is however common to use deterministic methods instead of stochastic methods. The stochastic demand can be replaced by its mean and then a deterministic model is used to determine the optimal lot size. Given this optimal lot size, other parameters like service levels and reorder points may then be determined using stochastic methods.

3.1.1 Periodic review and continuous review

Similar to Singha et al. (2017), Axsäter (2015) explains the difference of continuous review and periodic reviews as; in continuous review products are ordered as soon as the IP is less than the RP, whilst the in periodic review the products are ordered periodically,if at the time of review, the IP is less or equal to RP. This according to Axsäter (2015), implies that the uncertain period in a periodic review is larger than in a continuous review, which means that the need for safety stock is larger in a periodic review systems. However there are also benefits to using periodic review, including possibilities of coordination in ordering. The IP of the systems is illustrated in figure 5. The IL the system is given by equation 7.

$$IL = IP - Outstanding\ orders = Stock\ on\ hand - back\ orders \tag{7}$$

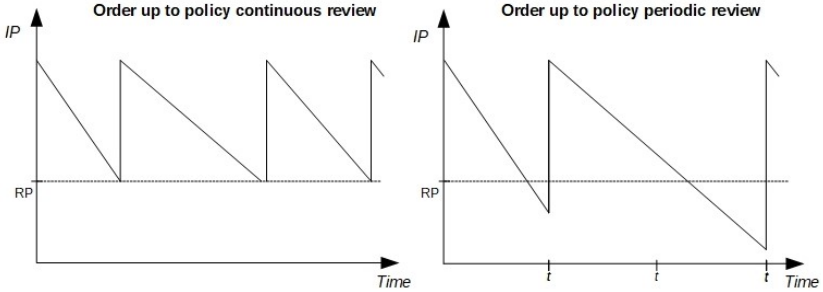

Figure 5: Periodic and continuous review policies

The assuming that the LT in a continuous review system is constant, the the LT in a periodic review system varies between LT and LT$+t$ where t is the inspection intervals Axsäter (2015). Making the periodic review system perform closer to a continuous review system when t is relatively small compared to LT.

3.1.2 Single Product Inventory Analysis

According to Axsäter (2015) the cost function for an inventory system where back orders are allowed, i.e. in case of a stock out the customer are waiting for the requested product to be replenished, is according to equation 8.

$$\mathbf{E}(c) = \mathbf{E}(IL^{+}) \cdot h + \mathbf{E}(IL^{-}) \cdot b + \frac{A \cdot D}{Q} \tag{8}$$

Using the same notation as in equation 6 with the addition being the back order cost, notated as b. Which is the theoretical cost acquired for a customer waiting one time unit. IL^+ are the positive values of the IL, if IL is negative it is regarded as zero. Similarly IL^- is the negative values of IL, where positive values are regarded as zero.

Axsäter (2015) considers both the case of continuous demand and discrete demand. Claiming that for product with relatively high demand it can be more convenient to approximate the demand with a continuous distribution. This does not generate exact solutions however but in many cases it is close enough. When the demand is low however, it is more natural to use a discrete demand.

When the IP is in a steady state in continuous review, the IP is uniformly distributed between R+1 and R+Q, assuming discrete demand. This is however not the case for periodic review Axsäter (2015). This is also evident by figure 5, even though the figure is assuming continuous demand. Before presenting the optimal solution following notations and statements are introduced according to Axsäter's (2015) definitions, given the IP=k, after LT time units the IL is equal to j which is smaller or equal to k with the following probability:

$$P(IL = j) = P(D(LT) = k - j) \tag{9}$$

Equation 9 gives the probability of a certain inventory level, by the law of total probability the expected inventory levels can be determined. The expected inventory, defined as the sum of holding cost and the back order cost, can then be determined through equation 10 by differentiating between by expected positive and expected negative IL.

$$\mathbf{E}(cost) = -b \cdot \mathbf{E}(IL^-) + h \cdot \mathbf{E}(IL^+) \tag{10}$$

The back order cost is often hard to evaluate, however sometimes companies are using a defined service level, Axsäter (2015) discuss 3 different types of service levels, two of which is important to this project according to the following:

- $S_2 \implies$ fill rate - fraction of demand that can be satisfied immediately from stock on hand.
- $S_3 \implies$ ready rate - Fraction of time with positive stock on hand.

For discrete demand there is the following relationship between back order cost, holding cost and the predefined service level (Axsäter ,2015), where R^* is the reorder point that that gives the predefined S_3.

$$S_3(R^*) \leq \frac{b}{h+b} \leq S_3(R^*+1) \tag{11}$$

Or for continuous demand:

$$S_2 = S_3 = \frac{b}{h+b} \tag{12}$$

Zheng and Federgruen (1991) proposes a solution to find the optimal settings in a continuous review (s, S) policy according to the following algorithm, using the definition of g(k) from equation

i. Set as the $S^0 = k$ such that g(k) is minimised for one period.

ii. Find the optimal s^0 given S^0.

iii. Find a value smallest value S^1 such that c(s^0, S) < c(s^0, S^0).

iv. Assign S^0=S and find the optimal s^0 given the new S^0.

v. Repeat from step iii while g(S) $\leq$ c(s^0, S^0).

3.1.3 Assemble to Order

Song and Zipkin (2003) defines a ATO system as a system were, several components are stored for a wide range of products. While customers are ordering the products it is the components that are stored. This lets companies offer a wide variety of products while keeping high service levels. This problem become more complex if the LT is uncertain, or if back orders are assumed. The challenge is how to treat the back orders? If the order can only be partially fulfilled, will the requested components be reserved for the order or can they be used to fulfil another order? According to Lu et al. (2003) the problem remains unsolved, when the end products are not known. In practice, the systems are simplified by the individual control of the components, using the methodology described in section 3.1.1 or similar. This is also the true at the case company.

Swaminathan and Tayur (1999) proposes a myopic solution to the problem, in each period they are determining what to order of each component denoted as $q_i t$. This results in the vector $\vec{q}_{it}$ which is the incoming goods combined with the leftovers from previous period. $\vec{h}$ is defined as the holding costs for each of the products. $\vec{s}_{it}$ is the vector containing which products assemble in period t. $\mathbf{U}$ is the matrix specifying which components a products consist of. $\vec{b}$ is the vector consisting of the different back order costs. ψ_t is the demand of components at time t. The proposed objective function is then according to equation 13 for period t.

$$min_{qt}\vec{h} \cdot \vec{q_t} + \mathbf{EQ}(\vec{q_t}, \vec{\psi_t}) \tag{13}$$

Where:

$$Q(\vec{q_t}, \vec{\psi_t}) = -max[(\vec{h} \cdot \mathbf{U} + \vec{b})\vec{s}_t - \vec{b}\vec{\psi_t}] \tag{14}$$

Such that:

$$\begin{gathered} \mathbf{U} \cdot \vec{s}_t \leq \vec{q_t} \\ 0 \leq \vec{s}_t \leq \vec{\psi_t} \end{gathered} \tag{15}$$

And for the T period problem the objective function is then:

$$min_{q_1 \ldots . q_t} \sum_{t=1}^{T} \vec{h} \cdot \vec{q'_t} + \mathbf{EQ}(\vec{q'_t}, \vec{\psi_t}) \tag{16}$$

where

$$\begin{aligned} \vec{q'_t} &= \vec{q'}_{t-1} + qt - \mathbf{U} \cdot \vec{s}_{t-1} \\ \vec{\psi'_t} &= \vec{\psi'}_{t-1} + \psi_t - \vec{s}_{t-1} \end{aligned} \tag{17}$$

3.1.4 Joint Replenishment

Variation in product demand increases the complexity of the supply chains, since it increases the number of components combinations (Hernandez-Ruiz et al., 2016). According to Axsäter (2015), in some cases all products should be ordered jointly, whilst, due to, for example transportation characteristics, Axsäter (2015) also suggests two different deterministic models for solving the problem of Joint Replenishment (JR). Viswanathan (1997), suggest a different method for determining parameters of JR. At the time, he shows that his method outperformed common methods of approaching JR.

3.1.5 Inventory control with demand dependencies

Moharana and Sarmah (2016) suggest a heuristic algorithm for solving problems of spare parts distribution that have demand dependencies. In their model they assume that the dependencies of the spare parts are present and that they impact the overall performance of the system. The impact is such that the sales of a major spare part impact the sales of a minor spare part. This is because maintenance is normally scheduled so that parts can be exchanged at the same point in time. The model is exhaustive and it only considers one dependency at a time, as well as ordering according to a Poisson process with a 1 for 1 replenishment in a periodic review system.The model optimises first for the major part, then optimises for the minor part, considering potential blockage cost of the major part in combination with other cost as presented in 8 to determine whether or not to order the minor part. Liu and Yuan (2000) managed to show cost savings in a two item system, with dependent demand. Their result also implies larger savings when the demand co-variance is relatively small.

3.1.6 Can - Must order

Balintfy (1964), proposes an alternative to individual management of products, using a can-must order system. The can order level is higher than the RP. This can be used in a system where there are common ordering costs. The system works so that, whenever the stock of a particular item has drooped to the reorder point, the stock level of the other items is checked, and those items whose IP which has fallen below the can order point will also be ordered so that the orders become jointly restocked. Silver (1974), through 104 examples of cases, where, fixed non zero LT and Poisson distribution was assumed managed to show an average of 18% saving compared to individual management of the products. From this observation, we conclude that (R,Q) policy does not perform well when there are dependencies in ordering.

3.1.7 Back-orders

According to Vijayan and Kumaran (2007), shortages are a natural phenomenon when it comes to real inventory systems. Shortages result in loss of customer faith, yet, at the same time it is difficult to measure the exact amount of shortage costs since they are many factors contributing to inventory shortage. In most cases, the demand during the stock out period is either considered lost sales or backorders. In instances where the customer is willing to wait for stock to be available, then the demand is considered as backorders. De Santis et al. (2017) add on to the managerial perspective of backorders. They argue that backorders is a popular supply chain challenge, with a direct influence on the service level delivered by a firm to its customers and its effectiveness in delivering orders.

In machinery and spare parts inventory control, the customer is usually bound to the original equipment manufacturer for a certain period of time. Hence most of the time, in order to secure warranties and sales contract agreements, in the event of shortages customers are forced to wait for restocks to arrive. However as mentioned by De Santis et al. (2017), a complication arises in the inventory management problem as companies try to satisfy all orders on time. In most instances the number of products that go on backorder is less than those that are usually in stock, This presents a class imbalance problem. Which products to focus on in inventory control and how to handle these. In this project, the approach was inspired by De Santis et al. (2017) who use machine learning to try to solve the problem of class imbalance when handling backorders.

The authors incorporate simulation as a way to predict the backorders of the parts likely to affect each other based on the commonality between the parts.

According to Song (2002), an assembly to order manufacturing system is one where a customer order typically consists of different items in different amounts. In such a situation companies strive to satisfy every part of the order and therefore measuring the average order based backorders is a critical measure of service level. Song (2002) also adds on by highlighting that, the number of order types that have overlapping items with this order is an important consideration in determining the stock prone to shortages. The thrust is then, to relate the order backorders to the customers' waiting time and thereby establish the order fill rate.

3.2 Warehousing

By running warehouses companies can better match the supply with the demand, even though running warehouses both requires labour and capital, it also provides the ability to respond to surges in demand, protection against seasonality, capacity, consolidation and a buffer to hedge against uncertain transportation (Bartholdi and Hackman, 2010). Section 3.2 is dedicated to theories relevant to the warehousing operations and this project.

3.2.1 Product Affinity

When products are more often than not, ordered together, they are said to display affinity. Product affinity is generally easier to recognise and exploit if the typical OQ is small. Some items may frequently be requested together and can often consist an entire order. In such cases the effect is that, multiple line orders can be converted into less order lines. This may be useful in order picking by travelling to their common storage location, picking both SKUs directly into a shipping container and thereby completing the order. Completing orders quickly mainly results in reduced work to consolidate orders before shipping. Normally it seems sufficient in most cases to consider only the likelihood of two combinations. The greatest number of common picks must occur among the first pair of combinations. Should there be no significant affinity to be found there, there is no use in searching among larger combinations (Bartholdi and Hackman, 2010). However, when the number of SKU's under consideration becomes very large, tabulation becomes rather complex. In order to solve this, simulation has been incorporated into this master thesis so as to assist with identifying the product affinities which will be later called demand dependencies.

Affinity analysis is a data processing technique that discovers co occurrence relationships warehousing and logistics activities as well. It is usually used when firms try to understand the purchase behaviour of their customers. The obtained data is then used to categorise fast selling and slow selling products, thereby influencing sales and warehousing decisions (PiranniZ, 2010). Cheng (2005), among others, presents two qualitative measurements for deciding weather or not two items display affinity; confidence and support. Given two sets of products or products X *and* Y as well as a set of orders T, the confidence level of $X \implies Y$ can be said to be the percentage of orders containing product(s) X that also contains product(s) Y the support for this relationship is the percentage of T containing X multiplied with the percentage of orders containing Y. Chen et al. (2005) presents a same method for determining the affinity, and introduces the terminology parent for X, in the given example and child for Y. Chen et al. (2005) writes about the challenges with determining affinity, claiming that, if a large set of articles needs to be analysed, then the confidence and support may not be the best indicators for product affinity, on a product level, since they generate a large set of relationship that may be too complex for any real managerial insights. On the other hand by splitting products into groups one could reduce the number of relationships but then the taxonomy of the grouping may be very influential on the result. A jacket could be a member of any one or all to the groups: Jackets, Outwear or a specific collection. After carrying out the analysis the support and confidence between X and Y can be compared to user specified levels.

To find a qualitative value for the cross selling, Chen (2005) suggests looking at the cross selling, i.e. the selling that occurs for products Y_i due to the presence of product X. This cross selling can not be determined exactly. Chen (2005) suggest a way of determining the range of the cross selling, according to equation 18 and 19.

Chen (2005) presents the following model for determining cross sell. To determine the cross sell, one must determine the range of sales for product x and y in period t. Denoted as $[V_s^x, V_L^x]$ and $[V_s^y, V_L^y]$ respectively. The association role for the products is then according to equation 18

$$x[V_s^x, V_L^x] \implies y[V_s^y, V_L^y] \cdot Support(X,Y) \cdot Confidence(X,Y) \tag{18}$$

Given the cross selling function, γ(x,y) is dependent in the range of the ranges of the sales given according to equation 19.

$$\begin{aligned} \gamma_{min}(x,y) &= \frac{V_L^y}{V_S^x} \cdot confidence_{xy} \\ \gamma_{max}(x,y) &= \frac{V_S^y}{V_L^x} V_L^y \cdot confidence_{xy} \\ \gamma_{min}(x,y) &\leq \gamma(x,y) \leq \gamma_{max}(x,y) \end{aligned} \tag{19}$$

4 Empiric

In this section the key empirics of the project will be discussed. The purpose of the chapter is to give the reader an overview of the parameters that governs the case in order to asses its relevance for another situation.

4.1 Case Introduction

The case concerns a producer of heavy machinery in northern Europe. The company is divided into three organisations, one of which produces mining equipment. The mining equipment has a wide variety of products. This equipment needs spare parts for maintenance and repairs. The key spare parts under consideration in this case consists of, two different product families which are dependent on each other in order to meet customer orders.

For product family A and B, the customers order is only satisfied if requested products from both families are in stock. Due to the characteristics of the products, customers are unlikely to order from only one of the product families. Both family groups are produced at the same factory, from where they are then distributed on the global market. Approximately 12 million metric tonnes are distributed from the facility per annum. This represents approximately one third of the entire annual volume of products distributed by the focal company.

The products are first, produced at the the case company's own factory and then stored at the PWH. From this warehouse, they are transported to Regional Warehouse (RWH), which are owned and operated by third party logistics providers. From there, the products are sold to the end consumer, either as individual units, or as kits according to figure 7. There is a significant number of SKUs from both products, customers are given many ordering options. Each product family is stored separately and the product families are merged at the point of dispatching a customer order, at the RWH.

4.1.1 Data Collection

The demand data was extracted through the ERP system used by the case company over a time span of 15 months (January to March). From this data, it was noted that there is a trend in the ordering which is reflective of the demand pattern: certain products are often ordered together by a customer. This then results in interdependent demand. For these products the degree of dependency was further investigated by running a program to determine the product affinities. According to Lofti et al.(2018), it is common for manufacturing processes or projects to order resources for two or more periods and therefore demand will have a co-relationship. They further argue that modelling demand interdependently gives a higher conformity with real world applications.This argument , together with the data observed motivated the use of the case data as interdependent demand.

The demand has then been approximated by using the data of the orders that were actually distributed. This means that customers that may have been unhappy with the case company´s ability to deliver due to, for example stock-outs, will be disregarded. Disregarding these orders from the demand results in a lower estimation of the demand, since some of the cancelled orders might be due to stock outs or long LT. The choice to remove these orders was done so that the model would mirror the physical flow of the distribution network.

Since there are many different organisations within the supply network, there will be differences in how the organisations perceive the demand. Simplified, there is one production unit with a consolidation warehouse, one RWH and several sales units within the geographical delimitations of this project. Each of these levels experiences the demand of the downstream unit and the sales units experiences the demand of the end consumers. The sales units can be both independent companies or a part of the focal company. They operate in a smaller regions, often limited to a single or a few countries. In the supply chain network,there are also smaller hubs for the distribution of the goods. The configurations of the network is such that the hubs should only keep stock that has already been sold, as well as a very small stock of fast moving, cheaper goods. The sales units comply with this configuration requirement to a varying degrees.

4.1.2 Current Parameters

To give a background of the current setup in the case, the important parameters will be presented here. The parameters have been presented so as to show the current setup and not to limit the applicability of the case study to the actual parameters.

- Three deliveries per week between the production warehouse and the regional warehouse.
- The case contains approximately 750 SKUs.
- The regional warehouse serves most of Europe.
- The production LT is approximately one month.
- The LT between the manufacturing unit and the regional warehouse is a few days.
- Transportation is carried out with standard 40-foot containers.
- Interest rate is assumed at 15% since it mirrors the ROI of the case company (Approximately).

Furthermore, the demand pattern was estimated with a back order model rather than a lost sales model. The reason for this is that the case company holds a monopoly over the spare parts supply, Customers requiring the spare parts have little choice other than waiting for the spare part to come into stock. Where the only other option would be to ship the product from a different region which would not necessarily lead to a faster delivery. A test to determine the type of distribution followed by the demand data was done in the program developed for this master thesis, The results showed that the demand data almost exclusively followed a Poisson distribution. This was verified for goodness of fit by a Chi Square test run in the same program. A Poisson Distribution is key in that , it means that the the demands are additive.

4.1.3 Product characteristics

The products are spare-parts for machinery. Due to normal wear and tear the exchanging of the spare parts can be considered routine maintenance, but there is also a smaller section of the flow going towards repairs. The section of the orders going towards repairs are mostly rushed orders. They will not be considered in this report since they are a proportionally small part of the supply chain and are governed by a different set of characteristics. The focal products can be split into A and B products, but there are also some minor spare parts in the supply network. The minor spare parts are often components such as nuts, bolts and tubes, while the weight of the A and B can range from 350 Kg to several tonnes, requiring special forklifts and reinforced pallets for handling purposes.

Generally, the smaller of the A and B products, have higher demand compared to their larger counterparts. A product A of size i can only be used together with a product B of a corresponding size. Within the i sized products, there are differences in the performances of the parts, and depending on the material handled by the machine, different setups might be required.

4.2 Work Flows

In this section the current work flow will be compared to that of a twin network.The twin network is in a different geographical area and is also distributing the same types of products. During distribution and storage, in the twin network, there is currently stacking of the products on the pallets, see figure 7 and 8. The notations used in the figures are illustrated in figure 6.

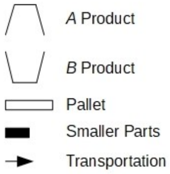

Figure 6: Notations

4.2.1 Current work process

The work flow of the current setup is illustrated in figure 7. From the factory, the products are controlled through a separate inventory management systems. Dispatches take place on average every other day. Products are sent one product per pallet in standard sized containers. Even though the products pallets are not currently stackable, special solutions have been adapted on the inside of the containers to allow for two layers. At the RWH the products are transported to bins (pallet locations). When a customer order arrives, if the order can be fulfilled, the A and B products are matched together with some smaller parts (that will not be studied in detail for this thesis) and then shipped out, each product on its own pallet. Making a total of three pallets for a complete kit(given a 1:1:1 ratio for the 3 parts of the order). This process is illustrated in figure 7. B products are also sent from the factory, but omitted from the figure to illustrate the independent ordering. The exception to this rule are products that are ordered very seldom in huge quantities, one set, for example was ordered twice over the 15 month period. Both times at a quantity of 44 units.

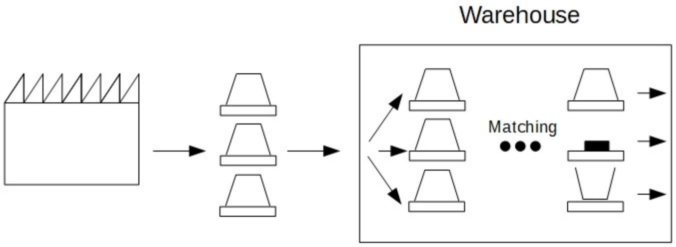

Figure 7: Current work process

4.2.2 Current work process of twin network

In the twin network, products are stacked on top of each other for the inbound flow to the RWH as illustrated in figure 8. The expected result of this is that the distribution cost per unit goes down while extra packaging is needed and there is some extra work in the picking process, since the order picker needs to break bulk. Work is however saved in the loading and unloading of the products since, an operator can move a larger amount of products on each trip between the shelves and the trucks. Having several products stored at each pallet location also leads to savings in the space required for storing the products.

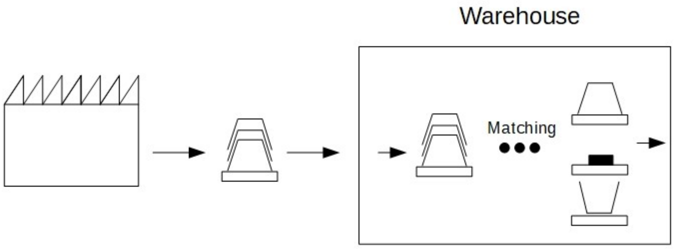

Figure 8: Twin network work process

4.3 Stacking of pallets effecting the cost

The cost analysis begins with an investigation of the current cost drivers in the distribution network. The processes in the physical flow are displayed in figure 9. The costs associated with the processes depicted in the figure are pallets cost, forklift mileage, working hours production warehouse, shipping fees, of loading at PWH, offloading at the RWH, stacking costs in PWH as well as un-stacking at the RWH.

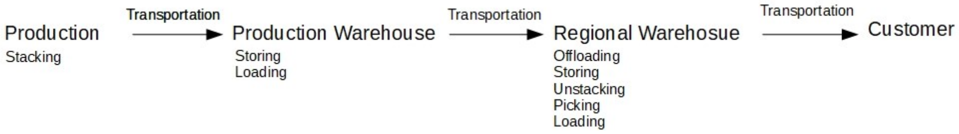

Figure 9: Processes under investigation

4.3.1 Current Cost Breakdown

The total pallets cost is the product of the number of items per product and the average cost per pallet. The 4 way pallets are reinforced and have been assumed to be able to carry the weight of the heaviest products. The actual size of the pallet does not have much significance since the master thesis seeks to use already existing pallets. Considering these pallets the biggest pallets can only fit one per width of the container. Likewise only one of the smallest pallets can ft per width. Hence the significance of pallet size is negligible for the purpose of this investigation.

The forklift transportation mileage has been considered at both the PWH and the RWH. At the PWH, a single trip consists of moving the product from the production plant to the warehouse storage location (400 meters),then an average of 200 meters from the warehouse storage locations to the loading bay.The same distance is covered on the empty return trip and hence the total distance incurred due to one product is 1200 meters. At the RWH, a distance of 200 meters is moved from the unloading bay to the storage locations and an equal distance to the loading bay and hence the total distance,including the empty return trip due to one pallet is 800 meters. Therefore the total distance travelled by a pallet is 2000 meters.

The handling of the products is also consuming time at the PWH and the RWH. The time has been split into the following activities; stacking (0.5 minutes), picking (0.5min), travelling to the PWH (2 minutes), put away (0.5 minutes) and travelling back (2 minutes). This leads to a total cycle time for one pallet is 5.5 minutes. At the RWH, the time for offloading is 2minutes, to the pallet location is 1min,dead heading is 1 minute and placing is 0.5 minutes. The total time required per pallet at the RWH is 4.5 minutes when receiving. For loading the truck the times are picking 0.5 minutes, travelling to loading truck 1 minute, loading 0.5 minutes and 1 minutes for dead heading, making a total of 3 minutes per pallet. The administrative cost has been excluded form the calculation to make it simpler to follow through. The storage location cost at the RWH 3 euros per day and pallet position. At the PWH the situation is slightly different as the focal company does not pay any rentals. Any reduction in number of pallet positions will result in increased warehouse capacity. It is highly unlikely that the PWH will sell this land off if there are any savings.

The transportation cost from the PWH to the RWH is the fixed transportation cost of 3000 euro, per container. The inbound handling costs at the RWH is the product of the number of pallets received at the warehouse at 6 euro per pallet. The RWH operates a crane for handling pallets carrying more that one item and the investment cost of this crane is currently 10 000 euro. During stacking the products use some packaging. Both to hold the pile steady and to separate the products so that they do not get stuck into each other. Very little of the packaging material is used and the cost has been assumed to be constantly negligible.

4.3.2 Investigation assumptions

The storage locations at the PWH have a height of approximately 1.4 meters and this has been assumed to be the same in the RWH. This implies that any stack that will fit in the storage location at any of the warehouses will fit in all the other warehouses. An even stronger restriction has been imposed by the Container Door Opening height which is 2.28 meters. This means that any stack that is higher than 2.28 metres will not be transportable by the container without being split. Any stack that does not fit in the pallet rack will be stored in a non racked location at both the PWH and the RWH. The parameters of the container has been assumed to be according to table 2.

Table 2: Container Parameters

Parameter	**Parameter Setting**
Loading Capacity [Kg]	25 000
Volume Capacity [m^3]	33.2
Internal Lenght [m]	5.9
Internal Height [m]	2.35
Internal Width [m]	2.39
Door Opening Width [m]	2.34
Door Opening Height [m]	2.28

The maximum carrying capacity for the pallets was taken as the dynamic loading capacity since the same pallets are used when the piece is in storage or being loaded. The assumption is to use the pallets that are already in circulation within the warehouse. The maximum pallet carrying weight has been taken as the largest weight for all the products since; this is based on the initial observation that heaviest products will be stored as singles per pallets. This weight has been approximated to 3770 Kg which is the weight of the heaviest spare part within the network. It has also been assumed that the pallet with the maximum carrying weight can also accommodate the base diameter of the widest product. Whilst the orders leave the production warehouse for the regional warehouse without a dedicated order, the assumption has been made that, the make to stock policy currently employed in the production system, is driven by reliable sales forecast based on historical sales orders data. Hence the production system is demand driven.

5 Model

In this chapter the solution procedure used in this case is presented. This will be done generally, and without specifics from the case, for case specific details the reader is referred to chapter 4 and 7. The chapter will start with a model explanation, followed by an example of how the suggested ordering process will work. After the ordering process has been determined, an analysis of using the possibility of stacking and the associated cost benefit will be done

5.1 Model Definition

The ordering system proposed in this report is loosely based on a (R, Qn) policy. With an R that may vary for a product, depending on the expected IL throughout an investigated time period, of the products that have a dependency on the said product. In practice, the case company is using a periodic review system to be able to consolidate shipments. This will also be used in the current model, since restocking is being carried out on a potentially daily basis. The demand for the products is a non negative integer and not historically dependant. According to (Axsäter, 2015), this implies that, the demand is a discrete and stochastic variable. Due to the fact that the demand per item over the observed 15 month period is relatively low, a discrete model was adopted. However when determining the expected IL, a continuous review system has been assumed in order to simplify the problem. This is possible since there is already frequent inspections. This means that the demand during the inspection interval is small.

The model is assuming that the demands of different products are dependent on each other, that is a certain demand of a product is made up of the sales of other products. Each of the sales of the group will then have a certain probability of triggering a sale for the considered product. The relation can than be reversed so that the demand of a product in the group can be determined through considering another group of products where the first product is included. This means that demand of the products will be considered interdependent on a system level, while dependant on a product level. This will reflect the fact that customers make orders of several types of products.

Instead of the actual LT that is a within the range of $\big[$Transportation time + Production LT, Transportation Time + Production LT + Inspection interval$\big]$, the LT is approximated with a fixed LT, equal to the transportation time plus half the inspection interval. The reason behind this is to simplify the problem. The constraint of inventory management is a specified service level, which is measured through the order fillrate, (see chapter 3.1.2) level rather than at product level. Within the given service level constraint, the goal is to minimise the cost.

The proposition of this report is that; whenever two products with a high confidence are ordered, (see section 3.2.1) the order cycles of the given products should synchronise so that whenever product a is available, product b should also be available. If there is stock of product b and no stock of product a, (such as is the case in figure 10, at t_1) the stock that was there of product b could not be distributed and was held in the warehouse due to the unavailability of a. This is because in order to complete an order, the case company requires all products within the order to be available. This can be considered to be waste since the available stock still incurs a holding cost, whilst the unavailable stock results in a back order cost.

In figure 10, the demand of the products are correlated 1:1. This makes the problem rather trivial, since, the company would synchronise the order cycles and use joint replenishment. Were RP and OQ and the order cycles would match. But the same argument can not be made when the 1:1 relationship does not hold. In such a case the order cycles that were once synchronised will "drift away" from each other. At a certain point this may be remedied by restocking one of the products even before the RP is hit. The imbalance is illustrated through figure 10. The products in the figure have the same order cycle time, it will be much easier to handle the synchronisation if the order cycle time of a and b are the same. However the cycles can be said to be synchronised if orders are placed at the same time every n^{th} time.

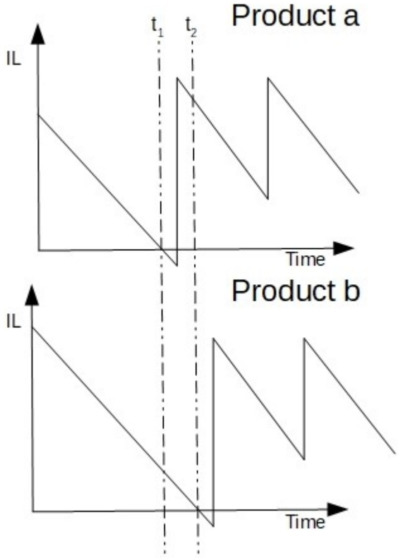

Figure 10: Unsynchronised order cycles

Asynchronous order cycles will lead to extra cost in situations like figure 10. In the figure the cycles have the same demand but the a product's cycle is slightly ahead of b. This leads to two stock outs instead of one, for this particular situation. At t_1 there is a stock out of product a, leading to back order cost for ab orders, while there is stock of product b, which also inquires cost. For a given a product cycle for a. The extra cost is then the extra stock kept in the inventory of b. Same holds for the interaction $b \rightarrow a$.

Assuming that products are distributed through a function, which is partially dependent on each other and partially independent, part of the total demand of product b is derived from the ab interaction, while part of the demand is independent of A according to equation 20, given that no restocks happen. $D_a(t)$ and $D_b(t)$ is the demand of a and b, respectively during t time-units, *f(x)* is the PDF of ordering b once A is ordered. This means that the demand of a product b derived from selling the a product in the interval [t, t+LT] can never be bigger than the IP of a multiplied with the confidence ab.

$$D_b(t) = \begin{cases} D_b(t) - D_b(t) \cap D_a & \text{if } IL_a \leq 0 \\ D_b(t) - D_b(t) \cap D_a + D_a(t) \cdot f(x) & \text{if } IL_a > 0 \end{cases} \tag{20}$$

Now, instead lets assume a product a and a group of products B, consisting of M products, b_1 to b_M. Let $f_{b_m a}$ be the confidence that the m^{th} product has in a. Now the demand of a is given by the demand of the dependent products in the group B, and the confidence that the individual products display in a under the constraint that the demand up to the point of the next delivery of product b_m is less or equal to the IP of b_m. Furthermore, a fictional dummy product can be created to make up for the fact that the sum of all the demands times the individual confidences may not equal the demand of the a product, in cases where a has been ordered alone. This dummy may also be used to approximate demand from products that only have very little effect on the overall demand of a. That is $D_{b_m} \cdot f_{b_m a}$ is expected to be small.

By using equation 21, the probability of a certain inventory level can be evaluated. This inventory level is the given by a combination of demands, from the constraints of equation 20, which were outlined in last paragraph. The probability of the IL being a certain value is than equal to the probability that the demands of the products in group B is such that the IL of a is achieved. Here the $f_{b_m a}$ is set as constant to limit the possible outcomes of IL_a and the combinations to get there.

$$IL_a(t) = IP_A(t-x) - \sum_{m=1}^{M} f_{b_m a} \cdot \min(D_{b_m}(x), IP_{b_m}) \tag{21}$$

In the system no fixed ordering cost has been discovered. During transportation, the containers are the cost drivers, and they are already following a high fillrate on average. This means that the product flow not the orders are the cost drivers. Based on this information, in order to reduce the total logistics cost, it is important to maintain a high fillrate in the containers rather than reducing the amount of total orders. To decide which products to order, all the products will assume the role of the a product, one after another. For each a product the B set will be established. Then the $E(IL^+)$ and $E(IL^-)$ can be determined trough the possible demand combinations of the B set, according to equation 21. The ordering benefit can thereafter be determined by comparing the expected inventory cost if an order of one pallet is made against the cost if it is not. The benefit is then redefined for the remaining products and the compliment of the set of orders that have been ordered that are also related to the B products.

The product with the highest benefit will thereafter be ordered, after which the remaining products will be evaluated again, to see which products are most beneficial to order. The process will continue until one container is filled. The process of adding containers will be repeated until such case that ordering i+1 containers is less beneficial than ordering i. Then i containers of the most beneficial products will be ordered.

To avoid the situation that the cheap products are ordered to fill up the container, for a product to be ordered it has to have a reasonable independent chance of stocking out. In this case this was set to 0.1% risk of stock-out. In practice since the demand will be lower or same when considering dependencies (due to stock outs of other products) this means that the risk of stock outs is $\geq$ 0.1%. Another addition that was added to avoid lock ups in the logic was a solution to the situation where a is not ordered because of lack of stock of b and b is not added due to low stock of a, the minimum IP was set so that, whenever a product reaches IP of 0 it will be ordered, no matter the stock of the dependent products. In practise this was only used on rare occasions since product dependencies had many combinations with other products, including the dummy who's IP was defined as infinite.

5.2 Determining the IL

From equation 21 the $IL_{a_i}(t)$ is an important aspect of determining the benefit of ordering a certain product. To determine the IL_{a_i} the demand of the a_i products are inferred from the demand of the associated products and their IP. The demand of the products are evaluated through distribution fitting. Then the probability of ordering 0,1,.., IP_{Max} can be determined, where IP_{Max} highest IP of a_is associated products.

$$\begin{pmatrix} P(D_{b1}=0) & P(D_{b1}=1) & P(D_{b1}=2) & \cdots & P(D_{b1}=IP_{max}) & P(D_{b1}<IP_{max}) \\ \vdots & \ddots & & & & \\ P(D_{bM}=0) & P(D_{bM}=1) & P(D_{bM}=2) & \cdots & P(D_{bM}=IP_{max}) & P(D_{bM}<IP_{max}) \\ P(D_{a}=0) & P(D_{a}=1) & P(D_{a}=2) & \cdots & P(D_{a}=IP_{max}) & P(D_{a}<IP_{max}) \end{pmatrix}$$

Figure 11: Demand of related products

The probability tree can there after be developed for ordering a certain amount of each associated product. An example of the probability tree is illustrated in figure 12. In the example the $IP_{max} = 3$ and there are three associated products. The probability of customers ordering a certain combination of associated items can the be evaluated according to equation 22. The IP of the associated products is taken into consideration by adding the probability of ordering more than the IP to the probability of ordering the IP. That means that if $IP_{b_3} = 2$, the probability of the combinations of ordering 3 of b_3 is added to combinations that include only ordering two of b_3, such that:

$$\begin{aligned} P(D_{b_1} = 1 \cap D_{b_2} = 1 \cap D_{b_3} = 2)' = P(D_{b_1} = 1 \cap D_{b_2} = 1 \cap D_{b_3} = 2) \\ + P(D_{b_1} = 1 \cap D_{b_2} = 1 \cap D_{b_3} = 3) \end{aligned} \tag{22}$$

The combinations of set of b_m products demand can be illustrated through figure 12. The demand of the products that are dependent to a are for simplicity's sake assumed to be independent of each other. The demand of a is then defined according to the following:

- Pick out all possible combinations for D_{b_1}, D_{b_2}, D_{b_3}...
- Get the implied demand of the a as previously described in chapter 5.2.
- Determine the probability of the investigated combination.

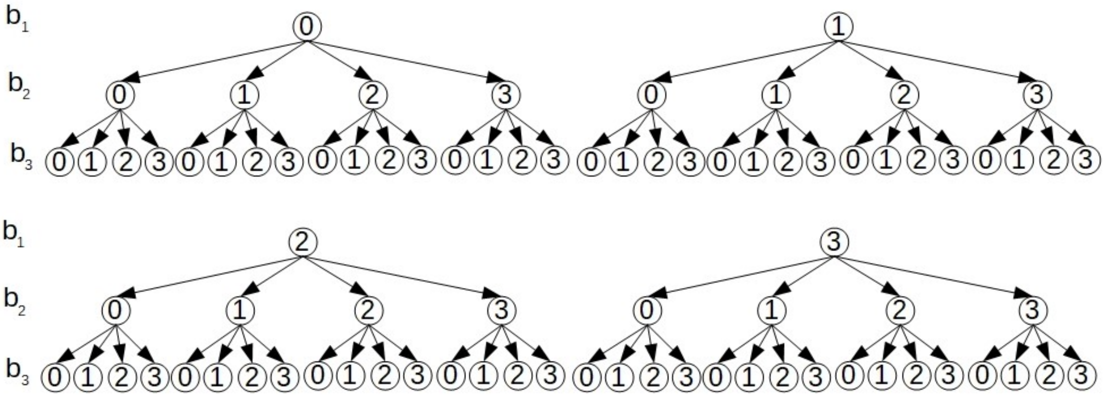

Figure 12: Probability of ordering for associated products

5.3 Ordering Example

For this example, the products a_1, a_2, b_2, b_3 are considered. All of which have a relevant confidence in each other. The expected cost is then evaluated for ordering q_i for each products, where i belongs to the set a_1, a_2, b_2, b_3 and q_i is the ordering quantity determined by stacking. If the product is not stackable then, q_i=1. At an inspection, the cost is evaluated for the next LT plus inspection interval. The cost for the products are evaluated for both ordering q_i of the products and not ordering. The cost will be evaluated through equation 21. The product that has the highest benefit of ordering will be ordered. The cost will then be evaluated for all the products again, taking into consideration the expected increased IL of the ordered product. Notice that the same product could still be most beneficial. Which means that the ordered amount $Q = q_i{\cdot}n$. The process is repeated until a container is full. After which the cost for the inventory, for the time "t" is evaluated. Once this cost is considered an additional container is added, as long as the inventory cost decrease and the warehouse has remaining storage capacity. Then the amount of containers will be chosen that minimises the total cost for the previously mentioned time period. This heuristic is visualised in figure 13.

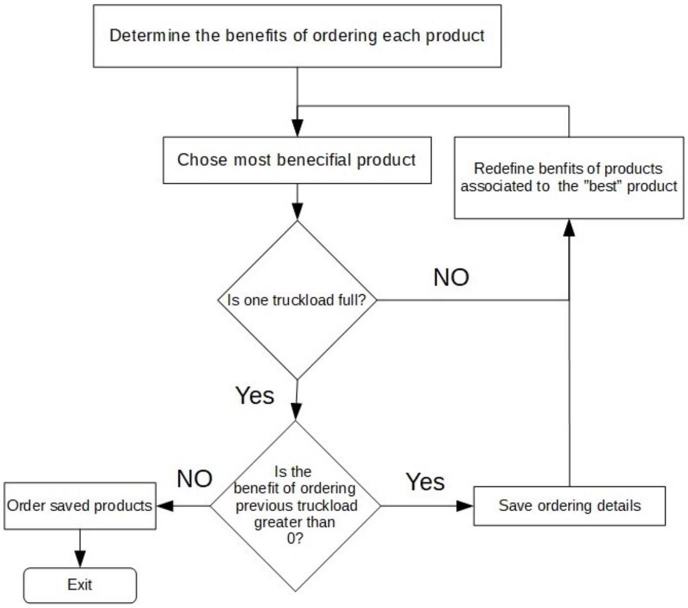

Figure 13: Ordering Heuristic

5.4 Stacking the Products

The benefits for the ordering policy based on product dependencies has been investigated further by looking at the possibility of stacking certain products. The focal company would like to realise the cost benefit in transportation, storage and operational costs considering that a certain number of items are stacked. The objective of this part of the report will therefore be an analysis of the possibility of this. The measurables to be pursued are;

i. Determine the stacking heights for products in the project.

ii. Determine the AS-IS situation with regards to pallet costs, forklift transportation mileage, forklift transportation working hours, storage location cost for the RWH and space requirements for the PWH and the transportation costs per unit carried (from the production warehouse to the regional warehouse), the handling costs for the pallets at the RWH and the labour requirements at the PWH.

iii. Determine the TO BE situation given that stacking is used. The parameters investigated will be the same as the ones in the AS-IS scenario.

iv. Determine the potential savings per annum of the TO-BE situation vs the AS-IS situation.

The products under investigation are those that have been produced in Sweden. The high level assumption here is that all products produced in Sweden are destined for the RWH and from there transported to the rest of Europe and other continents. Hence the focus will be on those products belonging to the commonly produced machines. There are seven different sizes of machines, the three smallest machines only have small differences, after which the size is increasing for sizes 4 through seven. The most popular products are the size one to three (the smallest sizes), which is illustrated in figure 14.

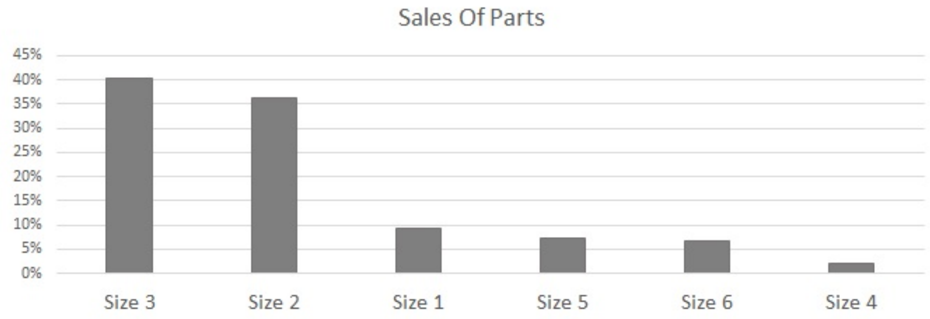

Figure 14: Sales of Parts, Aggregated to size configurations

Once the stacking height for a particular product has been determined from the stacking heuristic, this height is a fixed value and will have an effect on the minimum order quantities since we will always order the full pallets loads when using the new model.

6 Model Implementation

In this chapter the model from chapter 5 will be applied to the case. The road between the model and the result will be outlined. For a reader that is foremost interested in the result stemming from the model, this chapter may prove insignificant since the result of the analysis will be presented in the chapter 7.

6.1 Determining Confidence

When determining the confidences of products the method that was used is presented in chapter 3.2.1. When investigating the confidence $a_i b_j$, the set of orders containing a_i is analysed. The subset of orders, also containing b_i will vary in size. However in the data that was extracted from the ERP system, some products may only have been ordered a few times. For these seldom ordered products the points of which to draw the confidence for is small. This has prevented closer examination of what happens when a certain amount of products are ordered. In the best case scenario one would be able to go from a demand of B to the probabilities of ordering 0, 1, 2, 3... products of type a. Instead the confidence that was used was the confidence found through studying the actual orders captured by the system in the studied period as a whole. So for all orders containing **b** what is the probability that a is in there.

It is also possible for a customer to have several machines on site, at such times it is reasonable to assume that they will do both routine maintenance and breakdown repairs at the same time. This means that the customer may order several A and B articles at the same time resulting in the sum of the confidences for a certain product to products relation exceeding 100%. For a product a_1 the confidences was found to be according to figure 15. It was found that often there was strong confidence between a few products, in this case, two to three products, depending on how one defines a strong relationship as well as several small confidences. On a amount of articles a 1:1 relationship was discovered, this may also be a result of to few orders containing these articles or a limited amount of customer using them. There was also some confidences between the A products as a result of customer ordering for several different crushers at the same time.

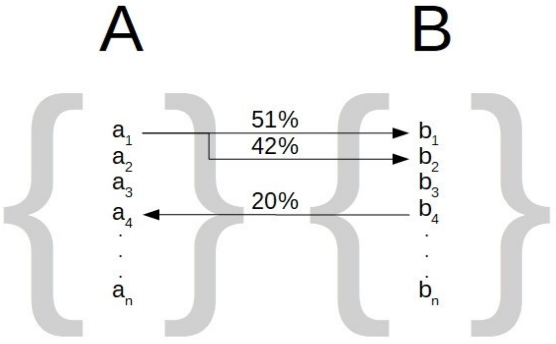

Figure 15: Sample of confidence

The confidences has been slightly tweaked. The purpose of the confidence as used in this project is; given that a product b is ordered, what is then the possibility of ordering a due to the ordering of product b. If several b products are ordered together with the a the common definition is not enough since the sum of the demand of the b products multiplied with their individual confidences would not add up to a larger value than the demand of a. Instead the likelihood of the contribution was split evenly among the products for all B products present in the order.

To easily find the products that give a high probability a_i, only products that a_i display confidence in need to be considered, since a non zero $a_i \to b_j$ confidence guarantees a non zero confidence $b_i \to a_j$.

6.2 Stacking Height

The stacking height is defined as how many products of a type that can be put on a pallet. Only products of the same type can be stacked upon each other, up to certain physical considerations, such as height and weight. When determining the stacking height, economical considerations were also made such as tied up capital, unstacking costs and transportation costs to not only determine the feasible stacking height but also the most efficient. To do this many high level assumptions was used, which will be outlined throughout chapter 6.2.

6.2.1 Method to Determine the Stacking Heights Based on Physical Constraints

A method to determine the stacking height has been developed based on observations of the setup of the twin network, mentioned in chapter 4. A heuristic has been developed which classifies qualifying products according to some criteria and then determines the stacking heights. These stacking heights will be maintained throughout the calculations for cost benefits and it is the desire of this master thesis that any implementation of the suggestions be based on the recommended stacking heights.

i. If the weight of the product W_i is less than or equal to 3768 Kg, then the product must be considered for Class A.The maximum weight than can be loaded on each pallet was determined to be 3768kg from the data.

ii. If the weight of the product W_i is greater than 3768 Kg then the product must be considered for Class B. Else skip the step and proceed to step (iii)

iii. Consider Class A products; if the height of the product H_i is less than 2.28m then consider it for Class A1.The mximum stacking height was determined by the container open door height to be 2.28m.

iv. Consider Class A products; If the height of the product H_i is greater than 2.28m then consider it for Class A2. Else skip and proceed to step (v)

v. Consider class A1 products; maximum stacking Max_w based on weight restriction equals $3768/W_a$

vi. Consider Class A1 products, maximum stacking Max_h based on height restriction equals $2.28/H_a$

vii. Consider Class A1 products, overall maximum Max_o based on both height and weight restriction is

Max_w if Max_w is greater than Max_h else it is Max_h. We consider Max_o is equal to Max_w first due to that the weight restriction is the independent factor and the height restriction is more dependent on the weight restriction

Consider class A1 products for the con-caves the stacking height H_s can be determined as follows;

H_s equals $(N \cdot 0.75H_i) + H_i$ which mus be less than 2.28 Where N = the number of items considered for stacking -1 and 75% is the height retained by the bottom product at each level of the stack and 25% is the height lost by the top product at each level of the stack.

If we consider the hypothetical product a whose height H_a equals 0.3m and weight W_a is 270 Kg.Then the above method could be applied as follows

i. a is a member of Class A because its W_a equals 270 which is less than 3768

ii. a is a member of A1 since the height H_a equals 0.3 which is less than 2.28

iii. If a is concave then consider stacking from 2, 3, 4, 5, 6...

From considering the possibilities of stacking within the constraint of the Container Door height of 2.28 meters in this example we conclude that we can stack item a eight products per pallet, since the next stack would be above the height restriction.

Consider class A1 products for the mantles the stacking height H_s can be determined as follows; $H_s = (N - 1) \cdot (0.5 \cdot H_i) + H_s$ which must be less than 2.28 meters. Where N = the number of items considered for stacking -1 and 50% is the height retained by the bottom product at each level of the stack and 50% is the height lost by the top product at each level of the stack. e.g. if we consider the hypothetical product b whose height $H_b = 0.3m$ and weight W_b is 270 Kg.Then the above method could be applied as follows

i. b is a member of Class A because its weight W_b equals 270 which is less than 3768 Kg

ii. b is a member of A1 since the height H_b equals $0.3 < 2.28$

iii. If b is a mantle then consider stacking from 2,3,4,5,6.....we get the table of results below.

H_s can be determined as follows; $H_s = (N - 1) \cdot (0.5 \cdot H_i) + H_i$ is less than 2.28 Where N = the number of items considered for stacking -1 and 0.5 is the height retained by the bottom product at each level of the stack and 0.5 is the height lost by the top product at each level of the stack.

From this example it is clear that the weight constraint is more stringent that the height constraint and hence the optimal stacking height, within the weight constraint is to stack five products per pallet. In the next section the analysis of the products shipped from PWH will be carried out to determine their stacking heights. After the stacking heights have been determined a cost benefit analysis will be carried out for the potential savings.

6.2.2 Stacking height Economical Considerations

The physical considerations that have been considered in the previous section are further influenced by economic considerations. The trade off is to determine the optimum height that does not result in excessive inventory management costs. The inventory management costs considered were the holding cost based on the annual interest rate of 15% per annum, transportation cost from the PWH to the RWH, the receiving cost at the RWH and the rent per location at the RWH. The total inventory cost being the sum of these costs at every stacking height considered per product, up to the maximum stacking height possible.

6.3 Stacking Feasibility Analysis

An analysis of the product specification data drawn from the case company's ERP systems was done in Excel spreadsheets in an effort to determine the stackability of the product range in this particular supply chain. Of the different product types analysed, quite a number can not be stacked on the pallets: either due to a lack of cost benefit when stacking or because of the physical constraints, outlined in section 6.2.1. Figure 16 shows the portion of the product types that can be stacked, for the heights one up to five. There is a significant amount of products can be stacked two items on each pallet and very few product types should be stored more than three per pallet. However, these products have high sales volume, therefore they make up a large portion of the total flow.

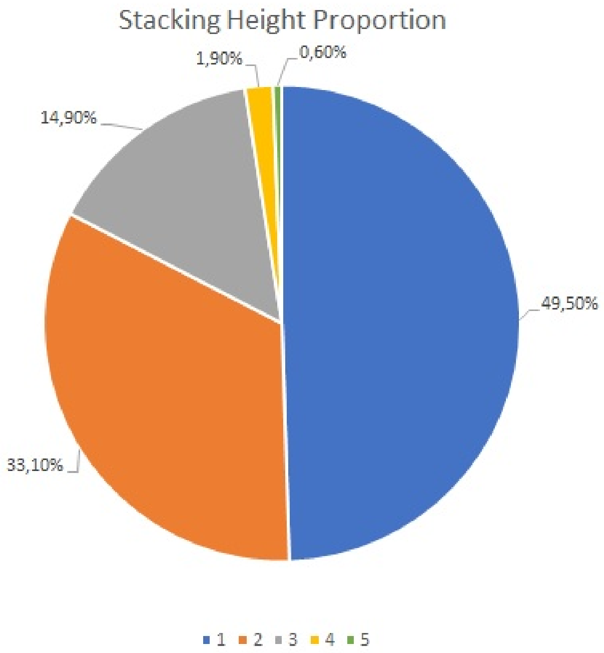

Figure 16: Stacking heights of products

In considering different scenarios, the maximum allowable stacking height was first of all determined based on the physical constraints approach. For each possible step-wise stacking ,and for each product, from the minimum stacking height, which is 1 to the maximum stacking height, a cost scenario for each of the inventory management costs was determined. The optimal stacking height was then determined as the height resulting in the lowest total inventory management cost.

6.4 Case Simulation

The case demand dependencies, distribution fitting and testing and determining the proposed ordering sequence benefits have been simulated through a dedicated program, specifically coded for this type of problem. This was motivated by the limitations in existing simulation software in capturing all the scenarios present for this particular type of spare parts supply chain. When simulating the case, it was very important to accurately depict the demand dependencies since these are the core of the analysis. To simulate the dependencies, the actual order characteristics was used to emulate new orders. That is, every time a new order arrives in the simulated warehouse, one order from the sample data is chosen to represent the new order. Whilst the amount of orders arriving on a particular day is taken from the actual distribution of the investigated data.

The operation is modelled through discrete events according to figure 17. Every day is characterised by a set of events that are carried out in the same sequence every day. These events are, starting from the top; using products that arrived the previous day to fill any potential *backorders*, after which *demand from incoming orders is generated.* If the present stock can not fulfil the orders, *new back orders are created.* If the stock can fulfil the orders the products are removed from the warehouse. This way, all products must be stored at least overnight. This can be considered reasonable, since, in reality, to distribute the product a booking has to be made some day before the actual dispatch. Once all the products that should go out are removed from the storage, incoming shipments arrive. Lastly, new orders are placed to the PWH, that are to arrive after the given LT has passed. Holding costs are determined through the average number of products held in the warehouse from start of business to end of business while the back orders are evaluated at the end of business each day.

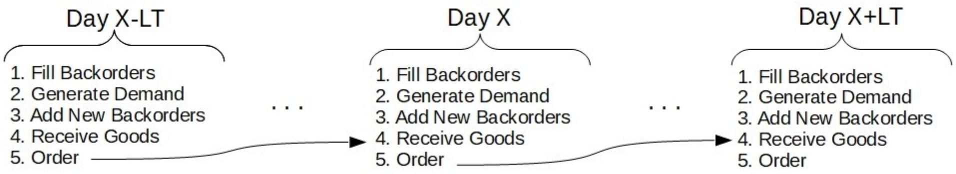

Figure 17: Simulation process

7 Result

In this section the key results of the ordering policy and stacking analysis will be presented. The chapter starts with results for the current ordering system at the company, (S,s) policy, with and without the stacking possibility. Thereafter, the possibility of stacking and not stacking using the proposed model are presented.

7.1 Stacking in an (S, s) Policy

To determine the effectiveness of stacking versus not stacking, the different settings have been simulated through the same program, putting the service level at 97,5%. This service level was chosen so that the service level of one *a* product and one *b* together reaches the case companies target level of 95% assuming that their IL are independent of each other. The result is illustrated in table 4. For both situations, the results for the holding cost and the amount of back orders are similar. The back order cost used in the analysis has been determined from equation 11. However, the holding cost is made up of 3€ per pallet location in rentals and the interest accrued from tied up capital at 15% per annum. In the stacking case, fewer pallets are stored. However, due to the optimal batch quantity determined by the stacking considerations, a larger amount of products are stored on each pallet.This results in an increase in the value of the products held on each pallet. The big difference in the costs is the number of containers transported. By stacking, more products can be transported per pallet and hence per container. Effectively, fewer containers are needed to transport the same number of products per given period of time. The number of pallets required to hold the same number of products per given time period decreases. Both of these parameters are to be expected since more products can be stored in the same area, in both the transportation containers and the RWH.

Since there is no fixed ordering cost associated with the ordering, the optimal policy is a lot for lot ordering system. When there are no stacking it means that products will be ordered one at a time, according to an (S, S-1) policy. However, when stacking is applied, products are ordered in the optimum quantity of which they are stacked. Effectively making it an (S, S-q) policy.

In table 4 the simulation results of the (S, s) ordering policy is presented. In the simulation full shipments are not required. Containers can be shipped independent of the whether they are filled up or not. This means there can be a relatively high number of shipments, resulting in daily shipments when stacked and possibly more than that when products are not stacked. When containers are shipped less than full truckload, the container fill rate will be much lower. However, without limitations of the frequency of the shipments the lowest number of back orders is achieved , for when controlling the inventory through an (S, s) policy at an assigned product service level of 97.5%.

For the sake of comparison a total cost has been determined at the end of table 4 (as well as table 4), where the activities specified in the tables are assigned costs which are relevant to the analysed network. The sum becomes a total cost. In table 4 this total costs show a benefit that could be achieved from stacking in the supply chain.

A key difference is that there is less handling required for full pallets , when stacking is used. However, additional costs of labour will be required for unstacking and stacking. The contributions of the mobile crane with an investment cost of 10 000€ can also be considered to substitute the labour. The stacking part has however not been considered in this analysis since it will carried out at the PWH, and will therefore not lead to significantly higher workload, since there is already adequate capacity to handle this scenario.

Table 3: Simulation results for a (S, s) policy

Assuming a (S, s) policy	**No Stacking Allowed**	**With Stacking**
Pallets in Stock	826.03	666.83
Average Number of Backorders	8.93	8.58
Average holding cost per day	837.32	880.84
Average containers received	1.127	0.99
Average Pallets Recieved	21.78	13.76
Averaged Pallets Shipped	21.81	20.66
Average Unstacking	0.0	5.70
Total Cost Per Day	7611€	6983€

7.2 Stacking and not Stacking in New Model

The result for using the proposed model is presented in table 4. The results show a significant decrease in workload, in the transportation process and also a decrease in carriers needed for the flow. Both of which can reduce the man hours needed throughout the supply chain thereby saving money in the in process. The amount of pallets that can be shipped stacked is relatively small. Since often times bulk is broken due to low ordering quantities by the customers.

The backorderdays however increase, due to two reasons. The assumed demand distribution will always be less than what is assumed in the (S, s) poilicy, due to potential stock-outs within the group of which a product is dependent, also, the model only releases orders every seven out of ten work days, compared to the close to every work day of the (S, s) policy. This illustrates difficulties in predicting the service constraint of the model.

Table 4: Simulation results Model, stacking or not stacking

Assuming model	**No Stacking Allowed**	**With Stacking**
Pallets in Stock	684.01	534.50
Average Number of Backorders	14.53	13.96
Average holding cost per day	616.06	656.66
Average containers received	1.01	0.72
Average Pallets Recieved	21.76	13.77
Averaged Pallets Shipped	21.80	20.67
Average Unstacking	0.0	5.72
Total Cost Per Day	7592€	6628€

7.3 Comparison of Inventory Costs

Table 5 show the comparison of the inventory costs for a (S, s) policy and the model through three different runs. In the (S, s) policy less than full shipments are allowed. In the run the service level of the (S, s) policy has been adapted so that comparisons between the model and the (S, s) policy could be achieved. Notable is a significantly lower inventory costs in the model due to less tied up capital since when chance for backorders are low, the model incentivises filling up the container with cheap products. To determine weather the model works better we assume the following values

Table 5: Simulation results Model vs (S, s), Stacking

Comparison Stacking	**Model**	**(S,s) Sim.1**	**(S,s) Sim.2**	**(S,s) Sim.3**	**Mean**
Pallets in Stock	534.50	573.61	539.26	540.20	551.02
Average Number of Backorders	13.96	12.83	15.537	14.90	14.67
Average holding cost per day	656.66	776.14	706.48	707.67	730.10
Average containers received	0.72	0.98	0.99	0.99	0.98

When stacking was not allowed the comparison of the inventory is illustrated in table 6. Again, the holding costs are lower when applying the model comparing to the (S, s) policy. However, the average pallets in stock went up slightly. This is an indication of the model prioritising the cheaper products. With a slightly higher number of back orders and non full containers, the amount of pallets are still comparable.

Table 6: Simulation results Model vs (S, s), No stacking

Comparison No Stacking	**Model**	**(S,s) Sim.1**	**(S,s) Sim.2**	**(S,s) Sim.3**	**Mean**
Pallets in Stock	684.50	654.47	646.18	652.78	651.14
Average Number of Backorders	14.53	14.931	15.537	14.61	15.03
Average holding cost per day	616.06	667,587	657.59	666.70	663.96
Average containers received	1.01	1,13	1.15	1.13	1.14

8 Result Analysis

The purpose of this project was to investigate how companies can coordinate dependent demand in their inventory management and distribution network and determine the associated benefits of doing this. To address the purpose, a model was developed to analyse the distribution, warehousing and inventory systems. The research questions introduced in Chapter 1 were pursued. In this section we have documented to what extend these questions have been answered.

8.1 Considering Demand Dependencies in Inventory Control

A suggestion for how the demand dependencies can be considered has been presented in chapter 5. In simpler terms the model is using the IP of dependent products to try to predict the demand of a product. Thereby trying to avoid overstock that can not be used due to unavailability of dependent products.

Considering the dependencies in the ordering policy has, through table 5 and 6, been shown to reduce the holding costs. In the model the overall cost savings is also increasing with the OQ. As table 5 shows, the model managed to perform with less holding costs while keeping the average backorders at the same level. This same result is also seen in the comparison when allowing for less than full truck load shipments in the (S, s) policy and only allowing full truck load shipments in the model.

To limit the amount of tied up capital, the model fills up the containers with cheap goods. As it so happens, in the case, cheap goods are also ordered more frequently as seen in figure 14. This is with the exception of size 1 and 4 which are new products, hence the after sales market of these products is still growing with the sales of the new equipment. The fact that smaller products are ordered to fill out the containers means that a higher availability is achieved for these products, on the other hand a higher availability on these products with the same mean also means the lower service level for the larger products which may partially explain the lower holding costs.

8.2 Service Level Implications

The proposed model has two major implications for the service level as a whole on a product level. In the model, due to lack of stock of dependant products, the expected demand is lower than that of a normal (S, s) policy. When all the dependent product are in stock the sum of the total lead time demand will be the same as the (S, s) policy. Once the products of which a focal product is dependent has low stock, the possible distributed goods of the dependent products will be less since the maximum distributed goods for the next LT time period will be less or equal to the IP of the products.

This means that the service level in the model will be slightly lower than what is excepted from the (S, s) policy. The service level could however be forced up by assigning a higher backorder cost for the products so that the same service level as the (S, s) policy is achieved. This has been done in table 5 and 6 so that bench-marking the performance of the model is possible. Also, the smaller, cheaper products are likely to have a larger service level than the bigger and expensive ones. Even though this may be the optimal way of solving the inventory management problem within the given service level constraint it may be a sub-optimisation with the overall business strategy. Likely the customers buying the larger products are also the customers that make the most profit for the case company. By then lowering the service level on these product one might disservice the *"best"* customers. This problem could also be considered in the model by manually forcing the back-order cost of these products upwards. However, no such analysis has been considered since it is outside the scope of this report.

On an order level this means that orders containing smaller products will have a higher service level than orders containing the same number of the larger products. Also that customers ordering the larger product might not be as satisfied due to bad service level, while customers ordering smaller products might get more satisfied.

8.3 Implications of stacking

An investigation into the possibility of increasing the inbound logistics fill rate and identify cost benefit possibilities in the distribution network, including any savings in warehousing and transportation, was conducted and the results have been presented in table 4 in chapter 7. The benefits will now be evaluated on cost and benchmark using order fill rate. In this analysis, pallets are received at the RWH inbound and shipped at the same warehouse's outbound.

The Forklift costs can be divided into the fuel costs and the maintenance and repair costs. Deducting from the simulation results for the flow when stacking is considered, the number of pallets handled per day when the products are stacked is lower than when the pallets are not stacked. The average pallets received per day is lower by 36.7 % and the average pallets shipped per day is marginally lower by 5.1%. The lower improvement in workload during pallets shipping is due to that there is break bulk of stacked pallets to satisfy customer order and in line with the optimum stacking heights already derived using both physical and economic considerations. What this means is that 36.7% less work will be done in receiving at the RWH and 5.1% less will be done at the RWH outbound. As a result, these reduced activities can lead to reductions of direct costs such as labour cost and equipment maintenance and fuel consumption.

The labour required to run the processes from PWH to RWH can be divided as follows. At the PWH the labour is required for stacking and operating the forklifts and for administrative purposes. Due to a 36.7% decrease in the number of pallets sent to the RWH per day, then the labour requirements for administration and operating the forklifts will also be influenced by the same ratio. However, more labour will be required to unstack the pallets or alternatively this process can be automised at an investment cost of 10 000€ per machine. At the RWH the decrease in the number of containers received also means less administrative costs and labour for receiving. Due to the fact that the stacking height and the customer order quantities are independent, most pallets have to be broken down into smaller stacks during picking.

The decrease in the number of containers to be loaded per day also has the hugely important effect of reducing the transportation cost directly by 28%. Synonymous the shipping cost per product will be 28% lower representing a significant saving. The container fill rate itself will be increased due to the stacking of products, the relative increase is however demand dependant.

At any given point in time, the number of pallets in stock when stacking is considered has reduced by 22%. This represents a direct reduction in the spend on pallets per month of 22% .Further on considerations on the pallet storage space required. The number of pallet locations required will decrease by 22% at both the warehouses. At the PWH, this represents and increase of 22% storage capacity. At the RWH this represents a decrease in 22% of rentals payed for storage space.

The holding cost per day due to capital tied up in inventory, at the regional warehouse will however increase by 6.5% when stacking is considered. This is due to that; since the ordering policy will be within the stacking height constraint, when stacking, more products is required to trigger a transported, which means that higher order up to levels are required. This holding cost is a sum of both pallet location rentals and the interest accrued due to tied up capital at 15%.

The amount of unstacking at the RWH will increase to 5.71 times a day. Whilst this increase is high, the cost for unstacking will still remain relatively low in comparison with benefits due to stacking. The back orders are the constant since we have a service requirement. The main objective of the stacking is to benefit from decreased distribution and warehousing costs within the given service level constraint to satisfy customer orders.

9 Discussions & Conclusions

This is the final chapter of the report. In in this chapter the results of the project will be concluded and discussed. Recommendations for how both researchers and managers my use and build on the results will be made. Some discussion about the methodology will also be included.

9.1 Result Discussion

A major assumptions when considering stacking was on the height loss and weight gain during stacking. Whilst it has been approximated as a constant depending on the product height and weight in this investigation, in reality the recommended amount of products stacked on each pallet may not be achievable. Either because the assumption on how much additional space each stacked product require or due to the instability of the stack, which may make it difficult to handle.

The simulation did not consider weight limitations on shipments and the volume constraint was only approximated with a fixed amount of pallets allowed, even though in reality if big pallets was shipped the the container might not been able to handle 30 pallets. The biggest effect of this is that it removes one constraint that otherwise would have been very present in the stacking of the products. Once stacking of the products happens the weight of each individual container will increase. From an academic standpoint this may be a minor point, since it does not limit the results of the model. But in practice for the case company and others looking to adopt the solution this a large obstacle. To get around this problem more shipments may be needed or alternative ways of transportation, moving from road transport to a railway based transport may be necessary. If possible the case company could look to partner with another company transporting less dense goods and ship mix goods in the containers.

When analysing the performance of the model, it can be said that it is outperforming the (S, s) policy, however, the results from the simulation is quite similar for both models, which begs the question how much impact one could expect when implementing the model. The model is such that it has an expected LT demand that is the same as an (S, s) policy, whenever all dependent products have stock. This means that as the service level approaches 100%, the differences in how the models perform is going to be less. On the other hand, as the risk for stock out increases the presented model should differentiate itself more from the (S, s) policy.

9.2 Conclusions

The master thesis has investigated the potential benefits of stacking products to improve the shipping container fill rates as well as introducing demand dependencies as an aspect into the ordering policy through a myopic approach. Using stacking within the distribution network of the analysed spare parts has a potential for saving both in distribution and warehousing costs. However, in this case study, only the major events and major costs associated with the RWH were incorporated. In practise the packaging costs and the stacking costs at the PWH would have to be fully analysed and incorporated into the cost model.

The thesis has also showed that benefits in inventory costs can be attained by considering the dependencies in the ordering policy (table 5). Still, there are challenges in that the dependencies introduce added complexities into the supply chain. In order to accurately capture the reality, modelling with the dependencies requires large amounts of data, expertise and tools to come up with a simulation complex enough to accurately capture the reality. If these parameters are in place, introducing a model similarly to the one suggested in this report can lead to savings in inventory cost, especially in a setting where: the dependencies are strong and the value of products are high. However, it is not recommended that an immature supply chains consider the dependencies because the benefits are relatively small put into relation to the added complexity and reduced predictability of the suggested model when comparing to the classic (S, s) policy

9.3 Managerial Insights

The case showed that for heavy machinery spare parts, cost reduction could be made from stacking products where the height of two stacked products is less than two times the height of the same product. Cost reductions can found in the transportation costs, the forklift maintenance and repair costs, the number of forklifts required and the personnel to operate them, the cost of storage locations at the RWH and the number of storage locations used at the PWH. Additional costs incurred in packaging material and time to stack are outweighed by the benefits mentioned.

Key considerations from working with dependencies in a inventory management is that the complexities decrease the predictability of the system as well as the manageability. Whilst it is relatively predictable how a standard (S, s) system operates, it is harder to predict a system considering dependencies. This will make it harder for the operators to tweak the system. For example; if an operator expects an increase in demand for a certain period in time, it would be easy to increase the RP and the order-up-to-level in an (S, s) policy. A semi skilled operator could go from a prediction of increase in sales volume to an increase in the RP while a very skilled operator is needed to tweak the system if an increase of the demand is expected in the presented model.

In the model, one could expect that the IL will decrease while the back orders will increase. The IL will decrease because ordering is less likely in the model, compared to the (S, s) policy. If the IP of the dependent products is low the likelihood of ordering the focal product decreases. That means that the model is more suited for situations where the objective is to reduce occupied storage space or tied capital rather than as a method to increase the service level. The model requires accurate data over a long period of time to work properly. In contrast, an (S, s) policy could be approximated through lesser data driven methods than the suggested model. In a changing setting, data could either be outdated or not available for a long enough time to see the benefits. Also situations such as new product launches will be difficult to take into the suggested model. In those cases these models could be operated though an (S, s) policy until such a time, sufficient data has been collected. This means that the model require relatively long product life cycles in order to be effective.

In the case there are some products that are only ordered once or twice during the 15 month period in relatively large quantities. This means that a large amount of products needs to be stored in order to fulfil the orders when they arrive. Another investment that could be made in these cases are discounts for ordering to production instead of ordering off the shelves or signing up the customer for a more long term plan, such as a subscription. This could save the case company large amounts of space and free up capital. The resulting effect of this is however outside the scope of the report an has not been analysed further.

9.4 Method Discussion

The method used in investigating the case company distribution and warehousing network was to approach the case from two different angles. Firstly, a model was developed to investigate the benefits of stacking within the distribution network. The other approach was to investigate the demand dependencies with the underlying assumption that both these systems can co exist without affecting the benefits of either stacking only or demand dependant ordering. In practise this may not turn out to be the case, but approaching the problem from this angle gave the ability to quantify the individual benefits of both approaches.

The validation and verification of the ordering policy was done in a simulation program. Simulation is a powerful tool that can be used so as to gain valuable insight into the real life processes. But, because the simulation has limitations, the real life aspect is not completely mimicked. Real life demand may not always follow the distribution fitting adopted in the program due to changing markets. Some high level assumptions have been incorporated into the simulation so that it can both be built within a reasonable time span and fulfil the purpose of answering the research questions.

Another way to validate the results of the model would be to implement it in the supply chain of the case company. Such implementation would however require much time and resources and making adjustments to the current flow. This may not be feasible and hence the simulation is a good testing tool before final implementation. Since implementation is out of the question another reasonable way of verifying the result could have been to conduct interviews with the case company. This, however comes with its own set of limitations because the interviewees would need to get a good enough understanding of both the result and the simulation steps, which may be hard to achieve.

9.5 Future Research

The transportation of the products from the PWH to the RWH presents a huge potential for cost saving. The number and quality of pallets used is also a huge contributor to be able to realise this. This master thesis used the current pallets in circulation for all calculations. One of the disadvantages of these pallets is that they can fit only 1 per width for the 20 foot containers. We therefore propose that , future research into the design of a flexible pallets that allows for the pallets to fit two across the width of the 20 foot containers. This will effectively increase the fill rate of the containers and further lower the transportation cost per item.

In this report, confidences has been treated in the same manner as in previous literature, such as Chen et al. (2005) as well as Cheng (2005), These definitions does not take into consideration, the amount of a certain product that is ordered. A more exact model could try to take into consideration the likelihood of a certain amount of a products being ordered given a certain amount of dependent product b_m. This would however require a larger data sample than was accessed in this project. For this to occur, it is required that the dependencies are clearer, and more well defined. Possibly in manufacturing where less ambiguity is given to the usage of said products.

This master thesis was conducted through a single case company. This enabled in depth analysis into the problem under investigation. The conclusions drawn from the study were based on data collected from the case company.However, in order to widen the scope of the project, the authors propose that future research could include a multiple case study. Since the core under standing has been availed by this master thesis, the benefits of future studies based in multiple companies could be, to see how the supply chains for different types of spare parts for other machinery compare with those of heavy machinery such as the ones studied in this master thesis.

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