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The Quick Response Inventory of the Future

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Preface

This master thesis concludes my two years studying Global Manufacturing Management at NTNU in Trondheim. I would start to thank my supervisor Fabio Sgarbossa, and the guidance he has given me both during the master thesis and specialisation project. You have helped me guiding me in the right direction and together with the other professors at the study program, have made these two years entertaining and knowledgeable.

I would also like to thank my Co-Supervisor Maria Flavia Mogos, SINTEF Manufacturing, SINTEF digital, and the case companies. My co-supervisor has been helpful as the link between me and the Quick Response 4.0 project. You have been part of the meetings, got me my own office at SINTEF, and been very supportive of my work, which I thank you for. I also would like to thank SINTEF and both case companies for allowing me to be part of the Quick Response 4.0 project, which I have found as a huge learning experience. Thank you to the purchasers, chief of factory, continuous improvement manager, CEO and CFO at the different case companies for collaborating with me by giving me the data I needed and participating in the different meetings we had together. Thank you.

Lastly, I would like to thank my friends and family who has been there for me throughout the master thesis and the COVID-19 pandemic. Thank you for supporting me during my five years as a student at NTNU Trondheim.

09.06.2021, Trondheim

Joakim Benoni Nilssen

Abstract

I have in this master thesis created a detailed framework for inbound inventory management relevant for Small- and Medium Sized Enterprises that are offering a high-variety segment of finished products. Through a case study of two Norwegian companies in the construction business with a low degree of digitalisation and multiple manual work processes, I have analysed their current inbound inventory management system, the consequences of it, and improvements that can be implemented together with digitally enhanced Quick Response Manufacturing. The framework is divided in four parts: i) *classification*, ii) *planning*, iii) *replenishment* and iv) *digitalisation*. Classification is done by using the five classification schemes: i) ABC usage value, ii) XYZ demand frequency, iii) SDE lead time variation, iv) FSN inventory turnover rate and v) HML volume. These five schemes are to be used in the Simple Additive Weighting classification method, that together with the companies' goals, results in five different groups that need different levels of planning and replenishment strategies.

Results from a simulation on the replenishment strategies along with recommendations from relevant literature reviews, suggests that the higher valued groups will need detailed forecasts, manual planning and dynamic control policies which utilises forecasts in its calculation as replenishment methods. The lower valued groups can use a digital system that automatically calculates replenishment utilising standard static control polices with safety stocks to accommodate fluctuations in demand or supply lead time.

Classification, planning and replenishment will be entered in a digital High Level MRP system controlling and updating the raw material inventory. A partially automatization by the use of RFID tags, bar codes and smart phones will update the inventory levels in real time. Use of the Quick Response Manufacturing principles such as The Response Time Spiral of Purchasing will ensure a better collaboration among the supply chain actors reducing the overall lead times for materials. The improved digital inbound inventory management system will ensure that companies can respond quicker to customer orders by having better raw material availability.

This thesis focuses on classification tools and replenishment systems, hence supplementary work related to simulations and forecasting principles will have to be considered. However, the basics and importance of forecasting have been brought up and included in the Simple Additive Manufacturing Matrix. Other considerations are also required for the implementation and transaction from the current inventory management system to a new digital system. It will require an update to modern IT technologies and training of the new system, processes and technologies.

Keywords: *Small- and Medium sized Enterprises*, *Inbound Inventory management*, *Quick Response 4.0*, *Make-To-Order manufacturing sector*, *Material Classification*, and *Replenishment Systems*.

Sammendrag

Jeg har i denne masteroppgaven laget et detaljert rammeverk for inngående lagerstyring som er relevant for små og medium store bedrifter som tilbyr høy variasjon i kundespesifikke produkter. Gjennom en case-studie på to Norske bedrifter i konstruksjonsbransjen med lav grad av digitalisering og mange manuelle arbeidsprosesser, har jeg analysert deres nåværende inngående lagerstyringsmodell, konsekvensene av dette og forbedringer som kan bli implementert sammen med Digital Rask Respons. Rammeverket er delt opp i fire deler; i) *klassifisering*, ii) *planlegging*, iii) *etterfyllings-strategier* og iv) *digitalisering*. Klassifisering blir utført av å bruke de fem klassifikasjonsmodulene: i) ABC brukerverdi, ii) XYZ etterspørsels karakteristikk, iii) SDE ledetidsvariasjon, iv) FSI omsetningshastighet og v) HML volum. Disse fem klassifikasjonsmodulene skal brukes i "Simple Additive Weighting" klassifikasjonsmetoden, som sammen med bedriftenes mål, resulterer i fem forskjellige grupper som krever forskjellige nivå av planlegging og innkjøpsstrategi.

Ut fra resultatet fra en simulering av etterfyllingsstrategier av råvarer og søk i litteraturstudie, anbefales at gruppene av høyere verdi ut fra klassifisering krever detaljerte prognoser, manuell planlegging og dynamiske innkjøpsmetoder som bruker prognoser i kalkuleringen i etterfyllingsstrategien. Lavverdi gruppene kan kontrolleres av et digitalt system som automatisk kalkulerer innkjøp ved bruk av statiske innkjøpsmetoder med sikkerhetslager til å imøtekomme eventuelle variasjoner i etterspørsel og leveringstider.

Klassifikasjon, planlegging og påfylling vil utføres i et "High Level MRP"-system som kontrollerer og oppdaterer råvarelageret. En delvis automatisering ved hjelp av RFID brikker, strekkoder og smarttelefoner vil oppdatere lagernivåene i sanntid. Bruk av Rask Respons prinsippene, blant annet "The Response Time Spiral of Purchasing" vil sørge for bedre samarbeid innad verdikjeden og redusere den overordnede ledetiden for materialene. Den oppdaterte digitale lagermodellen vil sørge for at bedriftene kan raskere svare på kundeordre ved å ha bedre tilgjengelighet på råvarene.

Oppgavens fokus har vært på klassifikasjonsverktøy og innkjøpssystemer. Det må gjøres mer forskning på prognoser og simulering med aktuelle data for bedriftene. De viktigste prinsippene angående prognoser har blitt analysert og inkludert i Simple Manufacturing Matrix metoden. Det er også andre hensyn som må inkluderes i overgangen fra nåværende lagerstyingsmodellen og gjennom implementeringsfasen til det nye digitale systemet. Det kreves oppdateringer, eventuelle innkjøp av moderne IT teknologi og opplæring av systemet og prosesser for at det skal bli en suksess.

Forkortelser: *Små og medium store bedrifter*,*Inngående lagerstyring*, *Rask Respons 4.0*, *Make-To-Order bransjen*, *Materialklassifikasjon* og *Etterfyllingsstrategier*

Abbreviations

Abbreviation	Description
APS	Advanced Planning and Scheduling
ATO	Assemble-to-order
BDA	Big Data and Analytics
CODP	Customer Order Decoupling Point
DOQ	Discrete Order Quantity
EOQ	Economic Order Quantity
ERP	Enterprise Resource Planning
FGW	Finished Goods Warehouse
HL MRP	High Level Material Requirement Planning
IIOT	Industrial Internet of Things
ITR	Inventory Turnover Ratio
JIT	Just In Time
LE	Large Enterprises
LFL	Lot-for-lot
MCT	Manufactruing Critical-Path Time
MCDM	Multi-Criteria Decision Making
MPS	Master Production Schedule
MRP	Material Requirements Planning
MRP II	Manufacturers Resource Planning
MTO	Make-to-order
MTS	Make-to-stock
POLCA	Paired-Cell Overlapping Loops of Cards with Authorization
RMI	Raw Material Inventory
ROP	Reorder Point
POQ	Periodic order Quantity
QRM	Quick Response Manufacturing
RFID	Radio-Frequency Identification
SAW	Simple Additive Weighting
SME	Small- and medium sized enterprise
TBDS	Time-Based Dual Sourcing
WIP	Work-In-Progress

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1 Introduction

The need to know how much material or finished products to store at the warehouse has been studied for many years. Inventory management looks at both materials needed before production, under production and after production. Raw materials that are needed before production starts is difficult to determine as there are many factors to consider. For many enterprises, demand is constantly changing and suppliers who the enterprise source their materials from, does not always deliver at the promised, or agreed delivery time. These factors, including more, is crucial to include in *inbound inventory management* for the enterprise to become top of the market.

Norwegian Small- and Medium sized Enterprises (SME) accounts for two thirds of the Norwegian workforce, where many of these work within the make-to-order (MTO) manufacturing sector. The MTO manufacturing sector is categorised by offering high-mix, low-volume segments of customised products to their customers. Unlike the make-to-stock (MTS) manufacturing sector, who manufactures product to shelf, the MTO sector base their production process on customer orders. Each order can vary in colour, size, function, raw materials, etc.

This thesis will look at how inventory management can improve the performance of Norwegian SMEs within the MTO manufacturing sector. I have through a case study of two Norwegian companies in the construction business, where both companies produce customised products, studied the consequences and importance of efficient inbound inventory management and how it can be improved to gain competitive advantage in the market.

Figure 1.1: Inventory Management

1.1 Problem background

The number of MTO companies have over the years increased due to more advanced machinery that can adapt to the customer's demand. Therefore, customers can now pick and choose between firms and choose the one that suits their trade-offs. Globalisation has also changed the market, as companies from the Far East or Eastern Europe can export to the Norwegian market.

Foreign companies can offer lower costs due to lower labour costs. The quality delivered from these companies has improved over the recent years, enabling them to offer similar quality as the Norwegian companies, according to information from some Norwegian SMEs. It is important for the Norwegian SMEs to hold their marketplace as SMEs are the major driving force of global economies. This is regarding in terms of contribution to the nation's Gross Domestic Products and employment (Akindipe et al. 2014). To be able to compete for Norwegian companies in their own market, they are forced to reduce their lead times by responding faster to customer orders or have a wider range of specifications to attract customers.

To allow for more customisation, companies need a high portfolio of raw materials readily available to be able to respond to demand. However, one of the greatest sources of uncertainty for MTO companies is to determine future demand (Ortiz et al. 2010). Determining how much raw materials required at the warehouse has been studied for many years. Finding the perfect balance of inventory levels is difficult, but necessary since inventory level and associated cost can for some companies account for half of the company's total costs (Ivanov, Tsipoulanidis et al. 2019a). Too much inventory will result in overstocking and high inventory holding costs, while too few items available can result in stock outs and not being able to respond to customer demand. The latter can then result in lost sales and worst-case scenario losing customers. Efficient and good inventory management can increase productivity, avoid delays within the supply chain, reduce time spent on material planning and reduce the cost of raw materials due to less waste (Razavi and Haas 2011).

There are many methods, tools, and thinking's that can aid companies towards more efficient inventory management. Industry 4.0 have over the last couple of years proven to be effective and helpful tools to gain better inventory management and purchasing procedures (De Felice et al. 2014). However, implementing Industry 4.0 at SMEs can prove to be difficult as SMEs often lack the human resources, experience and assets to implement Industry 4.0 at the company. It is extremely costly and if not implemented or executed right it can be a major cost driver for the companies.

Lean Manufacturing is a cheaper and easier alternative for SMEs to consider. It's tools and methods are rooted in the removing of *muda*, or *waste* in English, both on the shop floor and at the warehouse. The Lean thinking is grounded in the fact that production do not start until a customer order arrives. This also goes for raw material acquirement. Raw materials are kept at a minimum and are ordered from the supplier when an order from the customer arrives. But there are several drawbacks with Lean Manufacturing for Norwegian MTO companies. Some of the Lean manufacturing principles is not suited for the high variety of products that MTO enterprises deliver. Further, some Norwegian companies sources their raw materials globally, making rapid material availability an issue not aligned with the Lean thinking.

This is where Quick Response Manufacturing (QRM), developed by Rajan Suri, comes in as an alternative to Lean Manufacturing. While Lean Manufacturing specialises in standardised processes that improves the production of standard products, QRM focuses on changing the enterprise's structure towards a company that responds better, quickly and effectively towards highly customised products. As with Lean, QRM does not only focus on shop floor improvements, but improvements within the whole enterprise. It suggests different internal and external strategies that reduces lead time and cost, while at the same time allowing for further customisation options and better quality. Several companies have reported higher lead time reduction and cost improvements after implementing QRM compared to when they tried Lean implementation (Suri 2010).

1.2 Research purpose and objective

I will in this master thesis create a detailed framework for inbound inventory management that is applicable to SMEs within the MTO manufacturing sector. I will start by suggesting how they can divide their materials into different classification to better understand which materials are of more importance over others. The classifications will look at different factors both for the companies and the respective manufacturing sector. Secondly, I will give a short explanation on the importance of forecasts and what should be considered when making forecasts. Next, I will analyse different replenishment policies that can be implemented by SMEs. The first three steps will be combined in a detailed framework that will be easier for companies to follow when conducting inbound inventory management. Lastly, is to show how this can be used in a digital system that is aligned with QRM. The digital system will contain all the information and make processes and information exchange easier for SMEs within the MTO manufacturing sector.

This thesis is done in collaboration with two Norwegian SMEs within the MTO manufacturing sector who are in the process of implementing digitally enhanced QRM in their business model. Both companies operate in the construction business and have since 2020 collaborated with SINTEF Manufacturing and SINTEF Digital towards better responsiveness and innovation. I have according to the objective pf the thesis created the following three research questions which will guide me throughout the paper:

1. *What are the appropriate classification analyses for inbound inventory management within the MTO manufacturing sector?*
2. *What replenishment methods should be applied for efficient inbound inventory management?*
3. *How can the proposed inventory management method be aligned with digitally enhanced QRM?*

1.3 Research scope

This thesis will look at the inbound inventory management of raw materials for Norwegian SMEs that operate within the MTO manufacturing sector. The results from this paper can be implemented at larger enterprises (LE), but these companies will most likely have the capacity and strength to invest in more advanced equipment and programs to perform procurement better. The recommendations can also be implemented at SMEs from other countries as well. Other countries can have the same challenges as Norwegian SMEs, with long supplier lead times, high costs and high demand for specialised products.

The scope of this thesis does not include considerations related to the manufacturing process. However, it considers the current situations at the shop floor for the companies, along with some QRM principles of shop-floor improvement, to see if it can be linked together with inventory management improvement.

The recommendations from this study is for a “normal” manufacturing scenario. It will be difficult for both companies to implement these recommendations under “non-standard” conditions such as the COVID-19 pandemic that started in 2020. Several companies have had various challenges with their suppliers, such as late deliveries and lower quality due to the pandemic situation. Other suppliers have gone bankrupt. Based on this, it is recommended to implement the recommendations from this when the global pandemic has ceased.

1.4 Research structure

The paper is divided in to seven sections, and are described in Table 1.1 below.

Table 1.1: Research structure

Chapter	Chapter description
Methodology	The next chapter presents the methodology that have been used to solve this thesis' problem. It starts by presenting why I chose the methodology I used, how I collected data and analysed it, and how I ensured quality.
Theoretical background	This chapter gives insight to the theoretical background for this study.
Literature findings	The fourth chapter will present the main findings from the literature review that is used to solve this thesis.
Case companies	This chapter contains the main information regarding the two case companies I collaborated with, along with a description on the Quick Response 4.0 project.
Empirical findings	I will in this chapter present the quantitative analysis on the raw material inventory of both companies, analysis on inventory control policies, and the results on the case study.
Discussion	This chapter will answer the research questions. I will compare the findings in literature together with the case findings, and discuss the research, and weaknesses.
Conclusion	The last chapter concludes the master thesis. Lastly, I will recommend further work to be done.

2 Methodology

This section will explain how I solved my problem and research questions. I will go in detail on how I chose the type of study, based on the description of the thesis. Then, I will show how I collected data from the various sources on the different methodologies. Next is to present the analysis tools which were used to solve the problem. Lastly, I will explain how I ensured good quality, along with the guidelines and restrictions I set to follow during the thesis' run.

2.1 Type of study

Since this paper is done in collaboration with two companies, it made the most logical sense to conduct a case study. A case study is according to Bryman (2016) a research usually associated with a location, where the emphasis are upon an intensive examination of the settings surrounding the location. A case study is commonly associated with qualitative methods. However, it can be conducted using both qualitative and quantitative work, as using only one of the two methods may give two different results (Bryman 2016). This thesis will therefore implement both qualitative and quantitative work. The results from this thesis is not only for the companies, as it can be implemented to other enterprises that share the same characteristics with the case companies. The case companies are presented in Chapter 5. How the different research methodologies is linked with the research questions are shown in Figure 2.1.

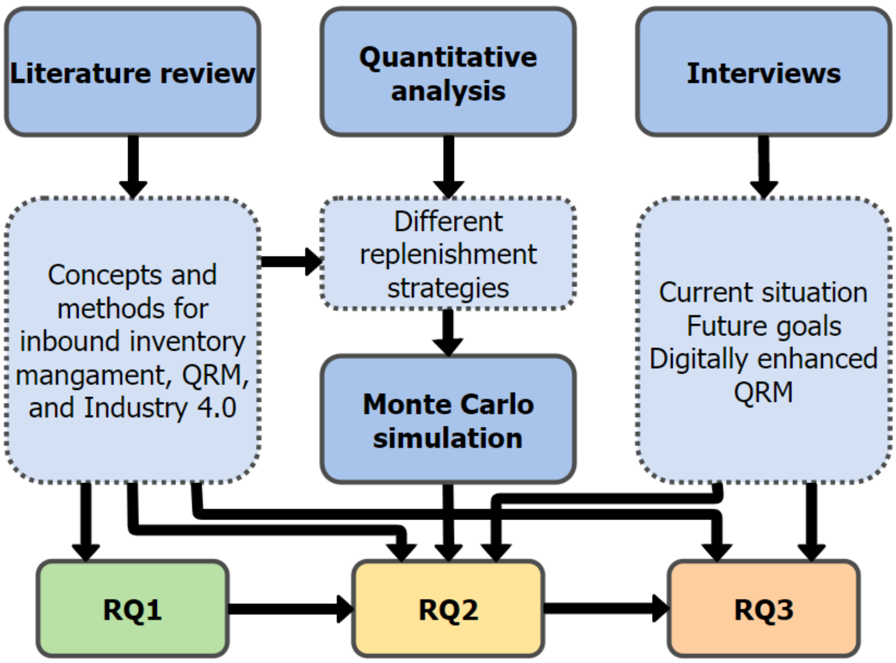

Figure 2.1: The methodologies of this thesis

The qualitative part of this thesis will be a literature review and interviews at the companies. The literature review will consist of looking at previous research done by experts to gain knowledge on different systems and methods. It creates the foundation that this paper is based on, as all three of the research questions will be either directly or indirectly answered by the literature review. The interviews have been conducted to gain more insight in how the business operates and runs their day-to-day material planning and purchasing process, as well as information sharing between the supply chain actors. This will strengthen the second and third research question, as it will help me understand which methods would suit them the best, along with information regarding the Quick Response 4.0 project. As mentioned, both companies are currently implementing digitally enhanced QRM into their business processes. Getting some information on the implementation process will help with the third research question, as they have already started the process.

The quantitative part of this thesis has been used to test different methods that have been recommended from the literature review. Firstly, there is a simple material classification done on both companies. This analysis does not directly affect the results of either of the research questions but will be used to compare the methods. Secondly is the main simulation on different replenishment methods. Here, I have studied several replenishment policies and how they affect the total cost and stock out by using data from the companies. This simulation will be used to answer the second research question, along with suggestions from the literature.

There were several meetings with the companies and SINTEF employees. Since almost each meeting were with people from different departments and with different purposes, I have listed all in Table 2.1.

2.2 Literature review

Most of the literature review was conducted last year, but there has been an initial literature study this year as well. The literature review has been used to get knowledge on the research field and is the most common method to get a research outcome, as it analyses multiple research conducted by experts to identify methodologies or techniques which can be applied to firms (Randolph 2009).

Data collection

The literature review began by searching on relevant research done by experts on the field in different data bases. *Google Scholar* and NTNU's *Oria* where the most used data bases as they both contained relevant articles that were available for me to read though NTNU's network. Google Scholar was used to find research articles and scientific papers, and Oria were used to check the NTNU library for available books I could borrow. I have also used books and curriculum that I have bought through my five years of study. My supervisors also helped me in the beginning by recommending different articles that would help me in the start-up phase of both the specialisation project and the master thesis. The articles I found on Google Scholar have been published by reliable journals, such as *Science Direct* and *Emerald Insight*, who sources a great deal of scientific work by acclaimed authors.

The search pattern used in the literature review is shown in Table 2.2 below. I used relatively simple search patterns in the beginning. I were recommended many different

Table 2.1: Meeting with the companies

Date	Attendance	Meeting description
01.02.	Both companies	Presentation on the results from the specialisation project, data collection 1, and further work.
23.02	Both companies and SINTEF employees	Presentation on the results from the ABC-XYZ analysis and further work.
02.03	Case Company B	Thoroughly review of the ABC-XYZ analysis for Company B and further work.
03.03	Case Company A	Thoroughly review of the ABC-XYZ analysis for Company A and further work.
08.04	Case Company B	Workshop for data collection part 2 and interviews.
13.04	Case Company A	Workshop for data collection part 2 and interviews.
10.05	Case Company B	Presentation on the simulation for Case Company B and second round of interviews.
25.05	Case Company A	Presentation on the simulation for Case Company A and second round of interviews.
25.05	Case Company A	Third round of interviews for Case Company A.
07.06	Both companies and SINTEF employees	Presentation on the master thesis.

articles, some not as relevant as others, which would help me get an overview what was available, as well as a brief introduction to the problem I studied. As the literature review advanced, so did my search patterns. I combined different search terms and exclusions to include papers that contained what I needed and excluded irrelevant subjects. I also added that articles had to be published in this century. Search terms like ”make-to-order” were often added to the search, so that I could find papers which were relevant for my field of study. Further, I started to look at the references in the papers I found more useful, so that I could check the paper for credibility and gain more insight. This method is also recommended by (Randolph 2009).

Analysis tools

The literature review has been used to gain more knowledge about research done on the area. As this methodology affects all three research questions, it became an important part of this thesis. After gaining insight to the situation at both companies, I analysed which methods would best suit the target audience of my paper. This method made it easier for me to choose replenishment methods that could be analysed in the quantitative analysis. Further I started compare different articles to check if the proposed methods were recommended by several authors. For example, an author recommended that SMEs within the

Table 2.2: Search terms used in literature

Focus area	Search term
Quick Response Manufacturing	”Quick Response Manufacturing”
	”POLCA cards”
	”AND Lean Manufacturing”
Inventory management	”Inventory management and control”
	”Inventory model”
	”Materiel Requirements Planning”
	”Material classification”
	”ABC-XYZ analysis”
	”Forecasting”
	”Replenishment methods”
Industry 4.0	”Industry 4.0”
	”AND inventory management”
	”AND supply chain”
	”AND information sharing”

MTO manufacturing companies can implement reorder point as a replenishment method. This was confirmed by other authors as well, and the recommendation to implement, along with the description for the companies, became stronger. This strengthens the qualitative part of this thesis.

Quality insurance

To ensure sufficient quality, I followed different parameters and talked to several people both at the companies, professors and workers at SINTEF, to ensure that no misunderstandings where to happen.

– Both my supervisors and professors at NTNU has been a good reliable source of quality. My main supervisor is professor at NTNU and has sent me relevant articles that have been conducted by other researches that were relevant for my study. My co-supervisor has a PhD degree and works at SINTEF Manufacturing, and has been the link between me and the case companies. They are also an expert in the field, and have in the beginning guided my in the correct research direction on what I should be focusing on and exclude from my paper.

– Books from previous courses or available at the NTNU library have been chosen for their credibility and have been considered a valid source of information regarding the studied topic.

– I have used research conducted by professional experts in the field. The articles have been chosen according to the relevance for today’s market and manufacturing environment, and I have tried to stay away from outdated articles, since both trends, machinery, and market definitions have changed. The articles that been included from the previous decade have been read and compared to more modern findings.

I made myself a couple of inclusions and exclusions that I had to follow when I conducted the literature review, as suggested by Randolph (2009). Inclusions and exclusions that were followed were:

– The recommendations on analysis tools and replenishment methods needs to be relevant for the MTO manufacturing sector with high product variety and low volume mix. Recommendations for the more stable MTS environment or the highly unstable ETO environment can be used to gain more insight in theory and other practices, but should be compared to MTO practices if they are to be included in the final result.

– Recommendations also has to be applicable for the relevant business sector. Replenishment systems and order policies for the food industry might not be as relevant to this paper due to the characteristics of the product.

– Papers used to solve the thesis' problem must be published after 1980. Preferably published in this century. Any research done between 1980 and 2000 must be checked up with more recent research to check for credibility. The only exclusion here is papers that contains the original formulas or descriptions useful for the calculation and analysis.

– Literature or research that have been published on either blogs or websites have to have an author that can be checked for credibility. Anonymous authors on websites, blogs, or other research papers are to be excluded.

2.3 Interviews

The interviews have been used to gain more information about both companies. At the start of the project, I got access to the information SINTEF already had gained from both companies, which I could use in this paper. The information was stored in different PDF, Microsoft Excel documents, and Microsoft Word documents in *Microsoft Teams*. However, the information I had access to was highly superficial and was summarised in multiple bullet list. To gain more insight on both the procurement process and the companies themselves, I had to perform a couple of interviews. The interviews could unfortunately not be conducted physically, due to the COVID-19 pandemic. Instead, we had video meetings over Teams.

Data collection

There were in total four interview five. Three for Company A and two for Company B. The first two rounds were conducted in co-operation with personnel from the purchasing department at both companies. The interviews were conducted separately, as it would make information gathering easier, and not mixed up. The questions were mainly targeted towards the current purchasing, inventory management situations, and the actors in the supply chain. The questions were prepared before each company, and there could be some variances in the questions for each company. The conversation was mostly one-sided, as I needed to gather as much information from them as possible. If I thought I misheard information, or needed to recap after an answer, I quickly asked them to confirm or exclude any of the information I received.

The last three rounds of the interviews were conducted close to the thesis' run. This time, I also included the contact persons from both companies. The meeting with Company A had to be split in two rounds, as the managers could not attend the same meeting at the same time. Key people from Company A included the purchasers of different raw materials and the "Continuous improvement manager". From Company B, the interviews included the purchasers from both the MTO and MTS department, along with the chief of factory. Before both interviews, I had prepared a presentation on the suggested implementations that could be implemented at both companies. I did this since some of the questions for this run regarded how this could be implemented at the companies, and they therefore needed to know my recommendations. The questions in this round could therefore be divided in three parts. The first questions where to gain more information from the companies regarding the factory improvements, digital improvements at the companies, supply chain improvements, and future goals. The second part of questions regarded implementation and how this could be solved, linking them towards the first part. Lastly, I had some questions to the purchasers, if there were something I needed to understand better. The interview questions are shown in Appendix B.

Analysis tools and quality insurance

The answers from the interviews gave me a more complete picture on both the current situation at the companies, along with what they both had set as future goals. The interviews where transcribed to pure text the same day as the interviews happened. Further, the results from the interviews would be linked together with the recommendations from the literature to see where improvements would benefit the most for both companies. For example, the companies struggle with a lot of the same problems regarding market and customer demand. However, they follow different inventory principles, and recommendations from the literature would therefore be different for each company. To ensure that the interviews were of good quality, I followed these points:

- Talked with the purchasing and production department at each company. Had detailed explanation on the thesis, and what was needed from them to make sure that no misunderstandings were to happen.
- My co-supervisor attended each interview round, as she also wanted to gain some insight in the interviews, since she supervises the Quick Response 4.0 project.
- I recorded some of the interviews, along with notes I scribbled during, so that I could hear it again and read their answers to make sure that there could be fewer misunderstandings, as recommended by Bryman (2016).
- When the interviews had been transcribed in text, I resent them back to the companies, so that they could check if I had understood their answers more correctly. This quality insurance would strengthen the information I had received from them, and could then be linked with the recommendations I proposes.

2.4 Quantitative analysis

The quantitative analysis was conducted to divide the inbound inventory in the different classifications for both companies. Further, I tested some replenishment methods for the companies by using data from the companies. The analysis uses formulas from Chapter 4.2 and 4.4, and are presented in Chapter 6.1 and 6.2.

Data collection

The first conducted analysis was the material classification analysis on the raw material inventory for both companies. A description on the classification matrix is presented in Chapter 4.1. Data needed for this analysis included the raw material demand, divided based on month, along with the unit cost for each material. The data were collected from the people working at the purchasing departments for each company, where I requested the data through an Microsoft Excel file that they had to fill in. The file is shown in Appendix A.1. The raw material usage had to be divided in months, so that the demand characteristic material classification analysis could be conducted correctly. I chose to request for each month in 2020. It was not a certainty that I would use all 12 months in the analysis, but only choose a handful of them to use. The chosen months would be based on eventual seasonal factors that were discussed with the companies. Data was reviewed with the companies, separately. Explained the numbers and what they meant for the company.

Workshops

When the material classification was completed, I called in the companies for a presentation and workshop. After the review and presentation for the raw material classification, the data collection for the simulation began. Which data needed from the company is based on the relevant formulas from the literature review on raw material lot sizing, which are shown in Chapter 4.4. As with the material classification, the data needed were collected using an Excel sheet, in which I designed a template were the company had to fill in the requested information. Both companies received the template by mail along with a description on each category, to better understand the meaning behind them. The template is shown in Appendix A.2 and A.3. Due to the thesis time limit, along with limits at the companies, it became impossible to request data for all the materials at the company. Therefore, I handpicked between six materials to ease the data gathering for the companies. The materials were picked based on their respective material classification, and for materials in the same classification, I tried to choose materials that had either different unit costs or demand patterns. This was done to check for variation in each classification.

There have been several assumptions in this analysis, notably regarding data from the company. Due to restrictions at the companies, some of the values for the different materials had to be made up or calculated. This was done through separate meetings with the companies, where we decided upon the values for each material. From Company A, the meetings included the purchasers of the different raw materials, while the workshop with Company B included the purchasers, chief executive officer, and chief financial officer. Data such as lead time, demand, unit cost, and something are kept as is. However, both companies did not have clear data on inventory holding rate and order costs. These parameters have in this case been made up close to the materials descriptions, unit cost, and characteristics. Further, demand data was received per month, and the analysis will look at weekly replenishment, to get more realistic answer to the situation at the companies. Forecasts has been made in Microsoft Excel based on previous sales data.

Analysis tools

For the material classification analysis, I used the formulas and descriptions of the different classification schemes as previously described. The analysis was conducted in Excel using the data received from the company. The second analysis needed more ”advanced” simulation, as it would have different variables, such as demand, so that it could compare the costs for the different replenishment policies. I chose to use the *Monte Carlo simulation*. The Monte Carlo simulation uses repeated random samplings and statistical analysis to find ideal result (Raychaudhuri 2008). It can be compared to a methodical way of doing a *what-if* analysis that uses input data in a mathematical model.

The simulation would use the input variables I collected from the companies and different variables, such as demand patterns. Each replenishment method was conducted separately using the same starting inventory levels and demand patterns, so that the results would be based on the same numbers. When the results were finished calculated, I used the *what-if analysis* in Microsoft Excel, to simulate the scenario 30 times. Further, I presented the results as the average of the 30 scenarios. I performed the analysis on a 52-week horizon. The results are presented in different costs, such as inventory holding cost and the cost of placing an order, and eventual stock outs.

Table 2.3: Demand probability - example

Demand	Probability	Lower limit
275	0,08	0,00
330	0,10	0,08
450	0,21	0,18
580	0,22	0,39
700	0,21	0,61
810	0,10	0,82
950	0,08	0,92

The weekly demand used in the analysis was based on demand patterns at both companies. I created a table for the different materials, with different demands and respective probabilities. Table 2.3 is an example on a raw material's demand probability. I chose the different values according to the demand patterns for 2020. For example, weekly demand of 275 materials happened rarely, and would get a probability of 8%. The simulation would then use a random variable generator with values ranging between zero and one. The random variable would then be connected to the *Lower Limit*, which is the cumulative value of the *Probability* of each demand, and give the respected *Demand* for that month. This method is not on par with the real situation at the companies, as they will have monthly rise and fall due to seasonal variation. However, due to time limits and complexity of creating demand patterns that would rise and fall, I chose to use this method, as it would include some variation in demand patterns, just spread out through the year.

Quality insurance

I followed these guidelines to ensure good quality for the quantitative analysis:

- I have used formulas from the literature that have been recommended from the literature. These formulas have also been accepted by my supervisors and professors at NTNU.
- Since the parameters needed for the formula was new for the companies, I set up meetings where I thoroughly explained each parameter, to get it as close to the truth as possible.

3 Theoretical background

This chapter will cover the theoretical background of the problem I am researching. I will start by giving a brief introduction to the MTO manufacturing sector and some of the challenges that may rise from producing customised products. Secondly, I will give a short introduction to material requirement planning. Next, I will introduce QRM. I will go through some of the main implementations and compare it to Lean Manufacturing. Lastly is a short summary of the Industry 4.0 principles.

3.1 Make-to-order

Customer orders in the MTO manufacturing sector is determined according to the customer's demand (Mudgal et al. 2020). The *customer order decoupling point* (CODP), which determines how much influence the customer has on the final product, for MTO companies is located at right after the procurement stage, before the manufacturing operations begins (Stevenson* et al. 2005). For MTO companies, this means that every product is tailored to the customer and production should not start before a customer order arrives. The procurement and purchasing stage, located before the customer decoupling point, is determined on the forecasts the enterprise creates. When the processes are based on forecasts and speculations, they are described as being push processes. Processes that are based on customer demand are pull processes (Perona et al. 2009). Figure 3.1 shows the different stages where the decoupling point can be placed for the four manufacturing strategies, Engineer-To-Order (ETO), MTO, Assembly-to-order (ATO), and MTS. ETO's business model is completely based on customer orders, down to the design stage. Shipbuilding is usually in the ETO sector. The CODP for MTO companies occurs after the purchasing stage. In an ATO manufacturing environment, the CODP happens at the assembly stage. An example here is designer furniture. The main design and layout are already made, but the last details like colours and fabric is added according to customer order. MTS is purely push-based, since the CODP is located at the end.

- Separation of order-driven activities and forecast-driven activities. This will not only affect the distinction between the two activities, but also the information flows and the flow, planning and control of goods needed
- Determines the amount of stock which should be produced to customers or to be stocked up to satisfy demand in a certain period.
- The degree of forecasting control and optimisation. The further upstream the decoupling point is, the harder it is to forecast production.

Since the CODP is located more upwards in the process compared to MTS production, it can create several challenges for MTO companies. One of the major problems according to Stevenson* et al. (2005) is the difficulty to choose the appropriate production planning and control system for MTO companies. This is due to the lack of repetitiveness in customer orders. The MTO manufacturing sector does not have the same advantage as the MTS manufacturing sector when it comes to forecasts, as they produce standardised

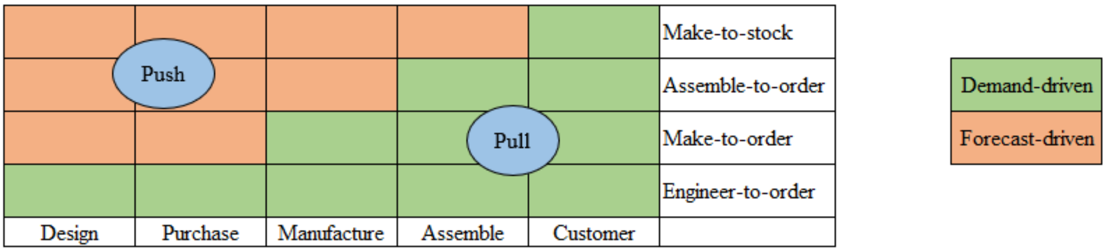

Figure 3.1: Decoupling point for the four manufacturing sectors

products with predictable and stable demand patterns. Choosing the wrong system(s) can be an expensive mistake for MTO companies, as they cannot apply the 'one size fits all' strategy MTS companies use.

In addition to minimising costs related to the manufacturing process, inventory should be minimised as well (Sawik 2007). This accounts for both the raw material inventory (RMI) that is used before manufacturing and finished goods warehouse (FGW) which stores the finished products awaiting shipping to the end customer. But when nearly all orders are different from each other in the MTO manufacturing sector, managing raw material inventory levels becomes challenging (Mudgal et al. 2020). To achieve the most effective inventory management for MTO companies, Sawik (2007) recommends to minimise the maximum levels of the input inventory levels. A decrease in the maximum levels will reduce the inventory holding costs for some materials, while it allows the company to store other raw materials, which is needed to accommodate for customisation. A minimum inventory level should also be set, so that the company can achieve the wanted service level.

3.2 Material planning

Material planning methods have over the years evolved along with manufacturing systems (Hvolby and Steger-Jensen 2010). It started with simple reorder calculations done manually with pen and paper but can nowadays be controlled by highly intelligent computerised systems. Some of these systems can even be using advanced artificial intelligence which are used to simulate how much materials are needed for the future periods.

3.2.1 Material Requirement Planning

Material Requirement Planning (MRP) systems came to the market during the 1960s and eventually replaced pen and paper as the main manufacturing control system (Rondeau and Litteral 2001). MRP systems uses the Bill of Material processors, which visualises the number of components and assembly route needed to complete the finished products (Hvolby and Steger-Jensen 2010). The system follows according to Segerstedt (2006) a deterministic model. Miclo (2016) adds that it also follows the push production process, where materials are "pushed" towards the end customer in a downstream operation. The information flow in a push production environment is generated from the MRP system, whose job is to schedule each work station and operation (Nicholas 2011).

After the MRP system were commercialised during the 70s, Manufacturing Resource Planning (MRP II) were introduced in the 1980's (Vihijärvi 2019). The MRP II could provide the planners with a "what-if" model that illustrated different scenarios and instructions if demand were to change. Later, the introduction of Enterprise Resource Planning (ERP) systems became popular. This system would also look at other departments and areas within the organisation in its model. Both the MRP and MRP II systems are usually integrated in the ERP systems. The integration allows the MRP to include more factors in its calculation as it has more data from the whole organisation to operate from. For the MRP to operate more flexibility from its full potential, it needs both changeable and updatable input information. Figure 3.2 illustrates some of the important inputs and outputs of the MRP system.

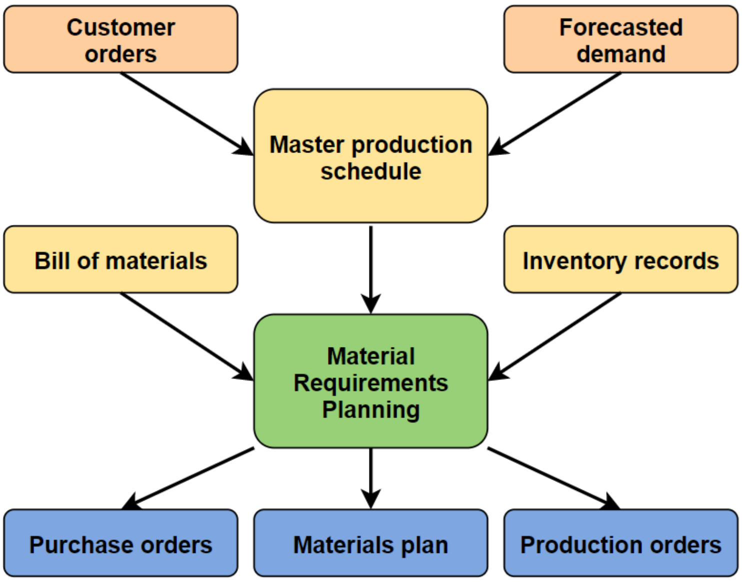

Figure 3.2: Inputs and outputs in the Material Requirement Planning

MRP systems calculate the production and the material plan in a Master Planning Schedule (MPS) (Sawik 2007). The MPS computes the plans according to both estimated and known future demand (Powell Robinson Jr et al. 2008). The MPS is used in during the tactical planning and is carried out over a medium-term long planning horizon. The estimated demand is taken from the forecasts made by the company. When the MPS has been revisited and validated by the planner, it will be put in the MRP and will further calculate the needed materials, components, and capacities needed to complete the job. After this is completed, it creates recommendations for replenishment orders (Miclo 2016). The master plan is often revisited according to the demand changes. Late changes can be costly for the company and can bring some inconvenience to the final production plan. Powell Robinson Jr et al. (2008) adds that an adequate MPS calculation can be difficult for companies that have a high-mix production, as available data from the customer can be pretty limited. Lot sizing and replenishment problems are essential in MRP calculation (Bookbinder and Tan 1988)

Powell Robinson Jr et al. (2008) also points out other limitations with MRP and MPS calculation for companies within the MTO manufacturing sector. Firstly, lot sizes created by the MPS may clash with ordering schedules which can arise from some customers. Secondly, changes in orders or new customer orders will negatively affect the final plan and may need a complete revisit if a more thorough plan is to take place. This variance in both lead time and demand are difficult for the deterministic system to implement, and the nervousness that arises from this can lead to higher costs for the firm, along with poor customer service if not properly handled by the material planner (Segerstedt 2006). One way to handle this problem is to provide the supplier with a stable order schedule from the MRP, which the supplier can use to plan their orders ahead of time. Further, is to establish a *frozen interval* within the MPS. A frozen interval locks the next period (days, weeks) of any changes. The frozen interval will also relieve some of the stress that may come from giving early replenishment orders to the supplier.

3.3 Quick Response Manufacturing

As mentioned in the introduction, QRM is a company-wide strategy that has a focus on reducing lead times by responding quicker to customer orders for companies that operate within the MTO manufacturing sector with high-product variety (Godinho Filho and Saes 2013). QRM was created by Rajan Suri in the 80s as a modern approach to reduce lead times. Suri (2010) divides the QRM approach into four core concepts. Each core concept has its own focus on lead time reduction within different departments at the company. The first concept, *The Power of Time*, focuses on the concept on lead time and its importance. The second, organisational structure, is about how companies can restructure their organisation by implementing *QRM cells* at the shop floor. The third, *System dynamics*, allows for better knowledge on how the different actors, materials, and equipment work together. System dynamics will guide the enterprise towards better capacity planning approaches, batch-sizing policies, and other important decision areas which will improve the firm's performance. The fourth and last, *Enterprise-wide application*, focuses on implementations throughout the entire organisation. This is from planning to purchasing and supply chain management, engineering, office operations, and new-product development.

3.3.1 Quick Response Manufacturing and Lean Manufacturing

Lean manufacturing's main focus is to eliminate muda, which results in improved quality, reduced costs, and even lead time reduction (Nicholas 2011). This is done through *standardisation*, where processes are designed to be quickly performed with preferably zero mistakes. Lean manufacturing utilises the card-based system *Kanban cards* (Stevenson* et al. 2005). Albores (2006) describes Kanban cards as a inventory replenishment signal, as in that the downstream activity only sends a Kanban card to upstream station when the activity needs replenishment. The cards contain all information needed for production or assembly. How much materials needed, and the quantity is described on each card. Kanban cards follows the *Just in time* (JIT) principle, which aims to reduce inventory levels as much as possible by only producing what is requested. The JIT principle works best in a Build-to-order manufacturing environment, similar to Toyota production systems (Buer 2020). Kanban cards and JIT is difficult or near impossible to use when there is large and unpredictable fluctuations in demand (Suri 2010). Further, Kanban cards does not work well if each demand or product is highly customised, as it requires thousands upon thousands of different Kanban cards for the different raw materials, work-in-progress (WIP), semi-finished products, and finished products. Using Kanban cards in the MTO environment lowers the inventory turnover, and products and raw materials will spend more time at the inventory stations (Suri 2010).

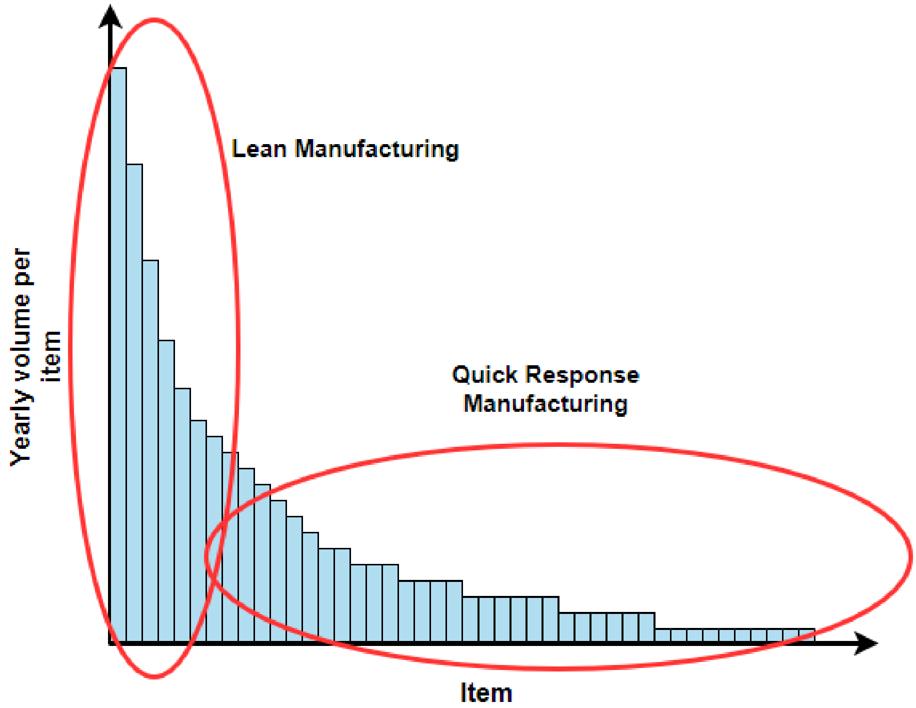

Figure 3.3: Lean vs. QRM

Source: Buer (2020)

While Lean manufacturing aims to reduce waste, QRM focuses on reducing the overall lead times, which has shown to eliminate more waste, reduce costs, and leading quality improvements (Suri 2010). Lead time reduction within QRM is heavily relied on the *Manufactruing Critical-Path Time* (MCT) metric. According to Suri (2010), MCT is described as the typical amount of calendar time from when a customer creates an order, through the critical path, until the first piece of that order is delivered to the customer. The reason for choosing calendar time instead of regular delivery time, is since the customer looks at the calendar days when they are awaiting their order. The MCT does not only consider the manufacturing lead time, but the planning lead time, RMI and FGW lead time, supplier lead time, assembly lead time, etc. which is not included in the calendar time the customer intercepts. The five main lead times are:

1. **External lead time:** The lead time perceived by the customer(s).
2. **Internal lead time:** The time it takes for jobs to move through the organisation.
3. **Quoted lead time:** The time customers are told by the salespeople of the organisation.
4. **Planning lead time:** The time it takes to plan the manufacturing and resource replenishment. Usually with MRP or ERP.

5. **Supplier lead time:** The time it takes to get raw materials and components from the supplier.

3.3.2 QRM cells

One of the major changes at the shop floor when implementing QRM at the company is going from the traditional ”functional” organisation to a cellular organisation (Suri 2010). This is achieved by dividing the shop floor in QRM cells. The concept of dividing the traditional organisation into a cellular structure is not a new concept. The difference between ”normal” cellular organisation compared to QRM cells is that the QRM cells are more flexible to change in demand. In a traditional cell, the job sequences follow a linear flow, and each cell has their respective *takt time* which determines the maximum time spent on the operation. The flexibility that comes from the QRM cell is based on the four strategies of *team ownership*, *cross training*, *MCT reduction*, and *capacity planning*. Further, each QRM cell is controlled and coordinated by the hybrid production control system *Paired-Cell Overlapping Loops of Cards with Authorization* (POLCA), which combines the features of both MRP systems and Kanban cards (Godinho Filho and Saes 2013). This makes each QRM cell dedicated, collocated, and multi-functional resources that can complete several operations for all jobs that belong to the company and its market.

POLCA and HL MRP

As mentioned, using MRP system the traditional way will result in longer MCT for companies within the MTO manufacturing sector. This is because some operations may be very complex due to the customer specific orders. Some products may need ten different operations before its finished, which may differ from product to product. Further, lead times for each operation is also changing according to the complexity of the demand. All these factors make the planning difficult, as the planner does not always know the exact lead times for the different operations. The MRP system requires that lead times are entered so that it may calculate the total lead time. Instead, QRM suggests that the MRP system is only used for *Higher Level of Material Planning* (HL MRP) of the inbound material flow and lead times between each cell (Krishnamurthy and Suri 2009). POLCA will then be used as the main control system for each operation by determining the operational lead time. HL MRP and POLCA allows the planner to spend less time on the MRP system planning production and can use more time planning material procurement.

As mentioned earlier, Kanban cards supports the pull production principle. POLCA on the other hand is a hybrid of both pull and push principles (Stevenson* et al. 2005). POLCA cards are capacity signal cards, unlike Kanban cards, which are replenishment signal cards (Godinho Filho and Saes 2013). When a POLCA card returns from one cell to another, it signals the operator that the QRM cell has available capacity to manufacture products. It does not control material movement within the cell, but between the cells. The POLCA cards apply to all products at the company that goes from one cell to another. POLCA is ideal to use in an environment that has a changing product mix and enterprises that has highly variable customer demand conditions.

3.4 Industry 4.0

Industry 4.0 is described by S. Vaidya et al. (2018) as an emerging structure in which manufacturing and logistics systems in the form of *Cyber Physical Production System* intensively use the globally available information and communications network for an extensively automated exchange of information and in which production and business processes are matched. This description was created by the German government, but Industry 4.0 does not have an established description of the concept (Buer et al. 2020). The aim of Industry 4.0 is to create a fully integrated, automated, and optimised flow by implementing the nine pillars of Industry 4.0 to the enterprise. Implementation of Industry 4.0 will result in greater efficiency for companies, improved process by changing from the traditional production relationships among all the actors in the supply chain, as well as better collaboration with humans and machines. The nine pillars of Industry 4.0 are shown in Figure something and described below (Rüßmann et al. 2015).

- **Additive manufacturing:** Additive Manufacturing can be in the form of 3-D printing which can be used to create prototypes and produce individual components. The individual components can be created in small batches. These products will be customised products of lightweight design that will reduce transportation distances from suppliers or within the factory and stock on hand.
- **Augmented reality:** This pillar offers a variety of services that helps the workers on the shop-floor. This can for example be visualised information displayed directly in the workers' field of sight by using augmented-reality glasses. The glasses will help workers with real-time information that improves the decision making and work procedures. Other applications can be virtual training.
- **Autonomous robot:** Robots and advanced machinery have in many industries been used to handle complex assignments. But they have become more advanced over the years and are now able to work autonomous, have greater flexibility, and co-operative by interacting and learning with other robots and human workforce.
- **Big data and analytics:** Big Data and Analytics (BDA) stores and analyses huge amounts of data. Optimisation of production quality and equipment service can be achieved by better analytics. Collecting and analysing data from many different sources - production equipment, suppliers, customers, and inventory management - is crucial to support real-time decision making and is an important factor in Industry 4.0.
- **Cybersecurity:** With the increase in digital connectivity, there is also a fear for cybersecurity threats and attacks on the system. By adopting cybersecurity that are secure, offers reliable communications, as well as sophisticated identity access, the threat for an eventual cyber-attack will minimise.
- **Horizontal and vertical system integration:** Full integration of the IT systems offers better information sharing across companies, suppliers, and customers. The integration also applies for within the companies at the different departments. Implementation of a system that is horizontal and vertical integrated allows for a truly automated value chain for the companies, departments, functions, and capabilities at the firm.

- **Simulation:** Simulations will help real-time data to mirror the physical world in a virtual model that includes machines, humans, and products. The simulation will allow enterprises to test and optimise processes before any physical changeover. The results will be reduced setup times and increased quality.
- **The cloud:** The cloud allows for increased data-sharing across sites and company boundaries. The reaction time of cloud systems has also increased in the recent years, achieving reaction times of just some milliseconds. At the same time, cloud systems will be able to monitor and control other processes outside of the shop floor and machines.
- **The Industrial Internet of Things:** Industrial Internet of Things (IIOT) allows more devices than previously be enriched with embedded computing and connected through standard technologies of modern wireless telecommunications. This allows devices and machines to communicate and interact with one another and with more centralised controllers (Atzori et al. 2010).

4 Literature findings

In this section, I will present the main literature findings from the specialisation project that I did last semester. The literature is divided in six parts. I will start the chapter by explaining inventory management and some of challenges that are common for both SMEs and MTO manufacturing companies. I will in the next subsection present some relevant material classification schemes that can be used to classify the raw materials. Next, I will quickly go through forecasting principles and the factors that need to be included when conducting future forecasts. After that, I present some replenishment policies that are relevant to use for ordering raw materials. Next subsection will cover some important methodologies within the QRM that can be implemented. Lastly, I will present some literature findings on digitalisation and Industry 4.0 implementation and how it can help companies thrive towards more modern processes that can help them achieve competitive advantage.

4.1 Inventory management

Inventory management at the enterprise is to control the stock of any item or resource that will be used at the organisation (Plinere and Borisov 2015). At some enterprises, the inventory value can be as much as 50% of the total invested capital, making it one of the most expensive assets the enterprise has. Efficient management and control of the inventory will influence an enterprises financial strength and competitive advantage in the market (Rajeev 2008), as well as having a total performance of the organisation and the managers of the company Akindipe et al. (2014). Chan et al. (2017) states that poor inventory management skills are one of the reasons for why SMEs struggle to become powerful competitors in the manufacturing market. The three main questions that defines inventory control according to Ma et al. (2019):

1. How often should the inventory status be observed?
2. When should an order be placed?
3. What should be the order quantity?

According to Zhang et al. (2019), the main function of inventory control and management is to minimise the inventory cost of materials without affecting the production and operation flow, which will result in effective control and management of the resources. Ivanov, Tsipoulanidis et al. (2019a) adds that it is also used to increase supply chain flexibility by holding inventory at the right places and to take advantage of quantity discounts and inflation. By finding sufficient tools and methods, they can reduce their inventory cost while at the same time have enough materials available at the warehouse to accommodate the customer demand.

There are several reasons for why SMEs struggle with inventory management according to Chan et al. (2017). One of the reasons is the lack of documentation and store records of current and past inventory. A lot of SMEs handle documentation manually and computation done by hand takes time, which in turn can lead to inaccuracy in documentation or misunderstandings. These factors will later result in inaccuracy in future material planning. Other problems of inventory management can also be underproduction, overproduction, stock outs, delay in delivery of raw materials, and discrepancy of inventory. Akindipe et al. (2014) adds that another factor that influences poor inventory management of SMEs is the poor liquidity position in the form of too much stock on hand. Materials kept at the warehouse has values attached to them, and to hold too much stock than necessary will result in capital lock-up of the inventory. They also add that many workers need to be taught proper inventory management for it to succeed. Many workers need to be taught how to efficiently use inventory models and quantitative methods to produce better information that can be used to determine replenishment.

4.1.1 Framework for inbound inventory management

Zhang et al. (2019) says that effective inventory control can be done through material classification, which further handles procurement, production, and sales of the enterprise. Accurate and stable performance is achieved by using more data, as it is easier to spot trends and market changes. Plinere and Borisov (2015) further adds that effective inventory management can be achieved by dividing inventory management in three processes. Firstly, materials should be classified in different and appropriate classifications to divide them based on the criteria of the classification. The second process is to create demand forecasts for each material. The forecasts can either be done qualitatively or quantitatively. The level of forecasting is based on the results from the material classification. Lastly, each material, according to the previous two processes, gets its replenishment policies which procures and controls the goods that are to be stocked at the enterprise or supply chain. For companies to achieve better inventory control, it is necessary to adopt scientific material classification and inventory control methods to ensure effective inventory management that are aligned with the performance and production stage of the enterprise (Zhang et al. 2019). The main function of the framework of inbound inventory management will be to know when to order and receive goods, how much to order, to contain previous sales data, and to indicate from what supplier to procure the materials.

4.2 Material classification

There are multiple analysis tools that can be used by enterprises to determine how enterprises should classify their materials, products, and other items (De Felice et al. 2014). Classification will help the enterprise choose the most thorough replenishment and inventory control principles, as each classification has its own rules and principles for how the material should be handled (Zhang et al. 2019). Each method has their own advantages and drawbacks, according to Dhoka and Choudary (2013). Which classification tool is the most sufficient can be answered by these three questions presented by Zhang et al. (2019):

1. How to select appropriate indicators for effective classification of multi-attribute materials?

2. Which material classification method is the most suitable?
3. How to propose targeted inventory control strategies for different classifications of materials?

The different classifications according to De Felice et al. (2014) can categorise the materials based on product value, demand frequency, delivery times, time spent at warehouse, inventory costs, risk of damage, etc. The classifications are usually divided in three classes, and enterprises can choose to include more classes to create a matrix with nine classes or a ”cube” with twenty-seven classes. The ”cube” with three different classifications tools can be used if enterprises need to distinguish materials more detailed.

4.2.1 ABC usage value

The ABC analysis is a material classification method used in inventory control that classifies the materials according to its usage value, calculated from volume and unit cost, over a certain period of time (Ortiz et al. 2010). It is rooted in the 80-20 Pareto method, where 20% of the materials accounts for 80% of the total usage value (Kolińska and Cudziło 2016). It is used to generate supply, inventory, and strategy based on the usage value of the material. It is a simple material classification tool to use, and can be paired together with other classification tools to get a better overview (Pitel and Alioshkina 2016). The three classes in this material classification analysis are A (high value - very important), B (medium value - moderately important), and C (low value - least important). The exact ratios for the different classes are not fixed and their value may differ according to the materials at the enterprise. However, the share of the classes in influencing the total value is constant. The description and formula on the analysis is as follows:

$$MV_i = \frac{U_i \times P_i}{\sum_i^n U_i \times P_i} \times 100\% \tag{1}$$

– Acquire all materials needed for the analysis along with the total usage for each material for a selected past period and its respective unit cost.
– Calculate the unit value of each product by multiple the previous usage U_i with the material's unit cost P_i.
– Divide each materials unit value on the total unit value of the inventory. This results in a percentage unit value MV_i.
– Sort the materials from highest percentage unit value to the lowest value.
– Calculate the cumulative usage value of each material and classify the materials according to their classification rules.

A-class items are the first 20% of the cumulative item value. They should represent around 80% of the total usage value. The next class, B-materials, should represent the next 30% of the cumulative item volume (between 20 and 50). This class should represent around

15% of the total usage value. Lastly, the C-class items will be the remaining materials. They represent around half of the total inventory and should have a usage value of 5% compared to the total usage value of the inventory. The exact number may vary from company to company, as some firms have materials that will stand out more than other. Figure 4.1 shows the different classes and each class is presented below (Hoppe 2006):

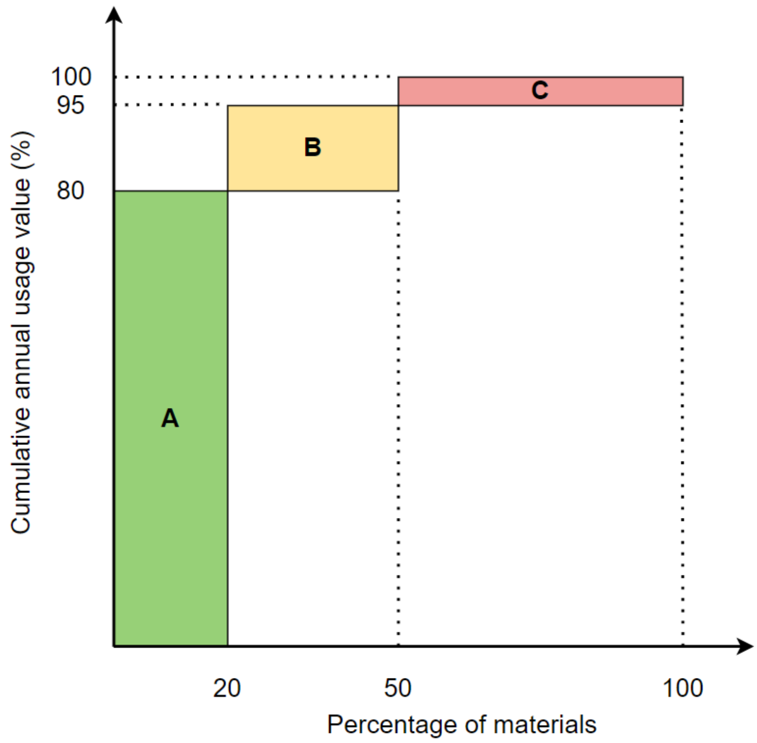

Figure 4.1: ABC values

- **A materials:** These materials are the most valuable items for the enterprise and should be handled with great care by the planner. Planning, handling, procurement can be done with program-driven requirements planning procedures, intensive market observation, exact inventory maintenance and control, and strong contracts with efficient suppliers. It is wise to find optimal lot size solutions for these materials by having less on stock, as the inventory cost will become high due to the high material value. Stock-outs or other negative situations that may affect production must be informed immediately, and back-up plans must be activated. Planning should be conducted deterministic with either an MRP system or more advanced planning systems.

- **B materials:** This category contains the medium valued products. Their value is lower compared to the previous class, but there will be more materials in this class. The materials in this class can be furthered divided into two classes, depending on what the enterprise wishes. The unit value for these materials is not that high, but neither low, and can be ordered and stored at a normal rate, since it costs as much to store them as it costs to order them. Planning and procurement time should be less than the previous class since the value is lower. However, they should spend some time on it, as some of the materials have value to the company.

- **C materials:** The last category contains the materials that are least valuable to the company. It is also the class with the most materials. Planning and handling should be simplified and be done only to prevent stock outs. Stock-outs can prevent production from occurring and can be prevented by keeping safety stocks. It is less costly to have higher quantities of these materials at the warehouse due to the lower unit value. Other recommended strategies for C-class materials include single-sourcing, outsourcing, automated or digital driven procurement method, and stochastic planning.

There are limitations with the ABC material classification analysis alone, as it is with the other ones as well (De Felice et al. 2014). Since it only classifies the materials on its annual dollar usage, then all of the other aspects become homogeneous. This is not always the case, if a thorough qualitative analysis is done along with the ABC material classification analysis to escape the one-dimensional aspect that comes from the analysis (Pitel and Alioshkina 2016).

4.2.2 XYZ demand frequency

The XYZ material classification analysis divides the materials based on their demand variability (Calisir et al. 2017). This material classification divides the materials in three groups, namely the X-class (stable demand pattern), Y-class (fluctuating demand pattern), and Z-class (irregular demand patterns). The classification is given in the formula below by (Kolińska and Cudziło 2016) where the V_d is the fluctuating coefficient for each material, $\bar{D}$ is the average volume for the chosen periods, and σ_d is the standard deviation of the periods. The number of periods included in the calculation, as well as the length of each period, influence the results on the classification.

$$V_d = \frac{\sigma_d}{\bar{D}} \tag{2}$$

If the fluctuating coefficient for a material is between 0 and 50%, then it falls under the X-class. If it is between 50% and up to 100%, then it is in the Y-class. For materials with a fluctuating coefficient higher than 100%, it is in the Z-class. The fluctuating coefficient value represents the deviation of the demand for a certain material over a selected period of time. Fewer periods included in the analysis results in less accurate representation and can give to vague results. Too many periods can also affect the results, as there might have appeared or disappeared trends in the materials. Figure 4.2 below shows the difference in demand patterns for the different classes. Hoppe (2006) describes the different classes as follows:

- **X materials:** The first class contains the materials that are the easiest to forecast. The demand patterns are quite stable and will most likely stay on a constant level which makes it easier to create reliable forecasts. But it is easy to overlook any changes that might happen.
- **Y materials:** These items is neither constant nor sporadic in its demand patterns. Y-class materials can have some sort of seasonal trend that is easy to include in

the forecasts, but this might not always be the case. The demand might increase or decrease, stabilise, or fluctuate at random times.

– **Z materials:** The last class contains the materials which are the most difficult to forecast. They have highly irregular demand which can both fluctuate or occur sporadically. The materials can sometimes go over longer periods of time without being sold or used. They can therefore be distributed as Poisson distribution. Z-class materials require safety stocks to accommodate the irregularity in the demand patterns.

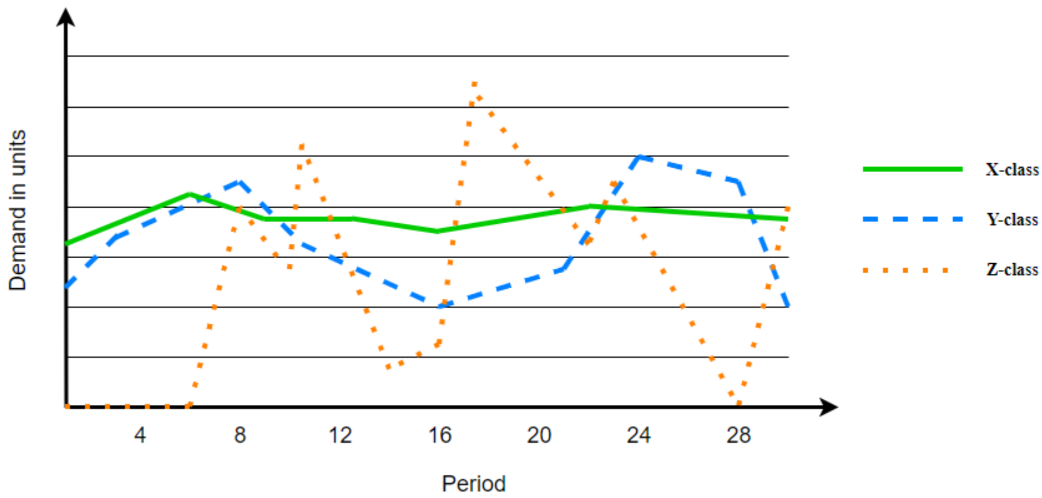

Figure 4.2: Demand characteristics for items based on the XYZ-classification

4.2.3 Other classifications

I will under list several other classification schemes that are of relevance to the MTO manufacturing sector.

SDE lead time variation

Some of the other classification schemes that can also be used are among other the SDE classification scheme (Ketkar and O. S. Vaidya 2014). The SDE classification is based on the availability on the raw materials from the suppliers. The categorisation is divided in three parts, the "S" (Scarce), "D" (Difficult), and "E" (Easy).

– **Scarce materials:** The Scarce class contains the materials with the longest lead time from the supplier. The materials here can be highly specialised materials that are highly difficult to source from other suppliers, and the supplier may have some sort of monopoly on the material, making the lead time long if located far from the factory. There may also be other factors that results in the long lead times, such as poor management at the supplier.

– **Difficult materials:** This class contains the raw materials and items that have acceptable or moderate lead time. The probability to run out of stock is less low compared to the previous class.

- **Easy materials:** Here, materials or items are readily available from the supplier with short lead times. These materials can be from local suppliers, with whom the company can have long term contracts that results in the shorter lead times. Reasons for the short lead times may also include the quality of the supplier since they are able to respond so quick to customer demand.

FSN inventory turnover rate

Another classification scheme is the FSN classification which divides the three classes according to their consumption volume, or turnover rate (Devarajan and Jayamohan 2016). We look at the frequency and quantity of replenishment. Unlike the XYZ frequency analysis which looks at the difference between the frequency of transactions. The consumption volume is regarded as a fixed quantity of material. The calculation for this material classification is based on Inventory Turnover Ratio (ITR). The ITR is defined as the ratio of annual consumption of a material divided by its average inventory.

- **Fast moving materials:** If materials are consumed at a faster pace, e.g., within a week, is classified fast moving or ”F”. These materials can be used in almost every product and need constant replenishment policies. These materials have a ITR greater than 3.
- **Slow moving materials:** Materials consumed at a moderate pace is classified as Slow moving or ”S”. The consumption can be for example between one week and three months. The materials in this class have a ITR between 1 and 3.
- **Non-moving materials:** The last category contains the Non-moving materials, or ”N” category, which contains the materials that are in store for a longer duration compared to the previous materials. Continuing the previous examples, this can be for materials that are consumed for a period of three months or more. Materials in this category can be extremely costly for the company, since the inventory holding cost will be relatively high. Some of the materials in this class can also be materials that are not used anymore or are awaiting specialised demand. The ITR for the materials in this class is below 1.

The time frame between the classes is determined on the characteristics of the company, as raw material consumption can vary from company to company. The F class should be relatively short compared to the other. The consumption rate can also be determined qualitatively by the planner. If there is a high percentage of N class materials, who happen to have extremely long replenishment time, then it can be checked if it is necessary to keep the material at stock. The formula for the ITR is as described by Sunjoko and Arilyn (2016):

$$\text{ITR} = \frac{\text{Cost of goods sold}}{\text{Cost of average inventory}} \tag{3}$$

VED importance

The VED classification method divides the material classifies the inventory according to the relative importance of the materials compared to other materials. It categorises the products in the three classifications of V (Vital), E (Essential), and D (Desirable). The analysis is a qualitative method and is heavily based on the company's experience with each material and perception. Due to the qualitative nature of this method, it will take longer time compared to the other classification schemes. The company must include more personnel to determine each material in this class, as just the planner may lack some knowledge about each material that is essential to include in this classification. Further, some companies might have hundreds, if not thousands, of materials to classify, which will make classification determination longer. This classification scheme is often used in medical or pharmaceutical industries to determine the importance of different drugs or medicines (Kumar and Chakravarty 2015).

HML volume

This classification scheme is like the ABC usage value classification. The difference is that it looks at the total volume and does not include the unit cost of the products. The materials are divided in the three categories of H (High volume), M (Medium volume), and L (Low volume). The classification separates the classes according to the Pareto 80/20 principle, same as with ABC usage value.

Sustainable classification scheme

Materials differ according to their environmental aspects and can be categorised on how sustainable they are to the environment (Bahrudin et al. 2016). The goal of sustainability is to minimise the impact materials and humans have on the environment by choosing solutions that will not harm the environment as much as others. The three classes that come from resource renewability classification schemes are according to Bahrudin et al. (2016):

- **Renewable:** The renewable materials are made from natural organic resources. Examples on these materials can be bioplastic made from corn starch.
- **Semi-renewable:** These materials are made from two or more types of materials in which one or more of them are renewable. Examples on this category can be products that are made with both wood/plank and cement. Wood is a renewable material, while cement is not.
- **Non-renewable:** The last category contains the materials that are not renewable, and are therefore made from a finite natural resource that may be harmful to the environment, such as cement.

4.2.4 Material classification combination

Since each classification has their weaknesses, it is generally expected to include multiple classification schemes together to include more factors that influence the materials at the warehouse (De Felice et al. 2014). As mentioned earlier, two methods can be combined to create a matrix. However, there are cases where more than two have been coined together in a *multi-criteria decision making* (MCDM) tool (Ketkar and O. S. Vaidya 2014).

ABC-XYZ material classification matrix

One of the most common material classification combinations is the ABC-XYZ analysis (Calisir et al. 2017). The combination results in a material classification matrix with nine different classes (AX, AY, AZ, BX, BY, BZ, CX, CY, and CZ) that differentiate the materials both on usage value and on frequency of demand patterns. Figure 4.3 shows which categories contains the different characteristics of each the ABC and XYZ classification category.

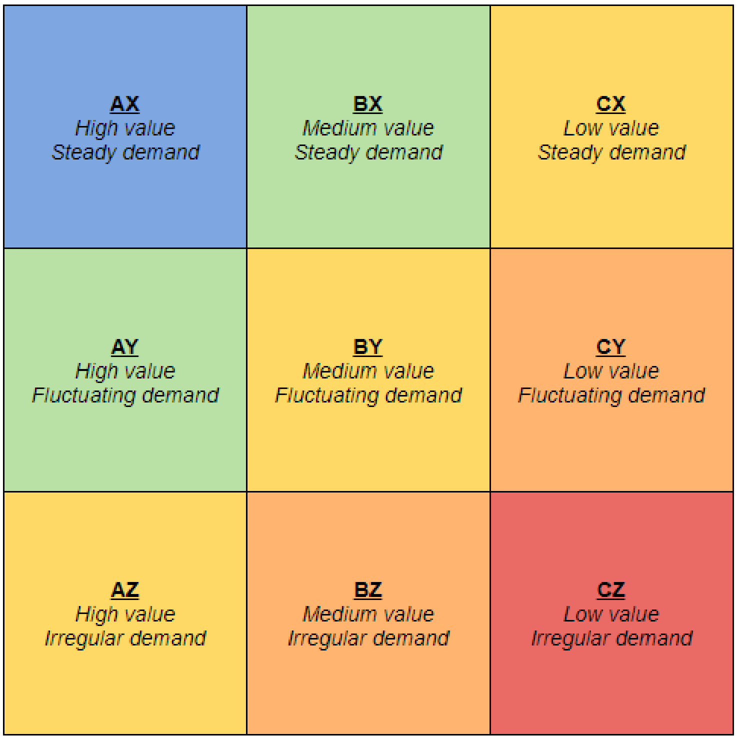

Figure 4.3: ABC-XYZ material classification matrix

The materials in the AX, AY, and BX category are relatively easy materials to forecast while having a high usage value for the company. Materials in category AZ is the materials that need the most attention, as they have both high value and highly irregular demand patterns. The CY, CZ, and BZ materials have medium to low categories and are difficult to forecasts and need higher safety stocks. The CX category is the category that requires the least amount of attention. The ABC-XYZ category can be conducted in an MRP system and controlled by it according to each classes specification (Calisir et al. 2017).

Simple Additive Weighting

Using only two material classifications may ignore some important aspects that are not present in the two models. Ketkar and O. S. Vaidya (2014) proposes to use a combination of four to five applicable material classification methods. The classifications are together with the company's goals calculated in a commonly used MCDM tool called simple additive weighting (SAW). SAW is a weighted linear combination or scoring method that is calculated from a weighted average (Afshari et al. 2010).

The approach done by Ketkar and O. S. Vaidya (2014) is to assign each material classification the appropriate weight, based on their suitability and applicability that are based on the decision and mission of the company. The corresponding weights are called classification weights and can be determined by senior officials and inventory managers. The classification weights are designated as cw_j, where the j is the considered classification scheme. Table 4.1 is an example on how companies can calculate their cw_j. The three goals used in this example are low cost, improved customer satisfaction and innovation. In this example, each goal is assumed to have equal weights, which puts the value at 33,3%. The example used by Ketkar and O. S. Vaidya (2014) utilises the ABC, HML, SDE, and FSN classification methods. Each classification is given a value between 1 and 4 for each goal to indicate how it can perform for a specific company goal. The classification weights cw_j is found by taking the sum of product of the value of the classifications with the weight of each goal.

Table 4.1: Classification weights example

Goals/Method	Weight	ABC	HML	SED	FSN
Low cost	33,3%	3	4	2	1
Improved customer satisfaction	33,3%	4	1	4	1
Innovation	33,3%	2	2	4	1
Classification weights (cw_j)		3	2,31	3,33	1,33

Source: Ketkar and O. S. Vaidya (2014)

Each material will then be given its respective class for each classification scheme the enterprise has chosen to implement. Further, in order to quantify the different classifications, each class are to be assigned a numeric value. If the ABC usage value is used, then the most important class, which is the "A class" will be assigned the highest value. A-class materials will be assigned a value of 3, B class materials will have 2 as the value, and C class materials will be assigned a value of 1. Each material classification methods will be given the same distribution of numbers. See table 4.2 for an example. The assigned classification value cv_i are assigned to each material i.

Once each material gets assigned the different classification values, we can compute the classification number cn_i for each raw material i given in formula (4) below. The classification number will vary according to the number of classification schemes used by the company. Ketkar and O. S. Vaidya (2014) recommends to divide the materials in five groups. The group with the highest value of cn_i are the materials of utmost highest importance which needs strict ordering policies. The materials with the lowest value cn_i

Table 4.2: Classification values to the different schemes

ABC	HML	SED	FSN	Classification value
A	H	S	F	3
B	M	E	S	2
C	L	D	N	1

Source: Ketkar and O. S. Vaidya (2014)

need less strictly ordering policies and can be followed loosely by the inventory planner.

$$cn_i = \sum_{j=1}^{4} (cw_j \times cv_i) \tag{4}$$

The SAW framework can be used to show which materials are of importance according to the company's goals. It is an easy approach that can be used in the first step of inventory management, which will guide the selection of forecasting and replenishment method choosing. It also tells which material inventory position should be closely monitored, and which can be more loosely monitored.

4.3 Forecasting

Demand forecasts form the basis of all supply chain planning (Chopra 2019). It is crucial to drive supply chains and ERP systems (Trapero et al. 2012). If we consider back to the push-pull principle explained in Chapter 3.1, all push processes are performed in the anticipation of demand, while pull processes are performance in response to customer demand. How easy it is to forecast certain products or materials is heavily based on the characteristics of both the product/material and the company. Mature products with stable demand, for example regular milk, are easier to forecast compared to specialised doors produced by MTO manufacturing companies. Forecasting is extremely difficult to do on both raw materials and finished products if the demand is highly unpredictable (Chopra 2019).

It is important to find the right balance between both objective and subjective factors when conducting the forecasts. There are several important factors to include when creating forecasts. Firstly, is to look at the past demand. It is important to differentiate between past demand and past sales, as past sales may exclude lost sales that could not be met due to several internal or external factors at the company. Lost sales are a part of the demand and has to be included in the forecast for it to be reliable. Secondly is to know the lead times of material replenishment and product manufacturing. Lead times are essential to know as they tell the planner of how long certain processes will take. Thirdly, is to gather eventual information on planned advertising or marketing efforts. Fourthly are the future planned discounts. Both the third and the fourth process will affect the future sales and is both needed in the forecast calculations. Fifth, is the current state of the economy for the company. There might have occurred a situation where the company do not have the capacity to meet future demand. This must be included in the forecasts as well, so that unnecessary replenishment does not occur. Lastly is to look at what the competitors might be doing. Maybe they have some discounts that might affect your sales negatively. These six factors need to be implemented when choosing the appropriate forecasting methods as they all will affect the final forecast. The four forecasting methods are (Chopra 2019):

1. **Qualitative:** These forecasts are primarily subjective and rely heavily on human judgement. Qualitative forecasts are mostly used when there is little to no historical data available to conduct quantitative calculations. They can also be applied if an expert on the field with market intelligence can conduct them. These methods can among other be used to plan years into the future.
2. **Time series:** The time-series forecasting methods use historical data to calculate the forecasts. They can be used if the assumption is that past demand history can be a good indicator of the future demand. Time-series forecasting are best suited when the demand pattern does not vary that much from one year to another. Many of these methods are quite simple to implement and conduct.
3. **Causal:** Causal forecasting methods finds a correlation between demand and environmental factors. The environmental factors can be included in the forecasts to determine future demand. An example on this can be price reductions. Price reduction and discount will in most cases result in higher sales, and this has to be included in the calculation.
4. **Simulation:** The simulation forecasting can combine the three previous methods to simulate the future demand. It includes both causal and time-series methods in its calculation. What will the future demand be if a competitor opens a store in the nearby area? How much will we sell if we reduce the price on specific products?

Companies might find it difficult to choose which forecasting methods is the most appropriate for their company. But there is no problem combining multiple methods to create a combined forecast that can be applied. The most used forecasting method, the time-series forecasting, is related to historical demand, eventual growth patterns, and any seasonal patterns that may show up during seasonal sales. The *Observed demand* can be explained as shown below.

$$\text{Observed demand} = \text{Systematic component} + \text{Random component}$$

The *systematic component* measures the expected value of demand. It consists of the *level*, which is the current seasonalised demand, and the *trend*, which is the rate of decline or growth in the demand pattern for the next period, and lastly, the *seasonality*, which us the predictable seasonal fluctuations that may occur in demand.

$$\text{Systematic component} = (\text{level} + \text{trend}) \times \text{seasonal factor}$$

Any forecasting method will also always contain a *random component* that cannot be explained by the historical demand and are deviated from the systematic part. All companies will most likely encounter this random component that may vary in size and variability, which will provide a measure of the forecast error. The aim of forecasting is not to eliminate the forecast error, but to filter it out and estimate the systematic component. Since the forecast error measures the difference between actual demand and forecasts, the rule of thumb is that a good forecast method has a forecast error that is similar to the random component of demand.

Even if most of the used forecasting methods are quantitative, there are some qualitative judgements involved. This is not only in the form of qualitative forecasting methods, but in the involvement and implementation of the forecasts. The five points should be followed when implementing and maintain the forecasts:

1. Understand the objective of the forecasting.
2. Integrate demand planning and forecasting throughout the supply chain.
3. Identify the major factors that influence the demand forecasts.
4. Forecast the appropriate level of aggregation.
5. Establish performance and error measures for the forecast.

4.3.1 Types of demand

To efficiently determine or calculate forecasts, companies should know if their demand patterns are deterministic or stochastic (Ma et al. 2019). Deterministic demand implies that the customer demand is either constant or dynamic over the chosen time horizon and is known in advance (K. C. Frank et al. 2003). Stochastic demand means the opposite. It deals with uncertainty in demand, and which replenishment strategy suits the enterprise best is difficult to determine.

If demand is not known in advance, or not constant, it is known as stochastic demand (K. C. Frank et al. 2003). The demand pattern can vary due to seasonal demand, market changes, or other factors from the customer. Stochastic demand can further be divided in two groups, the stationary demand and non-stationary demand (Ma et al. 2019). When the stochastic demand is stationary, the distribution of the demand patterns remains the same over a longer time horizon, finite or infinite. With non-stationary demand, the probability distribution of the stochastic demand changes over time, finite, or infinite. Figure 4.4 shows the difference between the two demand types, where the stationary demand is the one above. As one can see from Figure 4.4, there is a clear linear trend in the stationary demand compared to non-stationary, where the demand is unstable but with a slowly rising trend. Inventory control and replenishment is difficult to perform when the demand is stochastic and non-stationary (Komari Alaie 2013).

4.4 Replenishment systems and lot size models

MRP is an accepted approach for replenishment planning for many major enterprises (Dolgui et al. 2008). MRP has a "static" safety stock and ordering inventory control

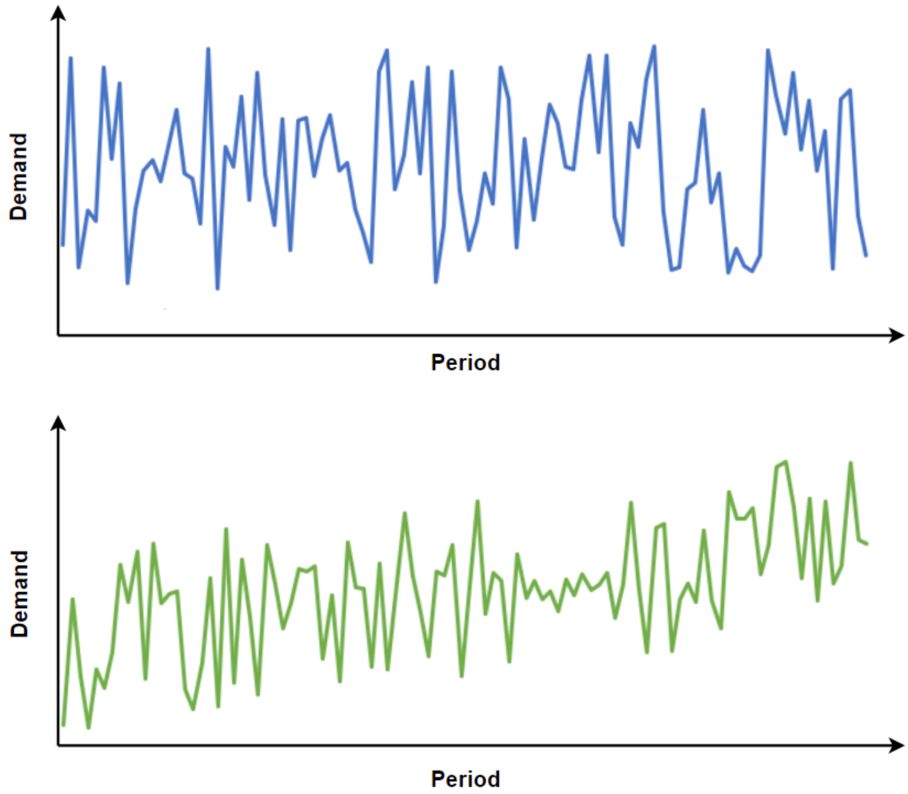

Figure 4.4: The two types of stochastic demand

policy which are computed based on demand history Babai and Dallery (2009), where the supposition that both the demand and lead times are known. This deterministic demand model is difficult since there might appear stochastic situations. Machines can break down, delays from suppliers might appear, or demand may change from customers. The deterministic assumption linked with MRP are therefore often too limited, and therefore need other replenishment policies.

4.4.1 Discrete order quantity

With the Discrete order quantity (DOQ), also known as Lot-for-lot (LFL) ordering, each order size equal to the actual customer demand for single need (Vihijärvi 2019). An example would be if an enterprise receives a customer order for three steel pipes where each pipe requires two screws, then the lot size order to the supplier would be for six screws. Table 4.3 below shows an example on the different lot sizes for each demand. Some of the advantages with the LFL lot sizing method is the reduction of both inventory levels and holding cost, since materials are almost immediately used and stays at the warehouse for a short time (Resa 2014). But this is also at the expense of having higher order cost due to more frequently orders.

The LFL method works both in pull- and push-production systems (Nicholas 2011). LFL also works regardless of if the customer demand is independent or dependent. *Independent demand* is when demand is either customer or market driven. It is independent since the demand for a product is created exogenous to the production system. The lot-size is

Table 4.3: Lot size example using the lot-for-lot method

Week	**1**	**2**	**3**	**4**	**5**	**6**
Demand pipes	3	7	5	2	8	12
Demand screws	6	14	10	4	16	24
Lot size	6	14	10	4	16	24

generated from demand forecasts, actual customer orders, or a combination of forecast and actual demand. *Dependent demand* means that an item is dependent on the demand for a higher-level item. The example with the pipes and the screws is an example on both independent and dependent demand. The pipes are based on the independent demand, as they are demand from the customer. Each pipe needs two screws to be made and are therefore dependent on both screws, making the screws be dependent demand.

Period Order Quantity

The Period Order Quantity (POQ) method is somewhat similar to the LFL as in it orders only what is needed for the future, but instead of ordering for each order, it restricts the frequency of the total number of orders (Vihijärvi 2019). The lot size is determined by demand that appears in a predefined time period. The period is determined by the enterprise and can be several days, or even weeks, determined on the characteristics of the company. As an example, each period is two weeks of demand for the metal pipes. By using the same numbers as with the LFL method, then orders will be sent out to the supplier during week 1, 3, and 5. Each lot size is presented in Table 4.4.

By applying this method instead of LFL, enterprises will reduce the number of orders and setups. The advantages that come with this method compared to LFL is the reduction of ordering costs, as orders are sent out less than with the LFL method. But it will result in higher inventory costs, as some materials will have to spend time at the warehouse since they won't be used until production starts. How high or low the ordering and inventory cost will be, is based on how long the predefined period is, as a shorter period results in lower inventory cost but higher ordering cost, and a longer period will give the opposite results. POQ works for both independent and dependent demand.

Table 4.4: Lot size example using the Periodic Order Quantity method

Week	**1**	**2**	**3**	**4**	**5**	**6**
Demand pipes	3	7	5	2	8	12
Demand screws	6	14	10	4	16	24
Lot size	20		14		40	

4.4.2 Static calculations

With the static uncertainty model, values of all decision variables are to be determined at the beginning of the time horizon. This accounts to both the time between deliveries, as well as the order sizes (Bookbinder and Tan 1988). Order quantities and time between deliveries are calculated as shown in the next few pages.

Economic Order Quantity

One of the most used lot size model for deterministic demand is the Economic Order Quantity (EOQ) (Kim et al. 2004). It was introduced by For Q. Harris in 1915 and aims to balance the cost of ordering materials with the inventory holding cost for a raw material, component, or product Zinn and Charnes (2005). The model estimates how much to order based on the annual demand of the material, cost of placing an order and the respective inventory holding cost (Nicholas 2011). The quantity found by the EOQ model finds the balance between ordering cost and holding cost, as opposed to other methods which may prioritise higher ordering cost for lower inventory cost or the opposite. Figure 4.5 shows how the EOQ is found by analysing the ordering and holding cost. The formula for the EOQ is:

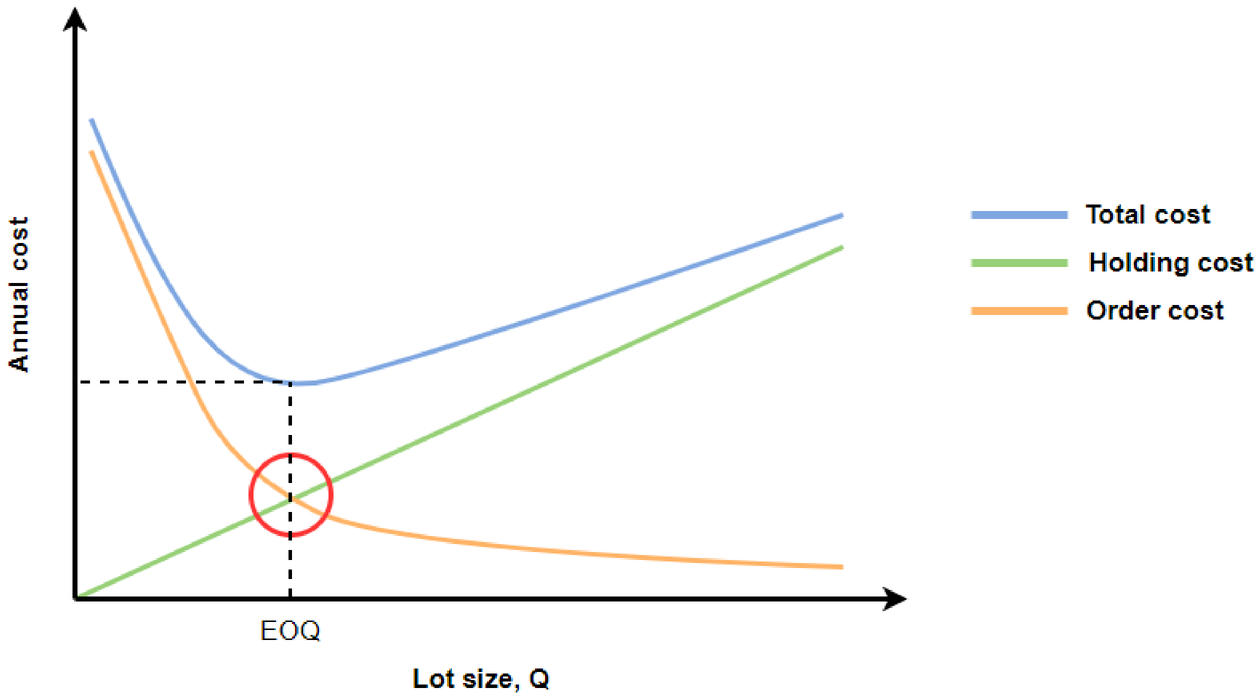

Figure 4.5: The EOQ cost model

$$Q_{EOQ} = \sqrt{\frac{2 \times S \times D}{h \times P}} \tag{5}$$

Where he Q_{EOQ} is the optimal lot size for the EOQ model, S is the cost of an order, D is the annual yearly demand in units, h is the average annual cost of holding inventory, and P is the unit product value. EOQ is easy to compute, but it has several disadvantages (K. C. Frank et al. 2003). Factors such as discounts are not included in the calculation. Further, demand might change from year to year, and the model is therefore not optimal to the current situation.

Reorder Point

The EOQ model tackles the "how much" to order, but not necessarily the "when" to order. This is where the Reorder Point (ROP) comes in as a calculation to find out when companies should replenish (Ivanov, Tsipoulanidis et al. 2019b). ROP is a replenishment system where a replenishment order for more materials is placed whenever the inventory level reaches the pre-calculated reorder level (Nicholas 2011). It is based on a minimum level of materials that are acceptable to hold before replenishment needs to occur. The replenishment level is estimated according to the amount of material used between the time when the order is placed until the replenishment batch is received from the supplier. The amount of material used between each order is based on the annual demand D for a given time. The replenishment system is computed using a historical approach to forecast the future inventory demand. The purchaser will then send an order to the supplier when the inventory level is equal to or below the calculated ROP. The order will be released after L days. ROP was mainly calculated manually up until the commercial mainframe computers were introduced in the late 1950s. The formula for the ROP is according to Nicholas (2011) shown below. Figure something illustrates the ROP in a perfect scenario with constant demand and lead times.

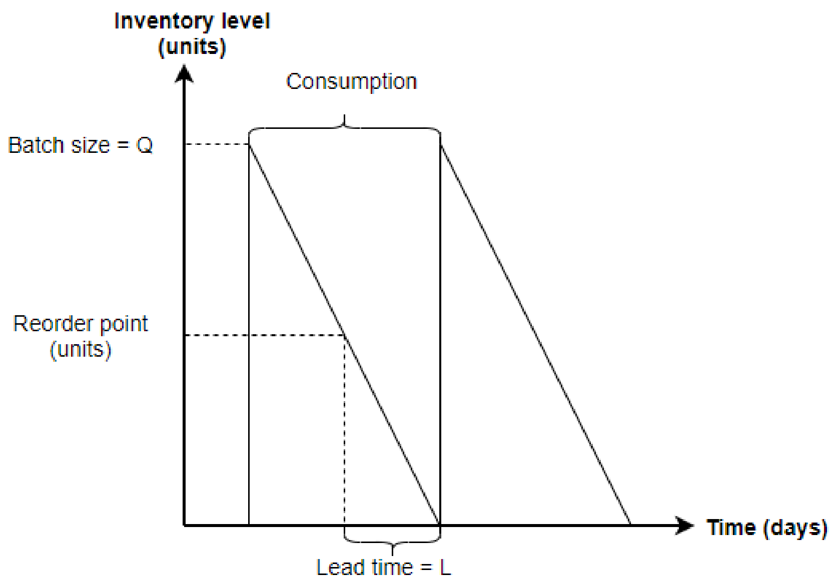

Figure 4.6: Reorder Point parameters

$$ROP = D \times (L + 1) + SS \tag{6}$$

If the demand is constant with little uncertainties, then the ROP is the same as the demand during lead time. This is not always the case as demand may change along with lead time variation. When demand is uncertain, a safety stock SS is included to accommodate for unexpected demand changes or variable lead times from the supplier (Plinere and Borisov 2015). The company can risk running out of materials if the SS is not included and can lose sales. The SS is computed by using the standard deviation of demand during lead time $\sigma_d L$ and a z-value (Ivanov, Tsipoulanidis et al. 2019b). The Z-value is determined according to the company's determined service level. One can use the table of probability distribution to find the z-value. The probability distribution table is shown in Appendix F.

As an example, if the wanted service level is 95%, then the z-value will be equal to 1,65. But there may be other uncertainties that has to be included in the safety stock. Demand or customer lead times are not always constant, which must be included in the safety stock calculations. Figure 4.7 shows the how the ROP works as well as illustrates the need for the safety stock in a realistic scenario where both demand and lead times may change. The four ways to calculate safety stock are therefore:

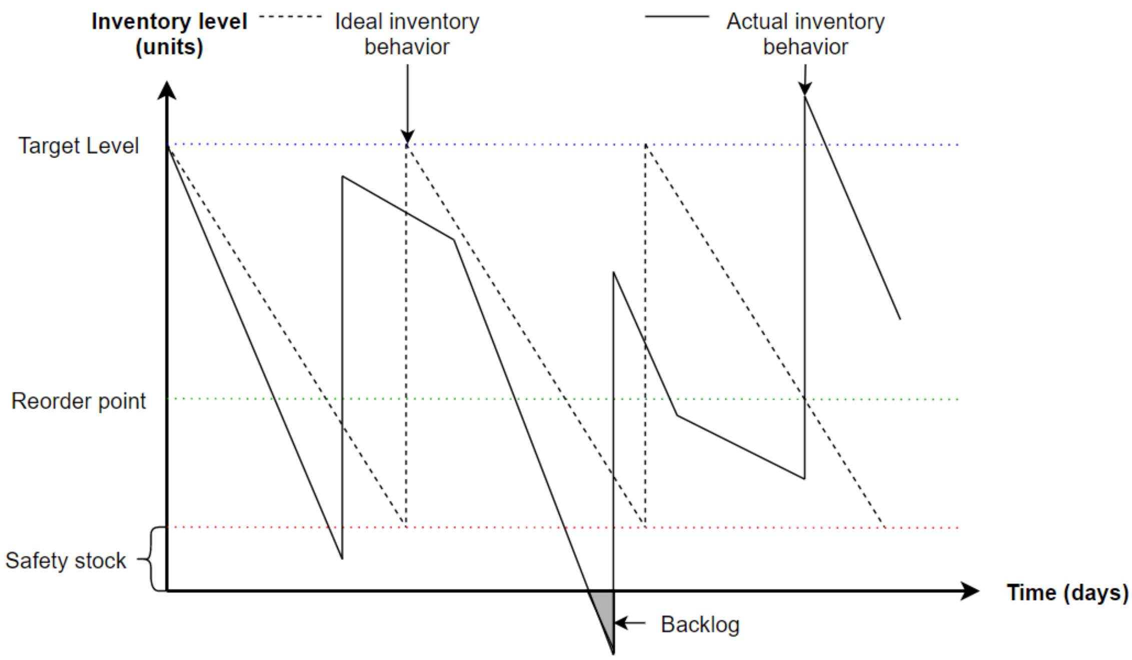

Figure 4.7: Ideal reorder point vs. Actual reorder point

When demand is assumed to be normally distributed during lead time, the following safety stock can be computed:

$$SS = z \times \sigma_{dL} \tag{7}$$

If daily distribution of demand is variable and lead time is constant, a standard deviation on demand σ_d is included:

$$SS = z \times \sigma_d \times \sqrt{L+1} \tag{8}$$

If daily demand is constant and lead time variable, then the formula includes a standard deviation of lead time σ_L:

$$SS = z \times d \times \sigma_L \tag{9}$$

Finally, if both lead time and demand are variable, formula (4) can be used:

$$SS = z\sqrt{L^2 \times \sigma_d^2 + d^2 \times \sigma_L^2} \tag{10}$$

There are two main reasons to use the ROP methodology instead of MRP based calculations according to Snapp (2014). The first reason is the ability to create efficient forecasts. If demand is predictable with continuous replenishment or if it is fluctuating and difficult or near impossible to forecast, it is better to use ROP. The second reasoning is ff lead times are short with relatively unconstrained supply. Snapp (2014) argues that raw materials that fits either of these criteria do not need advanced or semi-advanced planning techniques to determine replenishment. Materials with unstable demand will be difficult to determine without extremely advanced planning systems, while materials with relatively stable and predictable demand patterns will be continuously replenished between the same time intervals. The need for more advanced methods will give almost the same result, but with much more effort and costs.

Inventory control policies

The four *Inventory control policies* are managerial procedures that guides the enterprises to define how much and when to order (Ivanov, Tsipoulanidis et al. 2019b). When the demand has a stationary pattern it's modelled according to a fixed probability distribution over an infinite horizon (Babai and Dallery 2009). The review of each model may happen periodically or continuously. The four parameters are:

- T is the replenishment interval between each order. See formula (11) for calculation. The review period T is assumed to be a multiple of the elementary period.
- Q is the order quantity. It is calculated from the EOQ model in formula (5).
- r is the ROP. The calculations are from formula (6). For the the rest of the paper, formula (6) will be referred to as *r*.
- S is the targeted maximum inventory level. It is calculated according to formula (12) (Babai and Dallery 2009).

$$T = \sqrt{\frac{2 \times S}{D \times r \times P}} \tag{11}$$

Where the calculated value of T must be an integer multiple of the elementary period. Note that the value of T will result in a yearly interval. To gain the weekly interval, the value must be timed adjusted accordingly.

$$S = D \times (L + T) + SS_S \tag{12}$$

Note: The safety stock SS_S in formula (12) is the same as the previous safety stock calculation, except that the lead time calculation will be $(L + T)$ instead of $(L + 1)$. Further, if demand is discrete, the values of Q, r, and S must be rounded to the nearest integer, unless otherwise integer.

The four main static policies for stationary demand are therefore the (T, Q), (r, Q), (T, S), and (r, S). The (T, Q) policy issues a fixed order quantity Q between a fixed interval T

of periods. This model allows for little flexibility as it will consistently replenish the inventory each period no matter how the demand changes. With the discrete-time (r, Q) policy, inventory levels are controlled at the beginning of each period. The fixed order quantity Q is ordered when the inventory level reaches the reorder point r. The quantity will be delivered after L periods. The (T, S) policy follows a different approach. At the beginning of each review period T, a quantity is ordered to raise the current inventory level up to the replenishment level, or maximum level, S. The quantity Q_k will vary for each period, according to the inventory level at the end of period I_k. See formula (?) for the calculation of order quantity Q_k. The quantity ordered will here as well be received from the supplier after L periods. The last model, (r, S), reorders up to a fixed level $S$when inventory reaches a reorder point r. This inventory policy allows for more flexibility and is the optimal policy in each period if the inventory holding and shortage cost are linear. Figure 4.8 illustrates the four different static inventory control policies.

		Order interval	
		Fixed	Variable
Order quantity	Fixed	(T, Q)-policy	(r, Q)-policy
	Variable	(T, S)-policy	(r, S)-policy

Figure 4.8: Difference between static reorder policies

$$Q_k = S - I_k \tag{13}$$

4.4.3 Dynamic calculations

Using static control principles is not optimal to use if demand is stochastic and non-stationary due to the rise or fall that comes from these demand patterns. When the probability distribution of the demand changes significantly from period to period, the standard static inventory control policies results in either stock outs with unsatisfied customer demand or too much stock at hand with higher inventory costs (Komari Alaie 2013). In practice, planners need to revise the formulas in response to the various random variables that can occur over time. Dynamic uncertainty models take this into account by revising the plan and formula. It is revised according to the set period by the firm, which can be days or weeks in-between. Dynamic calculations include forecasts, and eventual uncertainties that comes from the forecasts are included in the calculation to provide a better estimation for uncertainty in future demand.

According to Babai and Dallery (2009), by extending both the classical discrete time

(r, Q) and order-up-to-level policy (T, S) by including review periods in each model to accommodate demand and forecasts changes. The (r, Q) is extended to the dynamic (r_k,Q) policy, where r_k is the reorder point, while Q is still the order quantity. The same goes for the extended dynamic (T,S_k), where T is still the review period and S_k is the order-up-to-level level. The following parameters are used for the dynamic calculations:

- $F_{k,k+j-1}$: The forecast of a given raw material at the beginning of period k for period j.
- CFD_PI: The cumulative forecast uncertainty over an interval of the protection interval PI for the forecast uncertainty.
- $\sigma_{CFD_{PI}}$: Standard deviation of the cumulative forecast uncertainty.

In the (r_k, Q) policy, the quantity Q is determined before the system starts, the same way as formula (5). The reorder point r_k is however different compared to its static counterpart. Same as with (r, Q), the protection interval is equal to the sum of the replenishment lead-time L plus an elementary period 1. Therefore, at the beginning of each period k, the dynamic reorder point r_k is equal to the cumulative forecasts and safety quantity SQ_k. The reorder dynamic reorder point r_k is calculated as follows:

$$r_k = \sum_{j=1}^{L+1} F_{k,k+j-1} + SQ_k \tag{14}$$

The two parameters in the extended (T, S_k) formula are the review period T and the replenishment level S_k. Same as with the static (T, S) formula, at the beginning of each period T, a quantity Q_k is ordered so that the inventory level is replenished up to the calculated replenishment level S_k. Here again, the review period T is the same as formula (11),. The protection interval in the (T, S_k) policy is the replenishment lead-time L plus the calculated review period T. The replenishment level S_k is the same as the cumulative forecasts together with the safety quantity SQ_k. The formula for (T, S_k) is shown below.

$$S_k = \sum_{j=1}^{L+T} F_{k,k+j-1} + SQ_k \tag{15}$$

The order quantity Q_k will also be computed dynamically. After each review period *T*, an order is placed with the exact quantity needed to meet the maximal cumulative demand forecast over *L* + *T*. This is done by including the inventory position at the beginning of *T*. The quantity is therefore as shown in the formula below:

$$Q_k = \max\{S_k - I_{k-1}, 0\} \tag{16}$$

In static control policies, safety stock makes sure that the variability of demand is covered over an infinite horizon. Since demand is assumed to be stationary in this case, the safety stock is optimised and set up at the beginning of the time horizon to guarantee a target service level. But with dynamic control policies, forecasts and forecasts uncertainties may vary over time, which results in a variable safety stock. With dynamic control policies, safety stock has been dubbed "safety quantity" (SQ_k) as it changes for each period. It is calculated at the beginning of each period k, and its aim is to cover the forecast uncertainties that may occur under a pre-specified service level. The protection interval PI covers the lead time and the elementary period 1 or time series T, according to which dynamic calculation is used. The safety quantity SQ_k is calculated in formula (17).

$$SQ_k = z\sigma_{CFD_{PI}} \tag{17}$$

4.4.4 Replenishment usage

Calisir et al. (2017) conducted an ABC-XYZ analysis on the inventory and production control on a major manufacturer who often experiences problems with overstocking. The overstocking has led to high inventory costs due to the difficult of maintaining good inventory levels. The authors analysed 130 materials and divided them in the nine classes of the ABC-XYZ analysis. Around 60% of the materials were placed in the BZ and CZ class, with relatively low usage value and high fluctuations in demand. Calisir et al. (2017) recommended to have higher safety stocks for these materials and should follow a simple lot-size policy. This is supported by Babai and Dallery (2009), who found in their analysis that when forecasts are not reliable, it is better to use standard static inventory policies. If the forecasts are reliable, it is more advantageous and cost-beneficial to use the dynamic inventory policies, since the minimum and maximum levels will be more accurate towards actual demand. Most of the A-class materials have highly irregular demand as well, making replenishment for these materials difficult considering their high usage value. For the materials in the AX and BX category, the authors recommended zero safety stock, with a JIT principle that follows the LFL order policy to reduce the inventory costs. Every material would be managed in the company's MRP system, whose job was to give notice on replenishment and check inventory levels.

Hautaniemi and Pirttilä (1999) performed a material classification on an ATO company who experienced some troubles with using the deterministic calculations in the MRP system when they changed from an MTS environment towards ATO. They decided to divide the materials in five categories, based on the ABC usage value, replenishment lead times and demand patterns. The first categories were C-class items, which represented 5% of the total usage value and 80% of the material percentage. The materials in this class would be controlled by standard ROP systems. The second category contained A-class materials that had a replenishment lead time shorter than the final assembly time. These materials would be controlled by the firms MRP system, based on customer demand. The next categories are all in the A-class with a replenishment lead time longer than the final assembly time. The difference between them is the demand pattern. The third category had irregular or singular demand pattern. These items were controlled by ROP system. The fourth class had fluctuating demand patterns. The fourth classification had no materials in it. The last category contained materials with steady demand patterns. These materials were also controlled by the MRP system, but they did require some overplanning due to the long replenishment time. The MRP system would for these materials use forecasts.

4.5 Improvements with Quick Response Manufacturing

4.5.1 QRM purchasing strategy

The fourth core strategy in QRM suggests a set of rules and recommendations to achieve better delivery time and supplier relations when it comes to purchasing strategies (Suri 2010). Good relations with the suppliers are essential to achieve better orders and material deliveries. Companies should view their suppliers as part of the team rather than strangers (Sharma et al. 2011). Just like with Lean manufacturing, QRM suggests procuring materials more frequently in smaller batches, compared to buying larger quantities more frequently. The disadvantages of procuring larger batches are illustrated in the *Response Time Spiral in Purchasing*. It highlights a serious of events where the company orders larger batches, in the faith that it benefits them, when it will lead to longer lead times both internally and outside the company. The Response Time Spiral for Purchasing is illustrated in Figure 4.9

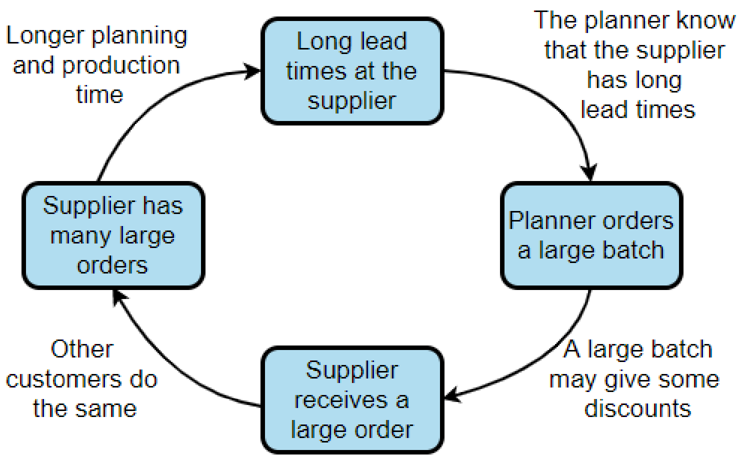

Figure 4.9: The Response Time Spiral

Source: Suri (2010)

The Response Time Spiral starts at the top with the supplier. The supplier has long lead times, which the planner considers when he sends an order. The planner then places an order on a large batch to make sure that the company has enough raw materials until the next order. The planner might also place a large order in hope to get a discount. The supplier receives the large order and start the production or delivery process. Other customers of the supplier might do the same, as they know that the lead times are long, plus the discount that occurs from placing large orders. This results in the supplier having many large orders and might have to rearrange their production strategy to produce bigger batches at each time. This will end up with longer production times for the supplier and promised delivery time to their customers. The time spiral will then continue itself even more.

Long delivery lead times can create a few problems even if the supplier offers low prices, excellent quality, and excellent track records on on-time delivery. Long lead times from the supplier affects the company's MCT, as the MCT also includes the planning and procurement process. There are also other uncertainty and negative results that comes from long delivery times, such as:

- High inventory costs since there will be more raw materials at the warehouse.
- Extra costs if a rush order has to be placed due to unexpected inventory shortage. This cost can be high if the supplier located far from the factory. It is also not a guarantee that an extra order placement will be delivered on time.
- More time spent on communicating with the supplier regarding the status on the order. This is wasted time that could be spent on other planning objectives.
- Changes in demand or forecasts can occur during the delivery time. To change an already placed order can be difficult and time consuming to negotiate with the supplier.
- Further, demand changes that can't be fixed will reduce the inventory levels. The flexibility to respond to demand will be reduced if the raw material is not available at the warehouse. There have been cases where some companies have reported lost sales after they outsourced raw materials from suppliers located in the Far East.
- Custom-engineered or special parts that is essential to the customisation will negatively affect the promised delivery time the company has promised its customers. The quicker the specialised parts are received; the shorter quoted lead time can be given to the customer.

The QRM thinking recommends companies to use MCT as a primary metric for supplier selection. Companies should encourage their suppliers to produce and deliver orders in smaller batches as it has several advantages compared to larger batches. Won and Olafsson* (2005) points to how larger batches increases the time between an order is placed to it is received due to longer picking and production time, as the possibility of delays will be increased. They also point out on how it will increase the inventory turnover rate, as there will be more materials at stock. Smaller batches can also lead to better quality (Pillai 2010). However, ordering large batches will rising the inventory costs (Tjahjono et al. 2017). Pillai (2010) also argues that inventory effectiveness of a company can be measured in how short their lead times are, as lead time performance can affect the cost metric of firms. Short lead time can be a major trade-off for many customers. By comparing two suppliers, the first with delivery lead time of two weeks and the other with eight weeks, indicates that the first one is performing better compared to the second one.

Supplier selection for the different raw materials

The QRM thinking focuses on reducing its customer MCT, so that companies can order their products more frequently to eliminate the risk of late deliveries. Outsourcing to a foreign supplier located far away is not recommended. But there are some exceptions to suppliers with long MCTs. Some of the suppliers that are located far away might offer a unique material with mature design that is highly cost intensive to procure from a nearby supplier. QRM then divides raw materials according to how close the supplier should be located. The classification is based on volume and demand patterns.

There are some suppliers who can provide shorter delivery items, but not all of them. Many companies outsource their products from the Far East, as they can promise cheap products at reasonable or as good quality as locally suppliers. But the QRM thinking does not recommend outsourcing to a foreign supplier that is located far away from the warehouse, as the delivery time will most likely be long due to the distance. But there are exceptions to suppliers who have longer MCTs. There are some suppliers located far who offer unique materials with mature design that is highly cost intensive to source from a nearby located supplier. Suri (2010) divides whether or not company's should outsource to far-away foreign suppliers in three categories. The categories are determined by its volume, demand pattern, and speciality, as shown below.

– **High volume parts with predictable demand:** Raw materials that are frequently used, mature design, and predictable demand are easier to both forecast and plan. It does not matter where the supplier is in this category since it is easier to create forecasts for these materials. The transportation time therefore becomes irrelevant.

– **High volume parts with irregular demand:** As with the previous category, it may be more cost efficient for the company to source these items from suppliers located in the Far East. But due to irregularity in the demand patterns, changes in forecasts can occur, which makes the risk of placing an order with long delivery times quite high. The best option would be to source locally, but as mentioned, the costs might be too high for that. QRM proposes to implement a sourcing technique called *time-based dual sourcing* (TBDS). The TBDS strategy recommends using two suppliers. One can be located far away, if they offer lower prices, and one located locally, who can supplement the company if an extra order has to be placed due to the customer demand. The second supplier then acts as a back-up supplier, as changing already placed orders to the other supplier can be difficult to do.

– **Low volume parts and highly customised parts:** QRM does not recommend to use overseas suppliers for materials used in low volumes, regarding its demand patterns. The long MCT that comes from using overseas suppliers can cause additional costs when the volume is low, which can damper the manufacturing and planning stage. If the volume is ordered in large batches, there will be additional inventory costs, and more frequently orders with smaller quantities will result in high order costs. Firms should rather find local suppliers whom they can develop a good relationship with over time, while helping them reduce their MCT. It is difficult to manage the relationship with the supplier and shorten their lead times if they are located far away and the total order quantity is low. Specialised parts should be located nearby as well, since an eventual delay in delivery or forecast mistakes can dampen the whole production.

4.6 Smart manufacturing

During the last decade, manufacturing started switching from "intelligent" technologies such as artificial technologies, towards "smart" technologies (Yao et al. 2017). The term "smart" is described by Yao et al. (2017) as *the creation and use of data throughout the entire product cycle for the purpose of more flexible manufacturing processes that respond* *quickly to on-demand changes at low cost without harming the environment*. The smart technologies that have been implemented to create smart manufacturing are the Industry 4.0 principles of IoT, Cyber-Physical systems, BDA, and autonomous robots. Both CPS and IIOT aims to connect the cyber world and the physical world.

4.6.1 Technologies and methods

Internet of Things

Within IIOT, certain devices can sense, interact, and compute data needed (Mircică et al. 2019). Through IoT, enterprises have shown to become more harmonised and interconnected through more efficient data sharing, analysis, and cutting-edge technologies. It aims to integrate every object within the firm through embedded systems, which results in a distributed network of devices that communicates with human workforce as well as other devices (Xia et al. 2012). The smart products, such as Radio-Frequency Identification (RFID) tags, actuators, sensors, smart phones, etc. cooperate with each other to reach goals set by the enterprise (Atzori et al. 2010). Smart products knows their own identity, history, specification, documentation, and production processes (Sadeghi et al. 2015). They collect data before, during and after production, and are controlled by smart devices, such as smart phones and wearable (e.g., smart watches). The main objective of IoT is to allow the user to better find out what has been done and which processes remains before completing.

Some of the IIOT technologies that strive towards better inventory management is among other advanced tracking and tracing technologies. These technologies allows for better real-time information acquiring, automation, purchasing and check out operations, and inventory control (Subramanian et al. 2005). Decision-making is of vital importance for supply chain planning and knowing exactly how much is on stock and where it is located allows the planners to gather information faster. One of these technologies is the RFID tool. The RFID will stick to a material or products and will allow the company to know the exact position where it is located/needed to be located (Tjahjono et al. 2017). RFID tags can be connected with the company's ERP system or other digital system that tracks and controls the number of materials at the warehouse. The information from the RFID tags allows the enterprise to track movement in every stage of the supply chain, from purchasing, storage, production, transportation, distribution, and whenever the product or semi-product has reached the customer (Atzori et al. 2010). Whenever an operator reaches an operation or picking station, he/she may use the smart mobile to gain information from the tags through the company's web service. The information may regard number of materials needed for the operation and processes.

Big Data and Analytics

BDA is defined by Rajaraman (2016) as *a term that is used to describe data that is high volume, high velocity, and/or high variety; requires new technologies and techniques to capture, store, and analyse it; and is used to enhance decision making, provide insight and discovery, and support and optimise processes*. The main objective of BDA is to use advanced analytic techniques on the big sets of data (Russom et al. 2011). The need for advanced analytics has over the reason years become apparent, due to the larger sets of data. It shows enterprises what was previously done, what has changed, and how they should react to the eventual change. Further, there are multiple business opportunities that can be exploited from BDA, such as new customer segments, supplier selection, sales and seasonality, and product characteristics. An example is how it can be used in price optimisation models which computes the demand variance according to the current price trends. Combine this information together with the relevant cost and inventory data, BDA can be used to recommends prices that can maximise revenue and profits of the enterprise (Ivanov, Dolgui et al. 2019). BDA is an efficient Industry 4.0 tool that can manage inventory and demand forecasts, as it can track the previous customer behaviour and analyse future demand (Russom et al. 2011).

4.6.2 Improvements with Industry 4.0

Rüßmann et al. (2015) analysed the performance objects of several German manufacturing components after implementing Industry 4.0. Some of the technological advancement by implementing Industry 4.0 are productivity, revenue growth and employment. Revenue growth can come allowing more customisation through Industry 4.0, which attracts more customers. New employees is also needed on the different IT technologies and software development. There is however a need for high investment cost in the beginning, as new equipment and IT software has to be installed.

One of the benefits that comes from implementing Industry 4.0 is the ability to adopt digital technologies to gather data in real time (A. G. Frank et al. 2019). The data is then analysed and will provide useful information that can improve the manufacturing system. Another process that will benefit from Industry 4.0 implementation are the supply chain. Supply chain improvements through Industry 4.0, called the *Smart Supply Chain* will improve exchange of information and integration of the supply chain by synchronising production with the different suppliers to reduce the overall lead times and information misunderstandings that may produce bullwhip effects.

Lean Manufacturing has over the years been connected with Industry 4.0 to improve the lean manufacturing tools (Sanders et al. 2017). Some of the implementation is in the form of electronic Kanban cards, or e-Kanban, that can be implemented at the shop-floor (Ghobakhloo and Fathi 2019). E-Kanban can be directly linked with the ERP system. The implementation improves the performance and data tracking of the ERP system as visualisation and analysis of the workflow becomes easier since the e-Kanban will be constantly online. The ERP system can use this information to plan and manage the different departments within the enterprise, such as inventory management, purchasing, quality management, and order delivery. Entry errors and calculations will also become more reliable to compute, as well as the fear of losing the physical Kanban cards.

Ghobakhloo and Fathi (2019) presents some empirical results from an analysis conducted on a small manufacturing firm that implemented digital Lean to improve their business performance. The company reported better production and delivery accuracy, reduction on time spent on planning, tracking on suppliers' deliveries, and reduced inventory holding. They also experienced better relations with both their suppliers and customers, as the information from the e-Kanban and ERP system were linked to a cloud system that could be shared with the different actors in the supply chain. Information sharing became easier, misunderstanding became less, and the supplier gained better insight to the future plans, which in turn made the planning of future orders on raw materials better.

Another empirical analysis was conducted by Tortorella et al. (2019) on Industry 4.0 integration with some Lean manufacturing principles. Tortorella et al. (2019) showed that the two principles managed to improve the flow of information through better flow of materials and product/service related technologies. They found that Industry 4.0 can increase the performance of enterprises through newer business models and services. However, Tortorella et al. (2019) pointed out that some of the principles is limited to certain enterprises, due to their scales, and smaller companies need to choose the policies that they can manage to implement. For companies that are implementing both Lean practices and Industry 4.0 policies, they suggested to find the right balance between the two. For example, if a company implements many flow-related Lean practices, they should implement Industry 4.0 practices to the product/service part of the enterprise with the technologies such as cloud services, IIOT, or BDA. The balance between the two will improve the operational performance level according to the size of the company.

4.7 Summary

This chapter presents the three main categories that are relevant for this thesis, namely inventory management, Quick Response Manufacturing and Industry 4.0. Inventory management will guide the companies towards better material and ordering policies through material classification, forecasting, and replenishment policies. Material classification will help the companies understand which material need better planning over others. It will lay the foundation for future work and can aside from the framework be used to check for different factors that concern the materials. The subsection about forecasts shows some of the major factors that must be included when conducting forecasts. The forecasts will lay the foundation for some of the replenishment policies in the next step, and understanding the basics and importance of forecasts will help the replenishment policies. Standard static policies such as (r, Q) and (T, S) is recommended by several authors to be implemented if demand is unstable, forecasts are difficult to determine, or if demand is deterministic. For stochastic demand, especially non-stationary, it is recommended to implement dynamic policies that can adhear to the demand changes, as long as forecasts are reliable.

QRM is a useful thinking that can be implemented for MTO manufacturing companies that wants to reduce their lead times while at the same time respond faster to customer orders. The methodologies presented by QRM can be implemented throughout the organisation with a high emphasis on the MCT. Lastly, digitalisation principles and Industry 4.0 have some methodologies that will support the previous subsections through IT tools and digitalisation concepts. It is not recommended that SMEs go with a full on Industry 4.0 implementation, as they can look tools and human resources to do so. They can however choose some of the pillars at some departments within their organisation.

5 Case presentation

This section contains the main analysis for this thesis that have been done on the two case companies. I will start this chapter by giving a quick presentation on the two companies. The third subsection presents the Quick Response project that the companies are implementing in collaboration with SINTEF manufacturing and SINTEF digital.

5.1 Case Company A

Company A is a Norwegian manufacturing company that specialises in highly customised windows and doors for the Norwegian construction business. They are located in Western Norway and sell their products directly to construction firms, and not to private customers. The firm was established in the late 40s as a means to rebuild the local area after World War II. The company quickly grew and expanded their market to both Eastern- and Southern Norway. Their customers expect highly customised doors which follows certain safety regulations along with environmental benefits. Table 5.1 contains some information about Case Company A.

Table 5.1: Information about Case Company A

Characteristics	**Value**
Number of employees	255
Revenue	387 MNOK (2018)
Market share	10%
Customer locations	Norway
Number of products	8000 doors and windows, and 2000 outdoors
Delivery precision	96,6 %
Raw Material Inventory	Raw material usage on 41,8%
Finished Goods value	10 MNOK

Products and customers

Company A allows their customers to customise their production according to their wishes. Their products may differ in height, width, type of wood, colour combination (they allow for 1950 different combinations), and window glasses. They use approximately 400 types of glasses that ranges in both dimension and quality, according to the customer demand. Customers create their order in the firms e-store, which will automatically be generated to a customer order in the company's ERP system. However, there are some customers who still orders through email. These orders have to be manually inserted in the ERP system by the company themselves.

Manufacturing and lead times

From a customer order is created, it takes the company approximately eight days before the order is finished. The product use around 3,5 days in the manufacturing hall (2018). While the product is in production, they await for the delivery of the window glasses. The glasses are ordered according to customer demand from a huge glass supplier in Eastern Europe. After the product is finished, it may spend around four to five days in the FGW, before it is shipped to the final customer.

Future goals

The company has excellent track records with both quality and delivery precision. However, they have in the recent years experienced growing competition from Eastern European companies whom can deliver products of equal quality at a lower cost. Due to the rise in both national and international competition, they have realised that they have to allow more customisation and innovation to their products, as well as responding faster to customer order with even higher delivery precision. They are also shifting towards a company with high environmental awareness.

The company implemented Lean Manufacturing 15 years ago in the hope of removing waste and reducing their lead times, and they did achieve some lead time reduction after the Lean implementation. However, they found out that they could reduce them even more if their suppliers also implemented some Lean manufacturing tools so that the information sharing between them could improve. The company also experiences problems with the data transformation with their ERP system. There can often be time delays with the ordering system to their ERP and MPS system.

To combat this challenge, they have started implementing digitally enhanced QRM on top of Lean manufacturing. They want to implement it at multiple stages within their supply chain and factory. Furthermore, improvements in the digital system will improve the current information sharing, manufacturing surveillance at the factory, ordering systems, and supply chain control.

The company started implementing Lean manufacturing a couple of years ago and did achieve some lead time reduction. But they see that they could also benefit a lot more if their suppliers also implemented the Lean thinking method, so that information sharing between the company and their suppliers could improve. Company A also experiences time delays with the data transformation from the ordering system to their ERP system. To combat this challenge, Company A wants to implement QRM in multiple stages within both the supply chain and improve their digital systems which will improve information sharing, manufacturing surveillance and supply chain control.

One of the main goals with QRM implementation is to reduce the manufacturing lead time from 3,5 days down to 1 day, which they have already achieved. The goal is to use around 6 hours per product. The reduction in manufacturing lead time will reduce the operating cost with 40%, which is around 10-15 MNOK in savings. They respond fast to customer orders, but the lead times from the suppliers are still long. The goals regarding customer satisfaction and business model is shown in Table 5.2.

Table 5.2: Goals of Company A

Goals	Weight
Innovation	10%
Quicker responsiveness	40%
Low costs	20%
Delivery precision	30%

5.2 Case Company B

The second company specialises in both customised and standardised doors. The company were created in the 70's. The customised products are sold to the construction sites while the standardised doors are sold to private customers through their wholesaler. Their customers are geographically distributed over the Scandinavian market. Customers have a high focus on low price products, but they can ignore higher costs if Company B can deliver highly innovate products, promise shorter delivery times, while still regarding quality as an order winner. Quality is already a major factor with which Company B must work with due to governmental standards that the construction business has to follow. Table 5.3 contains some characteristics of Company B.

Table 5.3: Information about Case Company B

Characteristics	Value
Number of employees	180
Revenue	360 MNOK (2020)
Number of products	120 000 doors
Customer locations	Norway, Sweden, and Denmark
RMI Value	23-25 MNOK
FGW value on doors	1,7 MNOK on average
Market Share in Norway	20%
Delivery precision	70%

Products and customers

The Norwegian and Swedish customers' orders both customised and standardised products, while the customers in Denmark demand highly customised products. These products are fully designed according to the demand. The specifications the customers choose for the different products are based on material availability, safety regulations from the government, and machine- and equipment availability at the factory. The safety standards can for example be fireproofed doors. The company has two facilities, who split the workload according to the customer demand. One of the facilities specialise in the customised doors, while the other produces doors to shelf.

The company creates between 15 to 20 different modules in anticipation of customer order. These standard models will further be customised according to the specifications.

Orders usually comes via emails. Each order is reviewed by the company, to check if it meets the availability that they offer. If the order is confirmed, they will send the order confirmation back to the customer and start the design stage. They use the ERP system *Calvin*, which is an ERP system created for window and door companies.

Manufacturing and lead times

If a customer order for MTO products is confirmed by the planner, they will initiate the planning and manufacturing stage. It takes in total around six weeks from the order is accepted to the finished products is shipped to the customer. The first three weeks consists of planning and procurement processes. Within these three weeks, Company B plans the design, manufacturing, and order process. Firstly, the production plan for the order is created by the production planner in the ERP system. Next is to procure the raw materials with lead times short enough to fit this time slot.

Next step is the manufacturing and assembly process. The products are manufactured at the shop floor. After the product is finished, it will be packed and sent to the FGW, where it will spend some time before the shipment. These processes also take around three weeks.

Future goals

For the company to be able to operate economically in the future, they have realised that they need to respond faster to customer demand by reducing the overall lead time. The company has set themselves three goals for the future. The first and second goals is to reduce the overall lead time it takes from a customer order is created to it is sent to the customer. This is done by firstly reducing the time spent at the planning and procurement stage, and secondly to reduce the time spent at manufacturing. The aim is to go from the current three-week production process to just days. The last goal is to reduce the overall costs by 20%. The cost savings accounts to roughly 6-8 MNOK on a yearly basis. The company's goals to customer satisfaction is shown in Table 5.4.

Table 5.4: Goals for Company B

Goals	**Weight**
Innovation	20%
Quicker responsiveness	30%
Low costs	20%
Delivery precision	30%

Company B also tried Lean manufacturing implementation some years ago but did also not succeed that well with it. Therefore, they have also seen the need to implement digitally enhanced QRM. One of the digital upgrades will be a more upgraded digital ERP system. The aim is to achieve a digital day-to-day process by connecting the system with the machines. The new digital ERP system will contain all the necessary data that makes both retrieving and data tracking easier. The aim of the digitally enhanced QRM implementation is to improve the current information flow between the supply chain actors, inventory systems, and equipment collaboration. But today's solution does not support QRM and real-time information sharing within the company and the supply chain, and they see the need to reorganise the whole company.

5.3 Quick Response 4.0

Both companies are with the help of SINTEF manufacturing and SINTEF digital in the process of implementing Quick Response 4.0 throughout the organisations. The project started the spring of 2020 and are expected to be finished by 2023. The aim of the project is to help the companies strengthen their market position, reduce costs, and respond quicker to customer orders by implementing QRM, Industry 4.0 principles, and sustainable goals. The goal of Quick Response 4.0 is to reduce the internal and external company lead times by approximately 75-90%, reduce indirect production costs, reduce the working capital requirements, and increase the firms market share. As mentioned earlier, standard QRM is rooted in four core principles. However, within Quick Response 4.0, there are five core principles that companies are to follow. The first principle is to implement performance indicators that follows the time is takes to place an order, not only costs. The second core principle is to simplify the processes by adapting to the organisational structure. This will among other things improve the decision-making at the firm. Next principle is management of internal resources. Better balance of the internal resources helps enterprises become more flexible towards different customer demand. Fourth principle aims to adopt an integrated approach to every department in the company, as well as the whole supply chain. Lastly, with the help of digitised tools, companies will be able to track information and gain better overview over the processes.

The project is divided in four ”work packages” that each serves their own purpose at the companies. The first work package aims to develop a business model for Quick Response 4.0 Value Chain by. The second package has a focus on production development methods by implementing QRM principles such as QRM cells, digital POLCA cards, machines that operates with each other, and more. The aim is to develop methods that creates effective material and information flow at the factory. The third package is like the second one but has a focus on the warehouse instead. Improvements will result in digitalisation principles and control systems that will improve the current inventory and replenishment planning. The last package focuses on digitalisation and Industry 4.0, by implementing Data-driven Digital Twin system with Artificial Intelligence. All of these work-packages will help the companies achieve innovative solutions for smart and sustainable customised production.

6 Empirical findings

This chapter presents the empirical findings from the case study. Firstly, I will present the ABC, XYZ, and HML classification on the inbound inventory of both case companies. Next subsection contains the results from the Monte Carlo simulation. Lastly, I present the results from the interviews regarding the current situation at the companies.

6.1 Raw material classification

This subsection contains the raw material analysis of both companies. I have in this chapter used the ABC usage value, XYZ frequency, and HML volume analysis on the raw material usage of 2020 on both companies. I have based the analysis on the description and formulas from Chapter 4.2 on material classification.

6.1.1 Material classification on Company A

Materials				
	A	B	C	Total
X	58	77	52	187
Y	0	11	105	116
Z	1	8	180	189
Total	59	96	337	492
Percentage				
	A	B	C	Total
X	11,789 %	15,650 %	10,569 %	38,01 %
Y	0,000 %	2,236 %	21,341 %	23,58 %
Z	0,203 %	1,626 %	36,585 %	38,41 %
Total	11,99 %	19,51 %	68,50 %	100,00 %

Figure 6.1: ABC-XYZ analysis - Company A

The analysis was done on 493 materials, with the demand characteristics was divided on the 12 months of 2020. There were only one material that did not have any demand during the selected periods. The total usage value of the raw material usage for Company A in 2020 was around 41 MNOK. For Company A, only 10% of the materials accounted for 80% of total usage value. This is due to the high value of the three most valued products, which had a combined usage value percentage of around 30%. Materials in category B accounted for 15% of total usage value, at 20% of the materials, while C-class materials accounted for around 70% of all materials used, with a 5% usage value. When it comes to demand characteristics, the materials at Company A are fairly distributed over the three classes in the XYZ material analysis. Most of the Y-class and Z-class materials are in the C-category, which relieves some of the problems that can come when planning higher valued materials with irregular demand patterns.

By looking at the demand trend for the raw material with the highest usage value, it is easy to spot a trend. The demand slowly rises in the beginning of the spring and reaches

ABC data				
ABC	No. Materials	Usage value	% of total volume	% of materials
A	59	79,94 %	63,08 %	11,97 %
B	96	15,02 %	15,26 %	19,47 %
C	337	5,03 %	21,66 %	68,36 %
NO DEMAND	1	0,00 %	0,00 %	0,20 %
Total	493	100,00 %	100,00 %	100,00 %

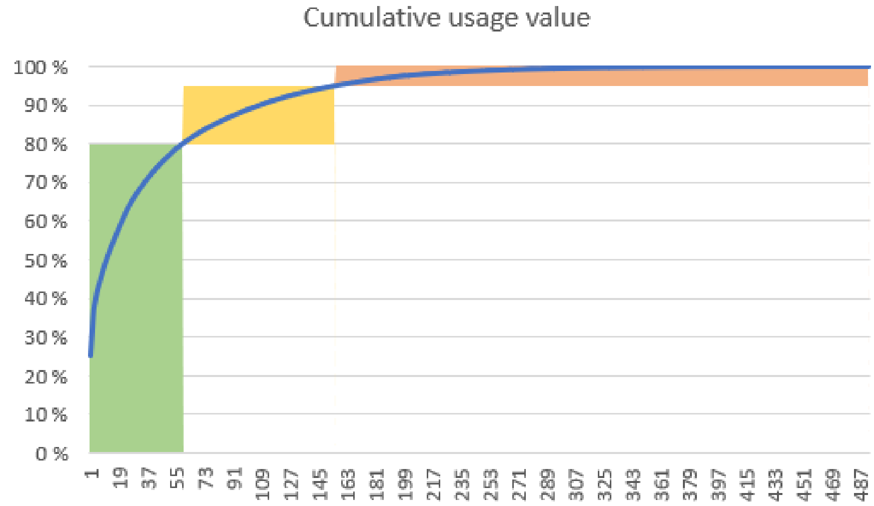

Figure 6.2: ABC data for Company A

XYZ data				
XYZ	No. Materials	Average fluct. coeff.	% of total volume	% of materials
X	187	36,47 %	94,37 %	37,93 %
Y	116	78,97 %	4,48 %	23,53 %
Z	189	230,16 %	1,15 %	38,34 %
NO DEMAND	1	0,00 %	0,00 %	0,20 %
Total	493	120,65 %	100,00 %	100,00 %

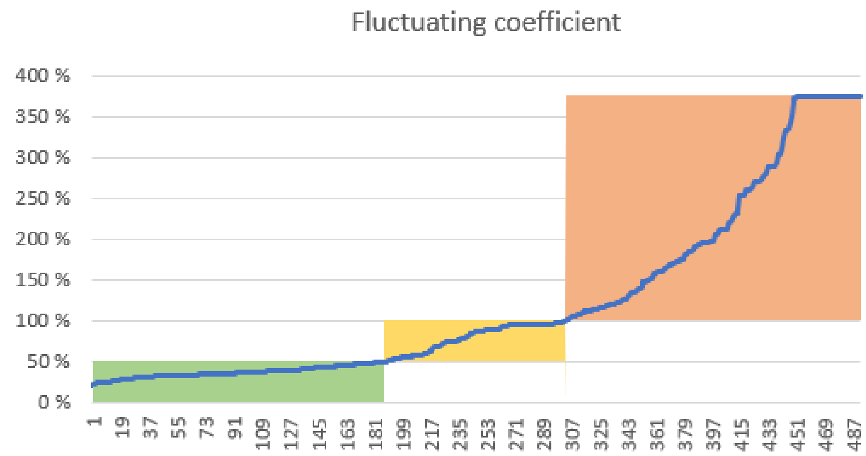

Figure 6.3: XYZ data for Company A

its peak in June. Its lowest month is during July and the company confirmed that this was due to the Norwegian join holiday, in which construction related projects takes three weeks' vacation. It also goes a bit down in April since the Easter break in 2020 occurred in that month. Several of the other materials, especially the X-class materials, share the same demand characteristics as the most valued raw material at Company A, with the rise in March, top in June, and lowest in July.

After conducting the ABC-XYZ analysis, I performed an HML analysis on the raw materials usage during 2020 on both companies. The results for the raw materials for Company A shows that around 10% of the materials accounts for 80% of the total material usage volume in 2020. The material with the highest volumes is a type of screws, with a percentage of 21,7% compared to the total volume. The screws are also placed in the A-class in the ABC analysis but have a lower usage value due to the low unit cost. Some materials in the H-class are not present in the A-class, and vice versa since the unit cost of the material will have some impact on the ABC-XYZ analysis.

HML data				
HML	No. Materials	Average volume	% of total volume	% of materials
H	47	46506,85	79,98 %	9,53 %
M	78	5259,85	15,01 %	15,82 %
L	367	372,99	5,01 %	74,44 %
NO DEMAND	1	0,00	0,00 %	0,20 %
Total	493	5543,57	100,00 %	100,00 %

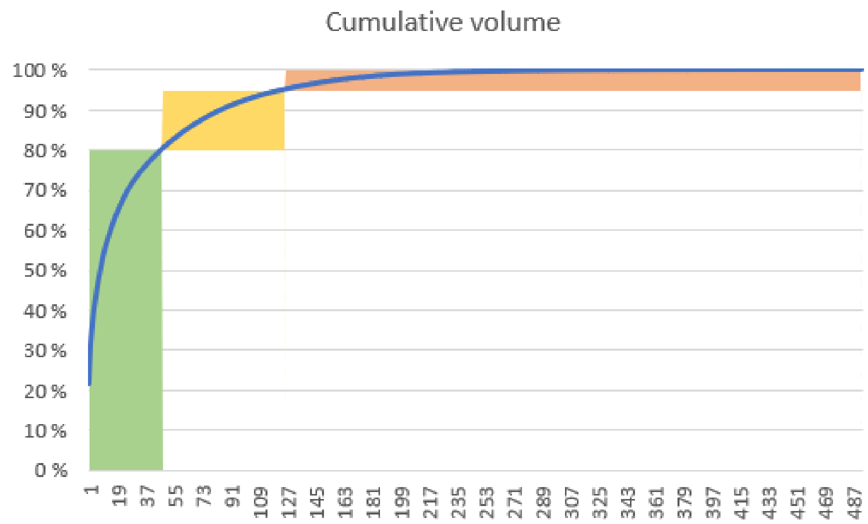

Figure 6.4: HML data for Company A

6.1.2 Material classification on Company B

The next materials classification was on the 809 raw materials at Case Company B. The ABC-XYZ analysis (Fig. 6.5) shows that out of the 809 materials available at the company, 803 of them had demand in 2020. Out of the 803 materials, 15% accounted for 80% of the total usage value, around 21% accounted for 18% of the usage value, and lastly in the C-class, around 64% of the materials had a usage value of 5% (Fig. 6.6). Company B has quite the similar distribution of the classes in the XYZ classification as well, with 15% of the 803 materials being X class items, 30% of the items are in the Y-class with fluctuating demand, and 56% are in the Z-class with irregular demand (Fig.6.7). Same

Materials				
	A	B	C	Total
X	66	34	17	117
Y	39	96	104	239
Z	19	38	390	447
Total	124	168	511	803
Percentage				
	A	B	C	Total
X	8,219 %	4,234 %	2,117 %	14,57 %
Y	4,857 %	11,955 %	12,951 %	29,76 %
Z	2,366 %	4,732 %	48,568 %	55,67 %
Total	15,44 %	20,92 %	63,64 %	100,00 %

Figure 6.5: ABC-XYZ analysis - Company B

ABC data				
ABC	No. Materials	Usage value	% of total volume	% of materials
A	124	76,94 %	69,79 %	15,33 %
B	168	18,04 %	21,95 %	20,77 %
C	511	5,03 %	8,26 %	63,16 %
NO DEMAND	6	0,00 %	0,00 %	0,74 %
Total	809	100,00 %	100,00 %	100,00 %

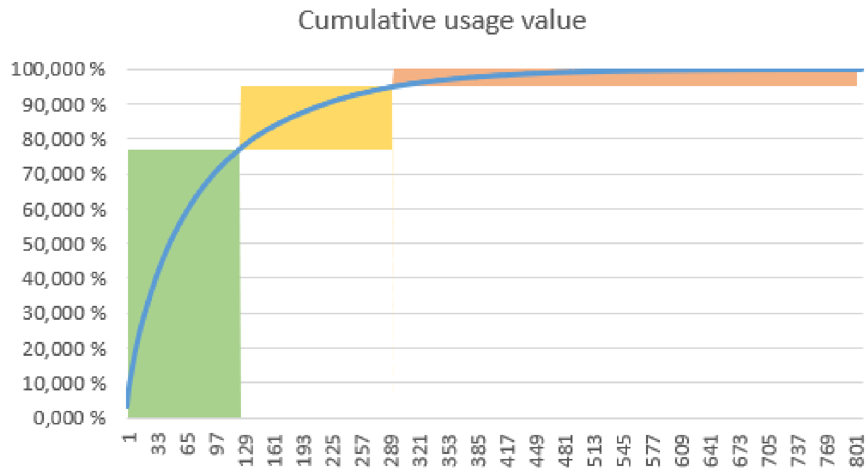

Figure 6.6: ABC data for Company B

as with Company A, most of Company B's materials are placed in the CZ class with low value and highly irregular demand.

Company B has quite similar results on the HML analysis as Company A. Around 10% of their materials accounts for 80% of the total volume. The material with the highest demand percentage is a type of mounting sleeve with 11,9%. Same as with Company A, this is a material with quite the low unit cost and is not the material with the highest usage value. It is non the less still in the A category due to the high volume. As we can see from the previous tables and figures, both companies have a lot of materials in the L class. A lot of these materials are also in the Z-class in the XYZ analysis. The materials have both

XYZ data				
XYZ	No. Materials	Average fluct. coefficient	% of total volume	% of materials
X	117	37,15 %	70,40 %	14,46 %
Y	239	73,87 %	23,43 %	29,54 %
Z	447	209,88 %	6,17 %	55,25 %
NO DEMAND	6	0,00 %	0,00 %	0,74 %
Total	809	143,16 %	100,00 %	100,00 %

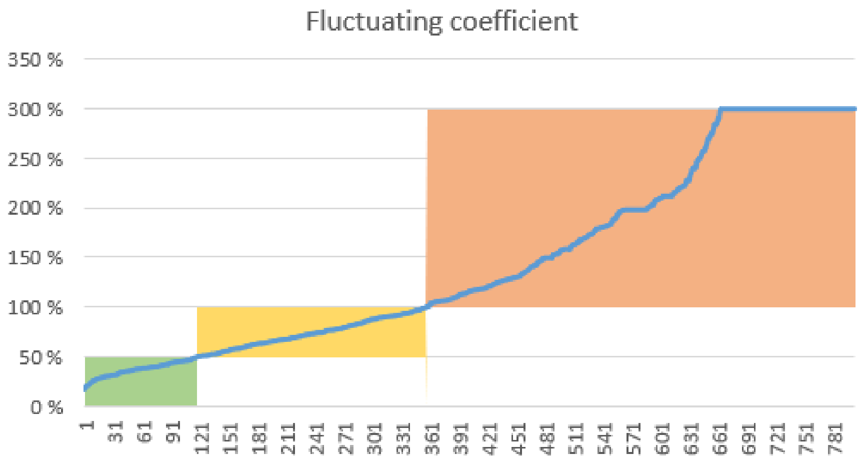

Figure 6.7: XYZ data for Company B

HML data				
HML	No. Materials	Average volume	% of total volume	% of materials
H	82	18872,78	79,97 %	10,14 %
M	121	2395,63	14,98 %	14,96 %
L	600	162,98	5,05 %	74,17 %
NO DEMAND	6	0,00	0,00 %	0,74 %
Total	809	2392,12	100,00 %	100,00 %

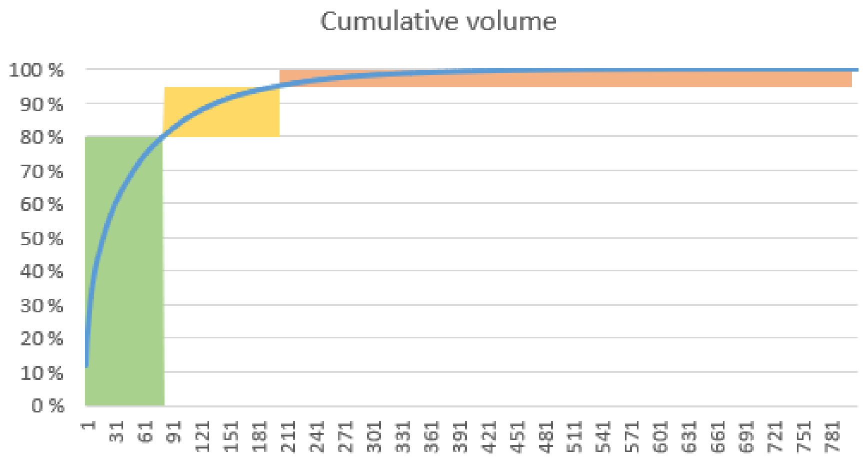

Figure 6.8: HML data for Company B

small usage volume and relatively unstable demand patterns. Figure 6.8 illustrates the results from the HML classification on Company B.

MTS

For the MTS part of Company B, which had 738 materials at stock, 688 materials had demand in 2020. The distribution of ABC-XYZ analysis can be seen in Appendix D.1. 20% of the materials were placed in the A class and accounted for 70% of the total usage value, 27% in the B class with 20% of the usage value, and 53% in the C-class with 10% of the usage value (Appendix D.2). The MTS department of Company B has quite the high demand fluctuation compared to the MTO department, with 85% of the materials being in the Z-class (Appendix D.3). 14% of the materials are in the Y class with fluctuating demand, and only 1% of the materials with demand are in the X class, notably the AX class. 40 materials did not have any demand in 2020. The HML classification scheme on the MTS section of Company B placed the materials fairly like the MTO section in each class (Appendix D.4). 19% of all the materials had high volume and accounted for 80% of total demand. 24% of total materials accounted for 15% of total demand. Lastly, in the L class, 41% of the total number of materials accounted for 5% of the volume.

6.2 Results from the Monte Carlo simulation

The results are quite similar for both companies. The results are shown as figures in the next sections, although most of the materials have been placed in Appendix E.

6.2.1 Replenishment methods for Case Company A

TFU96X61				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 66 661,42	kr 52 000,00	kr 118 661,42	6168,3
(r, Q)	kr 100 816,28	kr 54 400,00	kr 155 216,28	183,1
(T, S)	kr 82 261,86	kr 52 000,00	kr 134 261,86	842,3
(r, S)	kr 94 789,00	kr 67 333,33	kr 162 122,34	161,3
(r_k, Q)	kr 65 763,44	kr 54 000,00	kr 119 763,44	42,5
(T, S_k)	kr 41 470,72	kr 52 000,00	kr 93 470,72	0,0
(r_k, S_k)	kr 50 290,64	kr 68 133,33	kr 118 423,97	18,3

IPA_21193-17211-V				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 2 121,03	kr 1 800,00	kr 3 921,03	0,6
(r, Q)	kr 1 957,94	kr 1 660,00	kr 3 617,94	0,0
(T, S)	kr 2 613,83	kr 1 800,00	kr 4 413,83	0,0
(r, S)	kr 2 374,05	kr 1 300,00	kr 3 674,05	0,0
(r_k, Q)	kr 2 266,30	kr 1 740,00	kr 4 006,30	0,0
(T, S_k)	kr 2 236,70	kr 1 800,00	kr 4 036,70	0,0
(r_k, S_k)	kr 2 293,98	kr 1 800,00	kr 4 093,98	0,0

Figure 6.9: Comparison of replenishment method for TFU96X61 and IPA_21193-17211-V

Figure 6.9 shows the results for two materials from the raw material portfolio of Case Company A. TFU96X61 is the most valued product at the company with steady demand patterns for each month. The cheapest control policy with zero amount of stock outs is the (T, S_k) policy. Overall, the dynamic policies are shown to offer the lowest cost and fewest stock outs. At the bottom of Figure 6.9, we have IPA_21193-17211-V, with low value and irregular demand patterns. For this material, the Monte Carlo analysis shows that the static control policies of (r, Q) and (r, S) is the cheapest with zero stock outs.

The rest of the analysed replenishment methods for the different materials are shown in Appendix E.1. GIL19289 is also a high valued material with stable demand and have similar results to TFU96X61. SÆRBÆ_P161 is the only material at Company A in the CZ class. The material has the lowest cost with the static control policies (r, Q) and (r, S). However, the stock outs are lowest with the dynamic (T, S_k) dynamic policy. TFU96X96 has low value with steady demand pattern and have low stock outs for all control policies. The cheapest option is (T, S_k). The last material tested for Company A, FSK45X70PAN benefits from (T, S_k) or (r_k, S_k) both regarding stock outs and cost.

6.2.2 Replenishment methods for Case Company B

320-20280				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 47 498,18	kr 24 000,00	kr 71 498,18	172,83
(r, Q)	kr 37 281,06	kr 23 466,67	kr 60 747,73	1,43
(r, S)	kr 36 883,38	kr 23 200,00	kr 60 083,38	21,70
(T, S)	kr 37 854,05	kr 24 000,00	kr 61 854,05	53,63
(r_k, Q)	kr 31 508,29	kr 23 266,67	kr 54 774,95	0,00
(T, S_k)	kr 32 470,33	kr 24 000,00	kr 56 470,33	0,00
(r_k, S_k)	kr 27 122,42	kr 28 666,67	kr 55 789,09	0,00

200-22500				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 5 256,87	kr 5 000,00	kr 10 256,87	0,00
(r, Q)	kr 2 210,09	kr 1 420,00	kr 3 630,09	0,67
(r, S)	kr 6 041,01	kr 2 500,00	kr 8 541,01	0,00
(T, S)	kr 6 049,57	kr 5 000,00	kr 11 049,57	0,00
(r_k, Q)	kr 1 269,57	kr 953,33	kr 2 222,91	0,00
(T, S_k)	kr 3 094,05	kr 5 000,00	kr 8 094,05	0,00
(r_k, S_k)	kr 3 514,08	kr 5 000,00	kr 8 514,08	0,00

Figure 6.10: Comparison of replenishment method for 320-20280 and 360-21370

The results for Company B are quite similar to Company A. The material at the top on Figure 6.10 is the highest valued material at Company B with stable demand pattern. (r_k, Q) is the most cost beneficial with zero stock outs. Generally, the dynamic policies show better results compared to the static counterparts. For 200-22500, at the bottom in

Figure 6.10, the only control policy with stock out is (r, Q). The cheapest alternative is (r_k, Q).

Appendix E.2 shows the other four materials that were analysed during this thesis. 320-20095, with high value and stable demand, has the same results as 320-20280 in Figure 6.10. Material 200-70100 has high value and fluctuating demand patterns. The replenishment method with the lowest cost is the (T, Q). However, it has the highest number of stock outs. Unfortunately for this material, every control policy results in stock outs. But the policy with the lowest stock, the (T, S_k) out has the second to lowest total costs. Material 200-23905 is placed in the AZ class, and shows the best results with (r, Q) regarding both costs and stock out. (r_k, Q) also shows promising results for this material. The costs are similar for all control policies for 360-21370, expect for (T, Q), which has a fairly high cost compared to the other. (r, Q) is the only policy with stock out for 360-21370.

6.3 Current situation at the companies

Since it has become easier for customers to buy customised products from international suppliers, both companies feel the need to reduce the overall lead times to be able to compete in the market. Company A's goal is to reduce the shop-floor lead time, while they at the same time can offer customers more freedom to customise their products. While this paper will not look at the shopfloor and manufacturing configuration, it will look at the raw material and inventory management, which must be improved if Company A wishes for more customised products. For the company to be able to have a greater variety of products, they will need to systematise and organise the existing inventory system, so that they have enough raw materials available to account for the demand. Company B's main goal is to reduce the overall lead time from the order is accepted to final delivery to the customer occurs. Beside from just improving the manufacturing process, they could also benefit from improving their raw material handling process as well. By having greater access and control on inventory management, they could also shorten the planning and purchasing horizon which accounts for half of today's lead time. Both companies have also shown an interest in better information system that helps communication between both customers and suppliers.

6.3.1 Company A

Company A has a high emphasis on Quick responsiveness. They have therefore seen a need to upgrade their inbound inventory management by having raw materials available at the RMI, to be able to respond as quickly as possible. How the different planning and purchasing processes are done today is shown below.

Replenishment, suppliers and purchasing

How different materials are surveillance and replenished is according to the product family the material belongs in. E.g., every wood and plank material belongs in the same family and is controlled the same way. Table 6.1 shows the three different replenishment methods used by Company A. Category 1 are ordered as LFL, according to the customer demand. These materials are the glasses used in the window. The company is not able to store these materials in anticipation of customer demand, as they can vary in dimension and quality, and would therefore require a lot of space. They are also not able to produce the glasses in house. Company A will have some trouble with their delivery precision if the supplier does not deliver within the promised time horizon, as the waiting process is part of the MCT their customers have been promised. The second category contains the materials that are controlled using Kanban cards in the form of Excel sheets. They use the two-bin system by Lean manufacturing and replenishes a bin when the other is emptied. The min/max system of the two-bin replenishment system works similarly to the (r, S) replenishment policy. The last category is controlled by forecasts created in their ERP system. The forecasts are created with a short planning horizon.

Table 6.1: Replenishment method at Company A

Category	**Replenishment method**
Category 1	Customer order, LFL
Category 2	Kanban/Excel sheet
Category 3	Kanban/Forecasts

The biggest concern for Company A with purchasing is delivery delays from suppliers. The suppliers that supply the firm with plank and wood are quite trustworthy spring to autumn but can have some delays or prolonged lead times during winter. This is due to the glue that holds the material together uses more time to work due to the colder climate. This is considered when ordering during the winter season by the purchaser of wood materials at Company A. They also have troubles with other suppliers as well. One of the suppliers can be extremely unstable with their delivery precision. The supplier has a promised delivery lead time of six weeks, but it can sometimes take up to twelve weeks before the materials are received. It is also the supplier that has the most amount of defect materials upon delivery. Other suppliers have also had troubles delivering at the promised times due to problems that occurred from the United Kingdom leaving the European Union. Therefore, Company A has high safety stocks to accommodate for the delivery precision of the suppliers.

Forecasts are created by examining the demand from the previous years. The trends are relatively stable and have a small change of either rising or falling compared to the previous year(s). The planner and purchaser are also able to provide the supplier of hardwood with the forecasts, so that the suppliers can prepare themselves for the future replenishment orders. The forecasts sent are not 100% accurate but are used by the supplier to somewhat determine how much materials they can expect to deliver to Company A. Whenever new products are introduced; the company orders enough materials according to how much they think they might use it in future demand. Whenever the product enters the market, they will then closely follow the material to check for demand characteristics.

The forecasts are not all based on numbers and analysis. The planners add any information they might receive to the forecasts, which makes them more reliable. If a customer is having an upcoming project, then Company A will receive a notice in advance so that they can prepare for the upcoming customer order. Other ”regular orders” are received four weeks ahead of customer demand. This information is not a complete customer order but is included in the production and purchasing plan. The company also checks for any construction plans generated by the Norwegian government, as they will release information about upcoming projects. Some of the suppliers can also give notice to the company, if they think that there will be some delays in the future. For the suppliers who do not notify in regards of delays, whom the company have experienced problems with before, they order extra materials to be on the safe side. All this information is included together with the quantitative forecasts the company creates.

Company A's focus when it comes to raw material purchasing and inventory control is therefore not to run out of raw materials. Production must be stopped even if the tiniest material is not available at stock. This, along with the previous mentioned factors, means that the company can sometime have too much material at the warehouse. They are rarely out of stock at the RMI. Company A does also procure higher volumes on some materials if they can get a discount from the supplier. E.g., planks have to be ordered at a minimum of three thousand NOK for the price to be acceptable for the material planner.

Picking of raw materials are not registered in any system. The inventory levels are checked every fourteenth day, and current inventory levels are put in an Excel file which calculates eventual orders and quantities. The purchaser plans replenishment for the next four to five weeks ahead of time. The raw materials are stored on pallets, and multiple boxes are each day brought to the manufacturing hall early morning. Each box contains a list on where the different materials are supposed to be picked by and used for.

Other improvement areas

When it comes to digitalisation and improvements at the company, they are focusing on improving the FGW, manufacturing hall and the digital system. They do not as of now have no plans to improve the current inbound inventory management system, as they feel like it does not need improvement. Most of the projects for improvement are directed towards the manufacturing hall. The RFID chips that will be implemented are to be placed on the glasses and planks and will follow the product through the shop floor. The process will improve the delivery precision of the product, as they can scan the finished product.

As for supply chain improvements, they hope that they can implement AI and analyse and use it better than they are now. The Company hopes that they can procure smaller batches in the future, so that they can reduce their raw material inventory levels. Some of the suppliers has a focus on mass production where they manufacture huge batches and are allowing their customers to get price discounts if they orders enough.

6.3.2 Company B

Company B follows a different manufacturing strategy, as their lead time is around six weeks from a customer order enters the system to the customer specific order is shipped. They want to reduce this time and have realised that they need to plan supply orders ahead of customer orders, so that they are able to respond to customer demand.

Replenishment, suppliers and purchasing

Company B uses three replenishment strategies that are determined on both the value of the raw materials along with the delivery time from the supplier. Table 6.2 summarises the three categories. The first category contains the special raw materials that are procured according to the customer order. They are not held on stock awaiting customer orders. The last two categories contain the ”standard” raw materials. The second category contains materials that have a delivery time equal or shorter to six. They are replenished using a system similar to the (r, S) replenishment strategy by having the order equal to the difference between current inventory level and maximum inventory level. The last category contains the standard raw materials that have a delivery time longer than six weeks. They are ordered according to the forecasts that the company creates.

Table 6.2: Replenishment method at Company B

Category	**Replenishment method**
Category 1	Customer order (LFL) for special raw materials
Category 2	Reorder point for standard raw materials with delivery times up to six weeks.
Category 3	Forecasts for standard raw materials with delivery times longer than six weeks.

Company B experiences relatively few problems with their suppliers and procurement policies. Their biggest problem that has appeared in recent time is mostly due to the COVID-19 pandemic. The pandemic has caused problems with the prices, delivery precision, and material quality. Most of these problems are not entirely the suppliers' fault, as they also has their own problems in their supply chain. The suppliers receive materials with worse quality at delayed delivery times, making their processes longer and more difficult to adjust too. But in a time before COVID-19, the main problem Company B had with their suppliers was the delivery precision on one of their suppliers, who could have delivery times from everywhere between 10 weeks to up to 20 weeks. Therefore, Company B needs to plan when it comes to this supplier, as to make sure that they have enough safety stock in case of delays. How much they order from this supplier is calculated using qualitative forecasting methods, and the quantity is often drawn from thin air.

Forecasts for each month is calculated by combining the sales data for the same month the previous year and eventual trend differences. Whenever the customers' demands new products that are not in their portfolio, the company may find themselves forced to adjust, as the sales department of Company B want to allow the customer order products that are not developed yet to increase their customisation ability. They have over the last couple of years experienced a growth in the raw material turnover from 13,5MNOK to 15MNOK. Company B wishes to increase this turnover, as they feel like they could keep more at stock to accommodate for the customer specific orders. But due to limitations at the warehouse, they often find themselves forced to keep the inventory levels at where they are now.

Company B experiences some rising trends in some materials and products. The demand for wider doors has become more popular among the customer in the recent years, and

Company B have had to procure more materials needed for these types of doors. The MTS part of Company B calculates 90% of its sale on quantitative analysis. The MTO type of Company B is a mix between quantitative and qualitative methods, as some customer specific orders will include products and materials that have not been included in the quantitative analysis. The company can often order higher quantities of materials to fill out either a truck or a pallet, which reduced the order cost. They also used this method this in anticipation of future demand. This will sometime result in a lot of stock at the warehouses, since they may supply themselves with more materials than what is needed.

Company B uses a Norwegian ERP-system that has been tailored for the window industry. The modules in the ERP system contains many of the same feature as the more commercialised and standard systems but lacks some other aspects that could be useful for better planning and procurement.

Other improvement areas

The company is also improving the processes at the shop floor, warehouse, and throughout the supply chain. At the factory, they are in the process of decreasing the production lead time from weeks to days. They are today producing weekly batches of products, and are aiming to have daily batches instead, which will be based on the customer orders. One of the implementations at the factory will be POLCA cards that are a mix with physical cards and electronic cards. POLCA will mainly be to control the capacity of each operation, which will be operated by the ERP system they use.

The company has also started implementing RFID tags, but only their semi-finished and finished product. The tag is placed on the door leaf and follow each product through the manufacturing process. The goal is to also have RFID tags on the raw materials, so that they can track each material from upstream processes to they are used in production. But there are some limits, such as the smaller screws and items that will have problems with attachment. As of today, they manage to update the system when raw materials are used in production, except for paint, as it is difficult to determine the weight after use. The weight will change depending on both the product and the current humidity at the factory.

The main improvement when it comes to digitalisation for Company B is the development of the new ERP system. The goal is to have a digitalised ERP system that is linked with both machines and actors in the supply chain. Customers are to directly enter orders in the ERP system. The customers will have the ability to enter the different parameters, dimensions, and specifications. When the order is created, a signal will be sent to the factory and warehouse through digital screens. The screens will show the different operators the production plan and materials needed for the final product. The improvement will not only improve the information flow within the company, but also reduce the paper waste that the old system created, as they would use a lot of paper each week. The digital system will also tell the operators where materials are stored. The customers will be able through the ERP system to check the status of each order, such as status and eventual delays. The company would also like to link the system with their suppliers, so that information between them could improve as well.

7 Discussion

I will in this chapter answer each research question. This chapter discusses the theoretical and practical contribution of the research, by showing how inbound inventory management should be conducted based on the thesis' results. The first three subsections will be used to answer each research question respectively, while the later subsections will be used to discuss the framework for inbound inventory management in light of earlier literature, that can be implemented by SME within the MTO manufacturing sector. Lastly, I will go through the weaknesses and limitations of these master thesis. Before I answer the research questions, I will look at the importance of inventory management by comparing the literature with the situation at the case companies, to highlight where efficient inbound inventory management can be used to improve the performance of the company.

As mentioned by Chan et al. (2017), poor inventory management is one of the reasons why SMEs have a hard time dominating the market, as they can sometimes lack the resources or knowledge compared to the bigger competitors. The authors further adds that many SMEs still operate their day-to-day business by using digital tools that are simple and affordable, yet not necessarily appropriate. Both case companies use Microsoft Excel as the main system to determine forecasts and material plans. Further, Akindipe et al. (2014) adds that many SMEs keep too many materials at their warehouse, which results in higher inventory costs and a poor inventory stock turnover rate. Company A's inventory management policy shows that they keep much stock at the warehouse to ensure that there is enough in case of late deliveries or uncertainty in demand. They also order bigger batches to get discounts. Company B also follows this policy for certain materials. However, this is not recommended by QRM. As shown by the Response Time Spiral of Purchasing and by Won and Olafsson* (2005) in Chapter 4.5, buying larger batches will create troubles for both the supplier and for the companies. The companies will have higher inventory levels and inventory holding costs, while the supplier will suffer from the bullwhip effect that comes from the huge orders the companies' places.

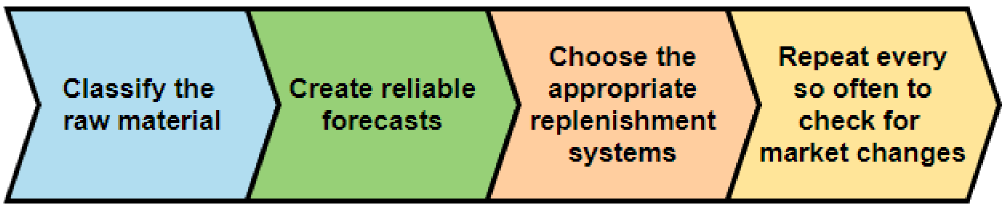

Figure 7.1: Framework for inbound inventory management

Source: Plinere and Borisov (2015)

To achieve better inventory management, it is according to Zhang et al. (2019) important to implement scientific methods in order to control the inventory better. The different methods will range in advancement, so it is important that SMEs choose the methods that are aligned with their performance goals and production strategy. Using input data such as lead time fluctuations, demand changes, and supply chain information, will increase the effectiveness and performance of the scientific methods as well. All of these factors are important to implement together with the framework for inventory management presented by Plinere and Borisov (2015). Figure 7.1 shows the different processes for effective inventory management.

7.1 Material classification for MTO companies

The first subsection will answer the first research question, *What are the appropriate classification analyses for inbound inventory management within the MTO manufacturing sector?* Material classification is an important step in inventory management, as it will highlight which materials needs more attention over other (Zhang et al. 2019). Material classification will be used to answer the three questions presented by Ma et al. (2019); i) how much attention the inventory should have, ii) when should an order be placed and iii) how big should the order be. The different material classification schemes will highlight the importance of the materials differently, and selecting the right ones is crucial. The logical way to material classification would be to combine multiple schemes, as it will include different aspects from multiple classification, instead of relying on only one, as suggested by De Felice et al. (2014) and Ketkar and O. S. Vaidya (2014). As mentioned in the literature review, De Felice et al. (2014) adds that only using one scheme do not highlight all the problems that are associated with the materials, as a valuable material might have troubles, for instance, with long lead times.

Zhang et al. (2019) presented the three questions on how to select the sufficient material classification schemes; i) how to select the appropriate indicators, ii) which schemes are most suitable and iii) how should each be controlled? One of the main indicators that determine the MTO manufacturing sector is unstable demand patterns on the customised orders (Mudgal et al. 2020). The variation that comes from the finished product affects the raw material inventory as well, since factors like dimension, colours, and functionality may vary. An example from the case study is the dimension on the windows Company A produces. The company has a type of plank that is used in almost all the products but will vary in length according to the customisation. The MTS manufacturing sector has the advantage of looking at the finished product, and according to previous demand can then calculate the need for the materials based to that. The MTO manufacturing sector, however, will benefit more from looking at past demand on the raw materials one by one, instead of looking at past demand for the final product and determining the raw material demand from the finished product.

So which factors are important to include in raw material classification for the MTO manufacturing sector? As mentioned, there will be materials that are used more frequently than others. The less used ones can come from irregularity in demand. It is easy to keep a lot of materials on hand for these products, as to ensure there is enough inventory in case of demand. This will in turn increase the inventory holding cost, as materials will spend a long time at the warehouse. Other factors that can contribute to overstocking is ordering to much in general, even if the demand is stable. How much certain materials is used will also affect the volume and usage value of the material. The next factor, which is long lead times, is not necessarily a problem for the MTO manufacturing sector. MTS, ATO and the ETO manufacturing sectors also suffers from long delivery lead times from the suppliers. Companies from The West often source their materials from Far Eastern suppliers. While this strategy may lower the cost of the materials, it will create longer lead times, which is an important factor to include in the material classification.

7.1.1 Comparing the material classification schemes

Before choosing which material classification scheme would be the best to include in a matrix or methodology, I will quickly go through the studied classification scheme and describe the value and importance each one. A brief overview of the classification schemes are shown below.

– **ABC Usage value:** The ABC usage value classification divides the materials according to their respective usage value, based on the Pareto 20/80 principle, where around 20% of the materials will account for 80% of the total value (Zhang et al. 2019). It will help enterprises differentiate between valuable and less valuable materials and is one of the most used material classification schemes. A-class materials should have rapid and detailed planning, while C-class materials will benefit from a digital system with some safety stock.

– **XYZ Demand frequency:** The XYZ frequency analysis divides the materials according to variance in the demand pattern (Calisir et al. 2017). X-class materials have steady demand patterns over the periods, while the Z-class materials will have irregularity in the demand pattern. The XYZ scheme highlights which materials has the most stable and unstable demand pattern. X-materials can be procured continuously, while Z-class materials require some safety stocks to accommodate the highly irregular demand patterns.

– **SDE Lead time variation:** This material classification sorts the materials according to the how long it takes before the materials are delivered to the warehouse from the supplier (Ketkar and O. S. Vaidaya 2014). The materials in the S class have the longest lead time, and is more difficult to plan and forecast, as lead time is an important factor in forecasting (Chopra 2019). It can also be used by the companies to evaluate the suppliers on their delivery lead times.

– **FSN Inventory turnover rate:** The materials in this classification will be divided according to their replenishment rate (Devarajan and Jayamohan 2016). The classes are based on the stock turnover rate. Materials that are placed in the ”N” category spends a longer time at the warehouse, which might be due to safety stocks or unstable demand patterns. N class materials will either be there a long time due to unstable demand patterns or overstocking of goods, and if the latter i the case, it can be a signal to the planner that they overstock.

– **VED Importance:** This classification scheme divides the materials based on their importance (Kumar and Chakravarty 2015). It is heavily based on qualitative and subjective feelings. The VED classification scheme is often used in pharmaceutical enterprises where they divided the drugs and medicine according to their importance.

– **HML Volume:** This classification divides the materials according to their volume, based on the Pareto 20/80 principle, where around 20% of the materials will account for 80% of the total volume (Ketkar and O. S. Vaidaya 2014).

– **Sustainability:** The aim of this classification scheme is to highlight the sustainability of each material (Bahrudin et al. 2016). Renewable materials are made from natural organic resources, while non-renewable are not.

The ABC-XYZ analysis alone will point out the difference in materials based on their usage value and demand variation (Calisir et al. 2017). This is useful information that MTO companies can benefit from, as they have many materials with highly irregular demand patterns and will also inform the planner which material is the most valuable to the company. This is also shown in the ABC-XYZ analysis on both companies from Chapter 6.1. However, as De Felice et al. (2014) pointed out, using only two classification schemes leaves out other factors that are crucial to include in inbound inventory management. From the ABC-XYZ analysis we can also see that a lot of materials (37 % for Company A and 48% for Company B) are placed in the CZ category. Many of these materials will have other internal factors that will further divide them on how important it is to categorise them, such as lead time variation between materials. Delivery lead times from suppliers can be long if they are sourced from foreign suppliers. This must be included in replenishment, as it will heavily affect the results.

Company B have this year removed around 300 materials from the raw material portfolio, due to no demand on the materials. They think that the ABC-XYZ will also help them spot other materials that aren't necessary to keep at stock. Company B were surprised by the number of materials which would be placed in the CZ category, and wants to continue removing some materials which will just take up space at the warehouse. By removing some of the materials from the portfolio, they can instead store more of the other materials. Company B wanted to increase the quantity of some materials, items, and products, but could not do it due to the limitations at the warehouse. The ABC-XYZ matrix alone can be used to determine the value of the material but will leave out other factors from a replenishment perspective.

The SDE classification scheme will suit both companies, along with other companies in the MTO manufacturing sector, as delivery lead times from suppliers is something both companies struggle with. From the interviews and workshops, it became clear that some of their suppliers have both long lead times and variability in the delivery lead times, which means that delays can often happen. Company B even experiences that materials will sometimes come before the promised lead time, which in it itself is better than late deliveries, but at the expense of higher inventory costs. The SDE prioritises the materials from longest lead times to shortest and will affect the final material classification so that materials with the longest lead times will be require better replenishment policies than materials with the shorter lead times.

One might argue that there is no need to include the HML classification if one already uses the ABC usage value classification scheme. But as we can see from the material analysis in Chapter 6.1, each analysis gives different results. Some of the materials in the A class have a high usage value due to its volume, but some are in the A class due to the higher unit cost. Many of these items can therefore have a medium volume and be put in the M class in the HML category. Further, the HML class can alone be used in the QRM volume/sourcing strategy presented by Suri (2010). By looking at which materials according to their volume, companies that are implementing QRM can use this classification scheme to guide them toward better supplier selection according to their volume. The

XYZ frequency analysis can also point out to the companies in which H-class materials have stable demand pattern, so that it becomes easier to differentiate between materials that can be single sourced and materials that need the TBDS. This will help the companies reduce their costs as there are for some materials no need to have multiple suppliers. Material with high volume and stable demand can be outsourced from suppliers located far away from the company as it will cost efficient to do so. Further, it is easier to maintain good relations with a faraway supplier if you source in high volumes. It is however difficult to maintain a good relationship with suppliers located far away who you do not source much from. Correct use of this method will reduce the overall MCT of the company, and they can achieve better supplier selection and delivery lead times. Further, if companies use this method and achieves shorter delivery lead times, more materials will move from the ”S” class in the SDE classification scheme.

The FSN classification can be useful regarding inventory costs. The materials in the N class can spend months at the warehouse without being used (Devarajan and Jayamohan 2016). The two factors of irregularity in demand or overstocking heavily contribute to if the material is in the N class. The XYZ scheme do point out which materials have unstable demand patterns, but it does not operate on how long it might spend at the warehouse, since some materials may have short lead times. This makes replenishment easy, even if the demand is unstable. Also, the classification may point out if overstocking happens. It is then a useful classification scheme to include in inbound inventory management.

Sustainability and environmental performances have become important for many companies over the years, and both of the companies have sustainability as an improvement area. The sustainability classification matrix handles the classification of each material according to their sustainability performance, and is an indicator on how sustainable the raw materials at the companies are (Bahrudin et al. 2016). The sustainability scheme could be implemented in an eventual framework that determines replenishment, to highlight the importance of it. However, the sustainability scheme does not classify the materials on factors that will influence delivery times, innovation, responsiveness, etc. It will only affect the sustainability goals of the companies. The materials do not need more or less advanced planning based on how sustainable they are. This classification scheme can instead be used separately by companies to improve their sustainability goals by looking at how high percentage renewable materials they have. To conclude on this classification, it is a material classification scheme that will not affect the inbound inventory management but will improve the sustainable goals of the companies.

The VED classification scheme is as explained by Kumar and Chakravarty (2015) often used in pharmaceutical enterprises. It does point out the importance of the material but takes a long time to determine. For MTO companies that operate in the construction business, such as the case companies, this classification is rather useless, as the raw materials do not necessarily have the same ”importance” on the final product as medicine or drugs have on patients. The ABC analysis alone will point out the more valued products, which is more suited for this type of business.

7.1.2 The Simple Additive Weighting matrix for the MTO manufacturing sector

Since each material classification will have their advantages and disadvantages (Dhoka and Choudary 2013), MTO companies can use the SAW method to include more classification schemes in their planning (Ketkar and O. S. Vaidya 2014). Some of the advantages with the SAW method is that it includes company's vision and future goal, like for example low cost, innovate products, and so on. The chosen material classification will according to their goals influence the final matrix and different classification will therefore have a higher impact compared to others.

Based on the case findings and the companies' goals, I have created Table 7.1 and Table 7.2 that they can use to classify their raw materials effectively. Further, it also includes the goals the companies try to strive towards. This table can also be applied to other SMEs within the MTO manufacturing sector. The goals will differ from company to company, as they have different priorities.

Table 7.1: Classification weights for Company A

Goals	**Weight**	**ABC**	**XYZ**	**HML**	**SDE**	**FSN**
Innovation	10%	2	1	2	4	1
Quicker responsiveness	40%	3	3	2	4	1
Low costs	20%	3	1	4	2	3
Delivery precision	30%	4	2	1	4	1
Classification weights (cw_j)		3,2	2,1	2,1	3,6	1,4

Table 7.2: Classification weights for Company B

Goals	**Weight**	**ABC**	**XYZ**	**HML**	**SDE**	**FSN**
Innovation	20%	2	1	2	4	1
Quicker responsiveness	30%	3	3	2	4	1
Low costs	20%	3	1	4	2	3
Delivery precision	30%	4	2	1	4	1
Classification weights (cw_j)		3,1	1,9	2,1	3,6	1,4

SMEs within the MTO manufacturing can use different classification combinations and tools for different purposes. The SAW methodology, that utilises the ABC, XYZ, FSN, HML, SDE classification schemes, will be used to select appropriate forecasts and replenishment policies. This strengthens and guides the next two steps in the inbound inventory management framework. The ABC-XYZ analysis alone can be used to look at the importance of the material and eventually remove the materials with the highest fluctuating coefficient and lowest usage value. The HML classification alone can be used in the QRM supplier selection principle. The SAW classification can also help the companies see which materials are the most renewable and environmentally friendly and can based on this classification remove the least environmental friendly materials. The five groups in the SAW methodology, along with the classification numbers cn_i for both companies are shown in Table 7.3.

Table 7.3: The groups in the SAW classification for both companies

Group	Classification number cn_i for Company A	Classification number cn_i for Company B
Group 5	12,4 - 17,4	12,1 - 16,9
Group 4	17,5 - 22,3	17,0 - 21,8
Group 3	22,4 - 27,3	21,9 - 26,6
Group 2	27,4 - 32,2	26,7 - 31,5
Group 1	32,3 - 37,2	31,6 - 36,3

Many of the materials that are placed in group 5 will have low usage value, irregular demand patterns, short lead times from the supplier, low item volume, and long inventory times. These materials will therefore as mentioned by Snapp (2014) not need much time on planning, as safety stocks can be used to control them. It takes short times to acquire the materials, they have low values, the demand is difficult to calculate, and are already spending a long time at the warehouse.

On the other hand, we have the materials placed in group 1, whom most will have high usage value for the company, high item volume, steady demand patterns, long lead times from the suppliers, and will spend a relatively short time at the warehouse. They need more rapid replenishment strategies, as they will be used more steadily in many finished products and need longer planning horizons due to the long lead times from the supplier. The need for more careful planning is essential due to the mentioned factors.

The SAW methodology along with the proposed classification schemes can arguably be the ideal material classification tool to use for MTO companies. Each classification scheme will point out many of the challenges that both the case companies and other Norwegian MTO companies experiences, such as long lead times, unstable demand pattern, valuable items, and inventory turnover rate. The methodology will also be directly linked with the goals the different companies have and make it more personalised. How each group in the SAW methodology will be planned regarding forecasts and replenishment methods, will be answered in the next subsection.

7.2 Material planning and procurement

This subsection will tackle the second research question; *What replenishment methods should be applied for efficient inbound inventory management?* To answer this question, I will look at the recommendations from the literature regarding forecasting and replenishment policies, along with the results from the analysis on the two case companies presented in Chapter 6.2, and the answer from the previous research question, as it will impact how replenishment should be handled.

7.2.1 Level of forecasting

The five categories from the SAW classification do not necessarily need five different replenishment policies. The SAW methodology illustrates which materials need the most attention in regard to planning. This also applies to forecasts, which are an important step when order materials (Chopra 2019). The different groups in the SAW methodology will need forecasting methods with different degree of complexity.

As for the companies, they use a mix between both qualitative and quantitative methods when they create forecasts. Both companies follow a time-series approach for most of the materials by looking at the usage for the previous years, while at the same time seeing if there are any noticeable trends that may have happened the last years. There are some materials which might need more careful forecasting, often where they must estimate future demand for the materials with unstable demand. This also applies to materials with variances in delivery lead time. The lot sizes of some of the materials can be difficult to determine due to the very unstable supply lead time. Inside information they get from both suppliers and customers are also taken into account when they conduct forecasts. Even though information from suppliers happens rarely compared to customers, it is seen as useful insight as they need to adjust the order quantity accordingly.

Qualitative, time-series, causal and simulation takes different amounts of time to perform and will all result in different outcomes. Qualitative and causal methods require more information and knowledge from different departments or actors in the supply chain and can therefore be time consuming to apply for all materials. Time-series is quicker, as the planner will most likely have the needed knowledge on how to conduct the calculation. But it most likely excludes factors that comes from causal and qualitative forecasts. Combinations or a simulation can therefore be useful, as you will get input from multiple factors.

7.2.2 Replenishment policies

Since SMEs will struggle with advanced calculations, it is more logical to use simplified scientific methods in the beginning, to soothe the transaction period towards more advanced calculations that comes from more advanced computers. However, as Suri (2010) points out, there is no need for any advanced calculation either, as long as replenishment is conducted in one system.

As the simulation shows, the (T, Q) strategy has both high costs as well as high stock outs of the materials. As the policy follows both a fixed quantity and timing, it can be difficult to implement such a system if demand is stochastic. When demand falls outside of seasonal sales, materials will pile up at the warehouse, resulting in higher inventory costs. During seasonal sales, the policy might not be able to catch up to the demand, resulting in stock outs and lost sale. This inventory control policy is mostly suited if the demand is deterministic with stable pattern from period to period, which is highly unlikely to occur for the MTO manufacturing sector.

The LFL and POQ methods are recommended by Vihijärvi (2019) to use for higher valued products, as they will most often account for a huge percentage of the inventory holding cost. However, it will mean that an increase in order costs will occur, as the LFL policy recommends ordering each period. The LFL policy can create several challenges for MTO manufacturing companies. Firstly, forecasts need to either be accurate, or demand must be known for the policy to have cost-reducing effect for the enterprise. Secondly, many companies have suppliers with both long and unstable demand pattern, which further creates several challenges, such as late deliveries and even more difficult to plan orders due to longer lead times. The LFL method is fairly similar to the JIT principle and is more suited to companies that have the supplier located closely with short lead times or when demand is known within a long-time horizon.

Both companies struggle with delayed lead times from the supplier. Some suppliers can have lead times that vary from just a few weeks to almost half a year. Naturally, after the pandemic started, the supply delays got even worse. This variation in delivery patterns can be solved by using the static calculations. The static calculations, as shown by Ivanov, Tsipoulanidis et al. (2019b), has safety stocks that include both variance in both demand and lead times patterns. By using the safety stock for materials with uncertain lead times, they can ensure that there is enough safety stock available to accommodate for the demand. It is important that the standard deviation of lead time σ_L is calculated, so that the correct safety stock formula can be used.

From the ABC-XYZ analysis on both companies, we can see that both companies have a lot of materials in the CZ class with low usage value and highly irregular demand patterns. If we look closer on the demand for 2020, we can see that both have some materials who have demand in only one of the 12 months. There are even materials with that have demand close to zero each month, except for one month where the demand for the material can rise to for example twelve. Both forecasting and replenishing these materials will be quite difficult, because of sudden spikes in customer demand. This is something that many other MTO companies struggle with (Mudgal et al. 2020). If the materials also have long delivery lead times, it will become even more difficult to select the appropriate inventory policies. One of the many limitations with the Monte Carlo simulation on the raw materials is the fact that I only conducted it on six materials for each company. The reason for this was mostly due to time limitations. The results on the six materials for each case company will not represent the real situation, as both companies have hundreds of materials in their raw material portfolio. However, some of the suggestions, such as using the (r, Q) static control policy for the low value materials in group 4 and 5 on the SAW matrix will be most beneficial. One of the reasons for this will therefore be linked to the unstable demand that many materials in the CZ class has. An example on this scenario is shown in Figure 7.2, which illustrates the demand pattern of a raw material from Company B. The demand is not normally distributed, but more of a Poisson distribution. The static policies will therefore be more suitable, as it will keep extra safety stock available in case of the sudden demand spike that can come from these materials.

As Babai and Dallery (2009) mentioned earlier, standard static policies such as (r, Q) or (T, S) is more suited when forecasts are not reliable. This is further recommended by Snapp (2014), who states that standard ROP is more suitable for materials with unstable demand patterns. We can also see from Hautaniemi and Pirttilä (1999), who uses it for the less valuable materials as well. Since there will be multiple material classification that look at both unstable demand patterns and lower values, it would be best to use the simpler static calculations. The materials that are placed in Group 4 and 5 in the SAW

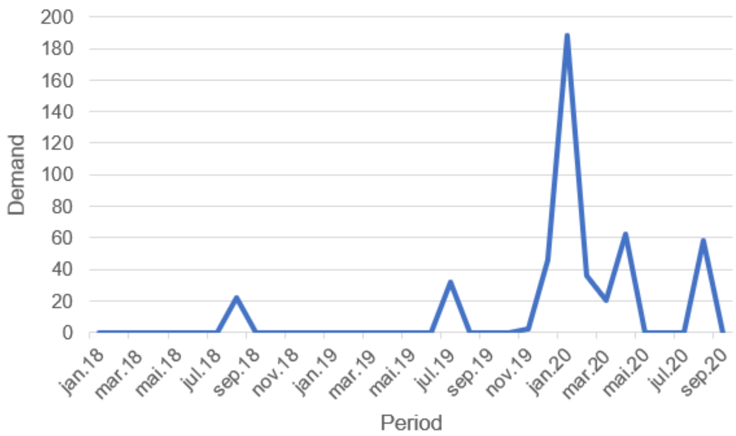

Figure 7.2: Example on raw material with irregular demand

method will benefit more from the simpler calculations that includes a safety stock.

The dynamic calculations as explained by Babai and Dallery (2009) is more cost-beneficial to apply when forecasts are reliable. The dynamic policies as shown in the simulation is able to adapt to future demand through forecasts. Both the ROP r_k and order-up-to-level S_k change for each period. They are therefore able to change to along the demand. However, there is a need for reliable forecasts with a low forecast error, as a mistake in the forecast will affect the replenishment strategy negatively. Reliable forecasts take time and a lot of planning to get right. But since the materials placed in group 1 and 2 require more time spent on planning compared to the other groups, then the dynamic policies might be the best option for these materials. Some of them do either have long lead times or high value or volume and are therefore more important to the company. The dynamic policies can aid in reducing inventory holding costs while minimising stock-out risk. The only factor that isn't included in the dynamic calculation is variation in lead times, as it instead calculates the safety quantity SQ_k according to forecast error. The solution to this can either be to improve the relationship with the supplier, and work with them to improve their lead times, or to order more than the calculated quantity requested.

7.2.3 Forecasts and replenishment for each group in the SAW matrix

Table 7.4 is a brief explanation on the the level of material planning, how much forecasting should be conducted, and which inventory control policies should be for the different groups in the SAW methodology.

The first group, group 1, contains the most important materials to control for SMEs within the MTO manufacturing sector. Most of these materials have as previously mentioned, the most stable demand patterns, highest volume and usage value, longest lead times, and spends the shortest amount of time at the warehouse. There should be extremely high degree of forecasting and planning for these raw materials. The forecasts should be a mix between qualitative forecasts, in the form of information from the suppliers or customers, and quantitative based on previous demand history. The goal of forecasting for these materials is to reduce the forecast error as much as possible, so to ensure few uncertainties. It is recommended to use the dynamic (r_k, Q) or (T, S_k) policies for these materials, as

Table 7.4: Replenishment and forecast strategy

Group	Forecast and planning	Replenishment
Group 5	Extremely low degree of forecasting and planning. Replenishment should be conducted by a digital system.	The static (r, Q) or (r, S) policy are the best options to implement. High safety stocks.
Group 4	Low degree of forecasting and time spent on planning. Replenishment should be conducted by a digital system.	The static (r, Q) or (r, S) policy are the best options to implement. Medium-high safety stocks.
Group 3	Medium degree of forecasting and material planning. Raw materials in this group should have a mix between automatic digital and manual replenishment strategies.	The static (r, Q) or (r, S) policy, or the dynamic (r_k, Q) policy, are the best options to implement. There should be low safety stock to accommodate demand or lead time fluctuations.
Group 2	High degree of forecasting and time spent and material planning. Mix between both qualitative and quantitative input. Manual control	It is recommended to use the dynamic (r_k, Q) or (T, S_k) strategy for these materials. Some safety quantity to reduce inventory levels.
Group 1	Extremely high degree of forecasting and material planning. Mix between both qualitative and quantitative input. Manual control.	It is recommended to use the dynamic (r_k, Q) or (T, S_k) strategy for these materials. Low safety quantity to reduce the inventory levels.

either the ROP or order-up-to-level will change according to forecasts. This method allows for more controlled and stable replenishment, since it will take trends, seasonality, and levels into account. The recommended policies will most likely recommend rapid replenishment strategies with many orders that contains low quantities. The safety quantity SQ_k should be as low as possible.

For the second group, materials should be controlled with a high degree of forecasting and planning. Though not as important as the previous group, they hold high value and importance to the company. As with the previous group, the forecasts should have a mix of both qualitative and quantitative methods, thou not as much quantitative information is required, as it can take some time to acquire all of the necessary information. The goal of the forecast error is to reduce it, but not as much as possible, as it will allow the safety quantity to become a bit higher to accommodate minor fluctuations in demand or lead time. These materials will also benefit from the dynamic (r_k, Q) or (T, S_k) policies, as they will change according to future demand patterns.

The next group should have medium degree of forecasting and material planning. Group three is the bridge between the other groups, as this one will be a mix between the more important (one and two) and less important (four or five). Raw materials in this group should have a mix between an automatic digital system that controls materials and manual replenishment. The ”easier” materials with stable demand patterns can be controlled digitally, while the materials with unstable demand patterns can be controlled manually, to achieve better replenishment. Information regarding future demand should be included when conducting replenishment, as these materials can be critical for the company. The static (r, Q) or (r, S) policy or the dynamic (r_k, Q) policy, are the best options to implement for this group. There should be low safety stock to accommodate irregularity in demand or lead times.

The raw materials in group four should have low degree of forecasting and planning, as their importance is lower compared to the previous three groups. From this group and on, materials should be mostly supervised by a digital system that handles both the inventory levels and replenishment, to reduce the time spent on planning. The only acceptable input or changes to the replenishment plan should come from qualitative forecast in the form of information received form the customer or supplier that will heavily impact the materials. This can for example be the need for more materials compared to what they have on stock in the future. The replenishment should be conducted by the static (r, Q) or (r, S) policies, as they automatically will control and replenish the materials. Any policy with the fixed order interval T will result in unnecessary replenishment and higher inventory holding costs. It is recommended to have safety stocks to accommodate both demand or lead time variances.

For group five, I recommend extremely low degree of forecasting and planning for the selected raw materials This is due to the lower values of the materials that most likely will have unstable demand patterns, short lead times and will spend a long time in the warehouse. Planners should not spend too much time on these materials and should instead let a digital system control and replenish. There should be little input by forecasts, as with group four, and the system are designed to operate without the planner. The inventory policies for these materials should either be the static (r, Q) or (r, S) policy. There should be high safety stocks to accommodate demand or lead time variances.

7.3 Digitally enhanced QRM

This subsection will answer the last of my research question, *How can the proposed inventory management method be aligned with digitally enhanced QRM?* It will be answered by looking at recommendations from the literature review and the results from the interviews regarding digitally enhanced QRM implementations at the companies.

7.3.1 Quick Response Manufacturing implementations

Suri (2010) focuses heavily on the reduction of lead times and MCT, done by the four pillars of QRM. Many of the implementation is rooted at the factory shop floor, and the ability to change the production process so that enterprises can respond to variability in demand. There is however few direct suggestions for inbound inventory management improvement on how to tackle replenishment. However, as mentioned, Suri (2010) says that there is no need for advanced calculations when planning the raw material inventory.

The new MRP calculations

Krishnamurthy and Suri (2009) suggests that MTO companies implements POLCA cards to the factory shop floor as the main control system for production. With the implementation of POLCA cards at the factory shop floor, companies will be able to use less time planning production on the so called HL MRP system, and can use the MRP application in the ERP system to focus on material classification, forecasting and replenishment. Figure 7.3 illustrates how HL MRP and POLCA systems controls production and planning.

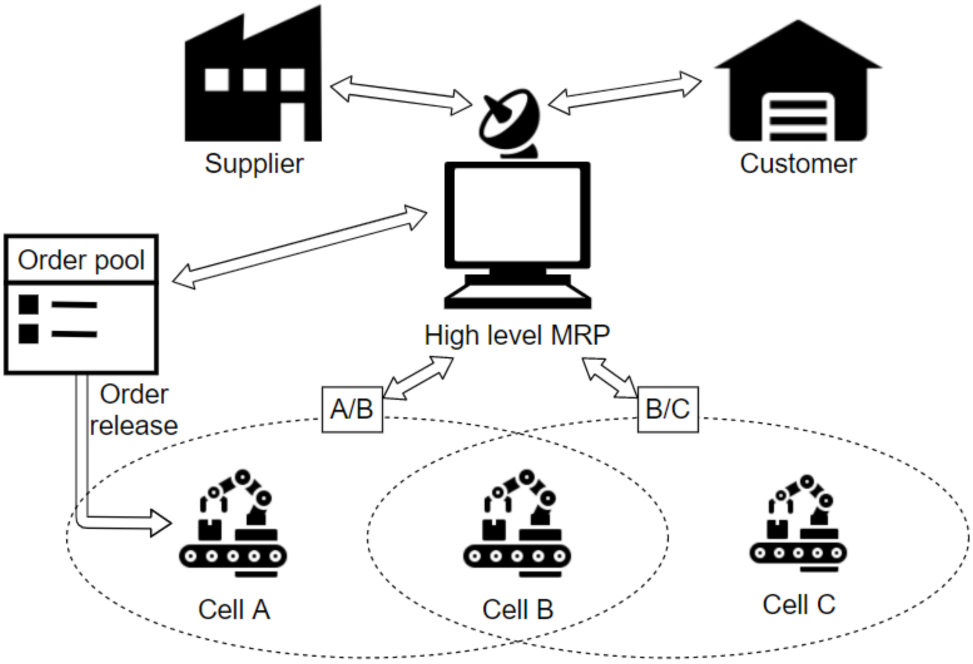

Figure 7.3: HL MRP and POLCA

Since the HL MRP and POLCA combination is a mix between push and pull production, it eases certain problems that can come from the deterministic nature of MRP systems Segerstedt (2006). As Powell Robinson Jr et al. (2008) adds, the MPS calculation is difficult for the high-variety sector that MTO companies operate from. The standard way to use MRP for raw material calculation is to look at the dependent demand for the raw materials, according to the forecasts which is based on the independent demand of the customer demand. The CODP separates the purchasing and production process for MTO companies (Stevenson* et al. 2005). Planning raw material and finished products should therefore be treated differently. Instead of using the Bill of Material application on the MRP system to determine the usage of raw materials according to future demand on the finished products, the HL MRP system can calculate future demand for each raw material based on previous usage of the raw materials.

Some MRP systems also has the ability to conduct material classifications and forecasts. The literature provided by Hoppe (2006) is for inventory management through SAP, which is a well known ERP system. Further, Calisir et al. (2017) entered the necessary inputs from the ABC-XYZ analysis they did in the MRP system, and based on the class each material were placed in, got different replenishment methodologies and safety stocks. Hautaniemi and Pirttilä (1999) also used MRP for certain raw materials, with overplanning for the materials that were of importance with difficult lead times and unstable demand. The dynamic policies do require more planning with the MRP system, but the static policies in group 4 and 5 are easy for the MRP to calculate. The calculations that determines the material classification and replenishment strategies is easy enough to implement in an MRP system, as long as the correct input data, such as lead time, demand, and forecasts are correct. Materials in group 4 and 5 can therefore calculate and control itself, as long as the data is correct, and can notify the planner whenever replenishment has to occur. The dynamic policies require some more attention to detail, and the planner has to spend more time on the MRP system calculating replenishment.

For the Case Company A, they would have to code these functions themselves, since they have created their own ERP system. From the interviews and conversations with the developer, it seemed like this was something he was able to do. Company B however may struggle with this, since their ERP system is first of all not that advanced, and not made by them. They would either have to develop these applications together with the ERP supplier, or find someone else.

Supply chain improvements

One of the ways to increase inbound inventory management through QRM and supply chain improvement is to order smaller batches more frequently. Both of the case companies follows the ”order larger batches to get discount” policy, which is normal for many other enterprises. While this may seem cost beneficial for the company, it creates a number of problems for the companies, as explained by the Response Time Spiral of Purchasing (Suri 2010). Firstly, the delivery lead times will be longer, as the suppliers have to use more time to put together an order. The longer times can also result in unstable lead times. As Suri (2010) points out, the only time it is acceptable to use suppliers located far away with long delivery lead times is if the demand is steady with high demand volume, which can be found out by using the HML and XYZ classification schemes. Secondly will be cost reduction, for both the supplier and companies. The case companies should invite some of their most important suppliers to a meeting to discuss the ordering policies with QRM. The goal of the meeting will be to encourage the suppliers to improve their delivery lead times by encouraging their customers to reduce their batch size. The suppliers should not encourage their customers to get discounts of they buy large batches.

Confronting the suppliers may also increase the collaboration with them, as companies are together with the suppliers increase each others performances. This mutual trust between the actors can improve the information sharing, which in turn will improve the planning to both parties. This also accounts to the company’s customers. Improvements in the supply chain will allow them to plan the operational strategy better, as it allows them to plan tomorrow’s production better through more efficient flow and highlighting eventual bottlenecks. This can be done by for example sharing real-time information about where the supplies are geographically and how long it will take until they arrive at the manufacturing sites or the customers. In the long run, improving the supply lead time of the suppliers will reduce the overall MCT of the enterprise and guide it towards a company that embraces QRM.

7.3.2 Industry 4.0 and smart manufacturing technologies

As both Chan et al. (2017) points out, SMEs will struggle more with implementing advanced methods and Industry 4.0 principles to their enterprise. Most of this is due to the lack of human resources and costs on more advanced principles. However, there are possibilities of implementing some principles, as explained by Tortorella et al. (2019). By starting slowly with the more advanced methodologies compared to what many SMEs are used to, they can shift their company towards an enterprise that improves their information flow and decision making through digitalisation and improved analysis tools. This will in turn give the SMEs competitive advantage and can later strive towards a full on Industry 4.0 implementation if they grow larger.

Some of the Industry 4.0 principles that SMEs can benefit from are IoT and the smart technologies of RFID chips. RFID chips and other mobile devices at the raw materials will both improve the number of counting(s) the companies' have to perform and help keep track of inventory levels. Whenever a material is registered that it will leave the warehouse, the operator will update the system, which will automatically register that the RMI has changed. The ERP system will automatically keep track of current inventory levels. There are of course certain raw materials that will have problems with the RFID chips or tags due to their size and/or material. Screws, bolts, and similar materials may have troubles with the tags sticking to them, and you can end up with a lot of RFID chips at the bottom of the box or pallet the materials are located in. These products can instead have bar codes that are attached to the side of the materials location. The operator can instead of scanning multiple RFID chips, scan the bar code multiple times to register picking. The RFID tags and bar codes can be scanned by a smart phone the operator carries at all times. When the operator picks materials from the warehouse, he/she will use the smart phone to scan and register the quantity that has been picked. The companies will also have problems with registering paint, as how much paint should be used is difficult to determine beforehand. The quantity of paint and other colour appliers is dependent on colour and the current climate at the company. A solution to this is to weigh the paint can before and after usage and use the density formula to calculate how many litres that were consumed, which can be entered in the digital smart phone after usage.

The RFID chips, information from suppliers and customers through cloud service, and MORE will generate a lot of data that needs to be stored and analysed by the companies. This can be done through Big Data and Analytics. However, advanced analytic tools are difficult to implement at SMEs, and can negatively affect the companies if not implemented correctly. But there is a need to both store and analyse it considering how much new information would be gathered from different sources. If a successful implementation were to take place with Big Data and Analytics, it could be used to further improve the forecasts, along with easier and quicker access to new information that is received through analyses.

7.3.3 The new digitally integrated inventory system

The biggest improvement for both companies, as well as other companies in the same situation, is the transfer from using multiple Excel sheets to conduct both forecasting and replenishment orders, and physical papers that will flow through the departments. All of this can now be implemented in the digital HL MRP system that is integrated in the companies' ERP system. The system will be able to create forecasts for the different raw materials with the ability to enter information from multiple sources, calculate the different order quantities and replenishment levels, as well as give notice to the planner and purchaser when an order needs to be made. Implementing the dynamic and static control policies to the HL MRP system removes some of the struggles MTO companies can have with using MRP systems the traditional way.

A lot of time on planning the less valuable materials, tracking, and picking will be reduced, and the companies can use this time to plan the more valuable materials at the company. If the inventory levels can update themselves using smart phones, bar codes and RFID tags, it furthers eases the time planners must spend on materials in group 4 and 5, as it will continuously update itself. Together with BDA, it will allow the companies to plan the higher valued materials even better, which in turn increases their performance, while at the same time reducing costs.

The suggested solutions regarding digitally enhanced QRM will improve the current inbound inventory management for the case companies. Company A deliveries multiple boxes to the production facility each day that are ready for production. The suggested solution will then be implemented at the warehouse, so that when the boxes are removed from the warehouse, they will be able to register the picking using bar codes, RFID tags, and smart mobiles. The information will be directly registered in the digital ERP system that will continuously update the current inventory levels. The need to perform every other weekly counting and entering in Excel can therefore be avoided. The company will also avoid one of the reasons why SMEs struggle with inventory management, which is manual documentation and storing.

7.4 Framework for inbound inventory management

Based on the three research questions, I have come up with a framework that can be implemented by SMEs that operate within the MTO manufacturing sector. Figure 7.4 illustrates of the supply chain, company, applications are linked in the HL MRP system, with a few benefits that can come from it. A description on the framework is as follows:

– Collect the necessary data for each raw material, such as historical demand data, supply lead times and eventual lead time fluctuation per supplier, current inventory levels, historical sales per product, information about the sustainability of the materials (e.g., level of CO2 and amount to regenerative materials per unit of raw material), and all costs related to the raw material (unit cost, inventory cost, and order cost). All this data should be registered in the company's ERP system.

– Categorise each material using the *Simple Additive Weighting* material classification matrix. The calculation is done by applying formula (4) in Chapter 4.2.4. The proposed classification schemes are the ABC usage value, XYZ demand frequency, FSN inventory turnover rate, SDE lead time variation, and HML volume. They, along with the company's goal, will divide the materials in five groups that each require different amount of attention and detail to both forecasting and replenishment. For instance, Group 1 and 2 require a much planning and detailed forecasts, while group 4 and 5 can be conducted automatically by a digital system. This step is crucial, as it sets the foundation for future work regarding inventory management and control. Some material classification schemes can be used separately for other purposes, such as the sustainability scheme to check for how renewable the materials are, and the HML and XYZ to determine supplier selections.

– Next step is to forecast each material. Which forecasting methodology is used is dependent on the grouping from the previous step. The amount of data used in the forecasts are also linked to the group the materials belong to. The more important materials require more detailed forecasts, as they contain the materials that are the most important to the company. Here, the companies can use a mix of different methodologies, such as qualitative input, time series, causal, and simulations. Qualitative information from the supply chain actors will significantly determine the quality of the forecasts, and through better relationships with the supply chain actors, gathering this type of information becomes easier.

– The different groups require different replenishment policies. Group 1 and 2 will use dynamic control policies, as they will adjust to sale and eventual trends in future demand by using the forecasts from the previous step. But the forecasts need to be reliable, as pointed out by Babai and Dallery (2009). The less critical groups, like group 4 and 5 do not need that much attention to its calculations but should not be completely overlooked. The proposed method for the less critical groups is to use the more simplified static control principles with higher safety stocks. The replenishment should be conducted by a digital system that automatically keeps track of the inventory levels and sends out replenishment whenever it is needed. The safety stock is to accommodate eventual fluctuations in either demand or supply lead times. Further, the dynamic policies will most likely recommend to order batches more frequently by the supplier, which decreases the total *Manufacturing Critical-Path Time*, as recommended by Suri (2010). The calculations for the static control policies are shown in Chapter 4.4.2, while the dynamic control policies are in Chapter 4.4.3.

– This method will be controlled in a digital *High Level MRP*/ERP system that is digitally integrated with Industry 4.0 principles such as *Additive Manufacturing*, *Big Data and Analytics*, and *Cloud Services*. The High Level MRP system classifies the materials in the respective classifications, keeps inventory levels, and informs the planner whenever replenishment need to happen for the lower level in the Simple Additive Weighting grouping. Inventory levels will be updated by the use of *RFID tags*, *bar codes*, and *smart phones* that continuously update the system whenever materials are removed from the warehouse. Lead time reduction through supplier relationship reduces lead time variation, and relationships with the customer increases information about demand. Further, by using Big Data and Analytics, they can analyse and simulate large amounts of data, and create optimisation algorithms for increasingly better forecasts for Group 1 and 2. It must be noted that operators and planners need to be taught properly if the new digital inbound inventory system is to succeed.

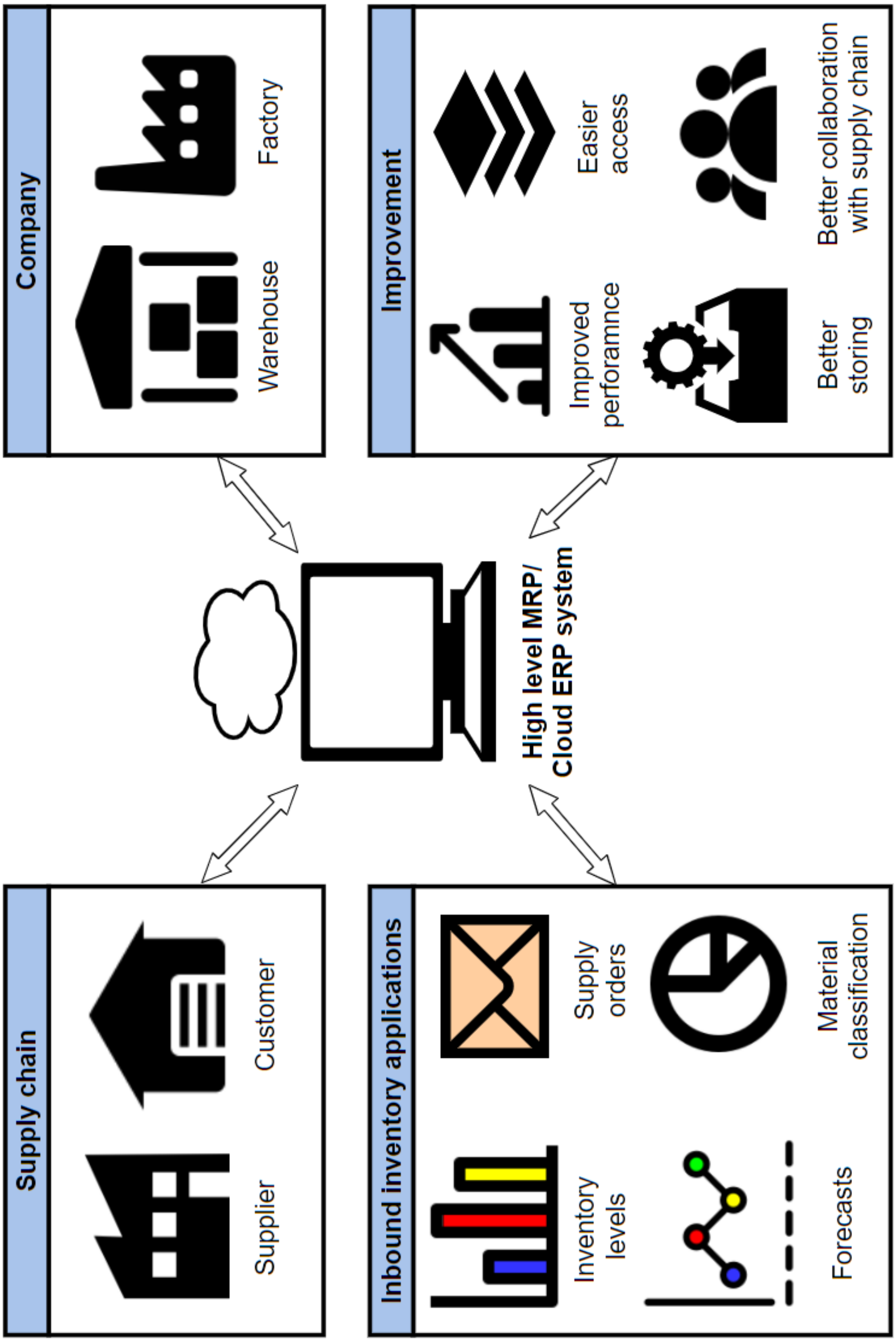

Figure 7.4: The new digital inbound inventory system

7.5 Limitations and weaknesses

There are several limitations with this master thesis. As previously mentioned, the simulation was only conducted on some materials at both companies, and the results will not be the same for all materials. The main weakness with the analysis was the lack of real forecasts used in the dynamic inventory control policies. I was not able to create forecasts for the next periods based on the previous demand data, while at the same time simulating real demand variance. The demand has seasonal peaks and lows but are in the simulation randomly distributed according to the probability. I also did not have access to inside information in the form of customer information that would affect the final forecasts. To illustrate how efficient the dynamic policies were, I varied the standard cumulative deviation of forecast error according to which classification the material was placed in. A material with stable demand had a lower forecast error, while a material with irregular had the opposite. This gave me an opportunity to illustrate how it would affect the dynamic calculations as the companies confirmed that it was easier to forecast materials with stable demand, but it is not true to how the forecast and forecast error are at the companies. One of the reasons for this was that forecasts were not meant to be a main part of the thesis and I did therefore not dwell too deep on the subject.

The results from this master thesis are not for every SMEs withing the MTO manufacturing sector. It is more applicable to the construction business, and similar enterprises, due to the nature of the case study. The suggested material classification is suited for materials that have a ”standard” shelf life. E.g., the food industry needs other classification schemes, such as food perishability. They need to include factors useful for their business structure. I also chose to exclude the VED classification, but as the literature suggest, it is useful in the pharmaceutical industry.

It must be noted that this system will not be effective until ”things goes back to normal”, as companies all over the world are struggling from the pandemic. The companies have found themselves in the need of other planning methods by sometimes overstocking to ensure that they have enough in case the supplier is either delayed or if they deliver materials of unacceptable quality. It will most likely take some time before everything goes back to normal. The companies can within this time better understand the framework for inbound inventory management, to ensure that when they do implement it, it will run smoothly, as there will be a transition period from the older planning system to this newer one. It will also give them time to test the replenishment systems with new data, such as the real order costs, inventory holding costs, forecasts, and lead time variation, as I together with the companies had to make some assumptions.

8 Conclusion

The overall purpose of this master thesis has been to investigate how inbound inventory management for Norwegian SMEs in the MTO manufacturing sector will improve their business and market performance. Through a case study of two Norwegian Companies producing highly customised products and who are in the process of implementing digitally enhanced QRM, it became apparent that both companies will benefit from improving their inbound inventory management systems and processes. The improvement will allow the companies to improve their material planning and ordering processes and at the same time being able to respond quickly to the highly customised demand. The improvements will also lower the inventory holding costs for materials that are overstocked, allowing different materials to be stored in optimised quantities and better collaboration with the supply chain actors.

The theoretical contribution from this master thesis is a detailed framework of inbound inventory management that will guide the enterprises towards better material planning through the four principles of *classification*, *planning*, *replenishment*, and *digitalisation*. All four principles together will create a digital inbound inventory system that will reduce the amount of planning needed material classified as less valuable allowing for more detailed plans for high value materials. The detail in this framework is based on concepts and recommendations from the literature review, along with the Monte Carlo simulation on the replenishment methods relevant for the two companies. The framework presented in this thesis is also relevant for other SMEs within the MTO manufacturing sector. Inbound inventory management is a key factor to success given the improved costs management and customer satisfaction as well as reduced overall risks. Customers are becoming more demanding to customised products and having raw materials available to respond to tailored demand is important to ensure competitive advantage.

8.1 Further work

It is further recommended to classify the raw materials used by both companies and a more thorough replenishment method simulation *using up to date data from the companies*. Given satisfactory classifications and simulation, the next step will be to implement the new system in their digitally enhanced ERP system.

Further research regarding inbound inventory management should be a more detailed analysis of different forecasting methods. There is a need for additional literature review and simulations to find the optimal forecasting methods that can be implemented in the SAW matrix, where the objective is to optimise the forecast error in Group 1 and 2. For companies in other industries it is recommended to find additional material classification schemes, e.g., for the food industry.

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Appendix

A Data collection

A.1 For the ABC-XYZ analysis

Category	Item number	Item name	January demand	February demand	...	December demand	Price/unit

A.2 For the Monte Carlo Simulation - Case Company A

Item number	January demand	February demand	...	December demand	Price/unit	Total demand	ABC-class	XYZ-class	Lead time	Service level	Fixed order cost	Inventory holding cost rate
TFU96X61	15029	14920		18757	kr 42,96	245171	A	X				
ASSA_S86150306001	164	165		182	kr 339,20	2635	A	X				
GIL19289	877	986		976	kr 13,21	12168	A	X				
SÆRBÆ_P161	0	0		0	kr 1 380,00	156	A	Z				
HOPPE_7194824	280	285		219	kr 28,35	4565	B	X				
SPILKA_305102	345	305		335	kr 9,25	5129	B	X				
ASSA_819965	55	34		110	kr 112,57	1093	B	Y				
HOPPE_1958641	13	187		97	kr 114,66	564	B	Z				
TFU96X96	23	37		27	kr 86,15	356	C	X				
6-32104-00-0-1	5	15		17	kr 13,45	155	C	X				
ASSA_2631480	11	9		4	kr 223,31	138	C	Y				
FSK40X60S	567	420		404	kr 0,33	11024	C	Y				
IPA_21193-17211-V	0	0		22	kr 128,61	162	C	Z				
SENSE_firkant	0	19		28	kr 10,50	138	C	Z				
FSK45X70PAN	73	381		0	kr 0,53	3531	C	Z				

A.3 For the Monte Carlo Simulation - Case Company B

Item number	January demand	February demand	...	December demand	Price/unit	Total demand	ABC-class	XYZ-class	Lead time	Service level	Fixed order cost	Inventory holding cost rate
200-0153	11	9		8	kr 4 246,78	130	A	X				
11-0021	28	23		25	kr 744,45	208	A	X				
200-0154	5	7		14	kr 4 223,79	118	A	Y				
40-0087	44	11		89	kr 105,42	571	A	Y				
10-0220	14	157		18	kr 598,52	829	A	Z				
200-0004	0	11		2	kr 2 518,96	32	A	Z				
90-0061	6	4		6	kr 329,45	71	B	X				
10-0019	4	14		10	kr 230,04	104	B	Y				
90-0500	1	1		1	kr 2 625,00	7	B	Y				
50-0050	1	0		1	kr 1 263,15	19	B	Z				
200-0186	0	1		0	kr 4 391,11	4	B	Z				
40-0070	5	5		7	kr 95,39	59	C	X				
90-0349	2	5		6	kr 125,32	46	C	Y				
12-0149	0	0		1	kr 3 043,00	2	C	Z				
42-0033	0	0		0	kr 276,08	30	C	Z				
90-0414	1	0		0	kr 50,30	6	C	Z				

B Interview questions

B.1 Round one

1. What are the biggest concern regarding the current purchasing policies?
2. Do you often have to much on stock?
3. Do you often have to little on stock? An if so, what is the reason for this? Is it due to variation in demand or is to due to poor inventory management?
4. How are the forecasts calculated? Do you have a mix between qualitative and quantitative data?
5. How good will you say the current forecasts are? Are they reliable?
6. Do you have any trends on certain raw materials or finished products?
7. How have you calculated todays min/max levels?
8. How do you plan replenishment from suppliers with uncertainties in quality and delivery lead time?
9. How many suppliers are located in Norway?

B.2 Round two

1. How are inventory levels being controlled?
2. How is the factory being digitally improved?
3. How is the supply chain being digitally improved?
4. How is the warehouse, both RMI and FGI, being digitally improved?

C Monte Carlo simulation

C.1 Data used in simulation

Table	2		
Demand	Probability	RN lower limit	RN upper limit
2500	0,08	0	0,08
3750	0,22	0,08	0,3
4250	0,12	0,3	0,42
4700	0,12	0,42	0,54
5600	0,12	0,54	0,66
6250	0,17	0,66	0,83
6500	0,17	0,83	1

Order quantity Q	9556
Time series T	2,0
Replenishment level r	24195
Max level S	29540

Item number		TFU96X61
Item name		FURU 96X61LAMINERT
Class	A	X
Weekly demand		4715
Stdev demand (week)		1418
Annual demand		245180
Lead time		3
Order cost		kr 2 000,00
Unit cost		kr 42,96
Holding rate		0,25
Service level (z-value)		1,881
Forecast plus		95
Forecast minus		-95
Stdev forecast		142

C.2 (T, Q)

(T, Q)												
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	Place order?	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	6500	6500	21790	0	Yes	5	kr 4 500,47	kr 2 000,00	kr 6 500,47
2	21790	0	21790	6500	6500	15290	0			kr 3 157,97	kr -	kr 3 157,97
3	15290	0	15290	6500	6500	8790	0	Yes	7	kr 1 815,47	kr 2 000,00	kr 3 815,47
4	8790	0	8790	3750	3750	5040	0			kr 1 040,95	kr -	kr 1 040,95
5	5040	9556	14596	4250	4250	10346	0	Yes	9	kr 2 136,85	kr 2 000,00	kr 4 136,85
6	10346	0	10346	5600	5600	4746	0			kr 980,23	kr -	kr 980,23
7	4746	9556	14302	5600	5600	8702	0	Yes	11	kr 1 797,30	kr 2 000,00	kr 3 797,30
8	8702	0	8702	6250	6250	2452	0			kr 506,43	kr -	kr 506,43
9	2452	9556	12008	6500	6500	5508	0	Yes	13	kr 1 137,61	kr 2 000,00	kr 3 137,61
10	5508	0	5508	3750	3750	1758	0			kr 363,09	kr -	kr 363,09
11	1758	9556	11314	4700	4700	6614	0	Yes	15	kr 1 366,05	kr 2 000,00	kr 3 366,05
12	6614	0	6614	3750	3750	2864	0			kr 591,53	kr -	kr 591,53
13	2864	9556	12420	3750	3750	8670	0	Yes	17	kr 1 790,69	kr 2 000,00	kr 3 790,69
14	8670	0	8670	5600	5600	3070	0			kr 634,07	kr -	kr 634,07
15	3070	9556	12626	6500	6500	6126	0	Yes	19	kr 1 265,25	kr 2 000,00	kr 3 265,25
16	6126	0	6126	3750	3750	2376	0			kr 490,74	kr -	kr 490,74
17	2376	9556	11932	4250	4250	7682	0	Yes	21	kr 1 586,63	kr 2 000,00	kr 3 586,63
18	7682	0	7682	6250	6250	1432	0			kr 295,76	kr -	kr 295,76
19	1432	9556	10988	6500	6500	4488	0	Yes	23	kr 926,94	kr 2 000,00	kr 2 926,94
20	4488	0	4488	5600	4488	0	1112			kr -	kr -	kr -
.....												
50	21878	0	21878	3750	3750	18128	0			kr 3 744,13	kr -	kr 3 744,13
51	18128	9556	27684	6250	6250	21434	0	Yes	55	kr 4 426,95	kr 2 000,00	kr 6 426,95
52	21434	0	21434	2500	2500	18934	0			kr 3 910,60	kr -	kr 3 910,60
Total							1112			kr 186 500,10	kr 52 000,00	kr 238 500,10

C.3 (r, Q)

(r, Q)													
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	End inv + previous order(s)	Place order?	Arrive on week	Holding cost	Order cost	Total cost
1	28290	0	28290	5600	5600	22690	0	22690	Yes	5	kr 4 686,36	kr 2 000,00	kr 6 686,36
2	22690	0	22690	3750	3750	18940	0	28496			kr 3 911,84	kr 0,00	kr 3 911,84
3	18940	0	18940	3750	3750	15190	0	24746			kr 3 137,32	kr 0,00	kr 3 137,32
4	15190	0	15190	6250	6250	8940	0	18496	Yes	8	kr 1 846,45	kr 2 000,00	kr 3 846,45
5	8940	9556	18496	4250	4250	14246	0	23802	Yes	9	kr 2 942,35	kr 2 000,00	kr 4 942,35
6	14246	0	14246	6500	6500	7746	0	26858			kr 1 599,85	kr 0,00	kr 1 599,85
7	7746	0	7746	6250	6250	1496	0	20608	Yes	11	kr 308,98	kr 2 000,00	kr 2 308,98
8	1496	9556	11052	6250	6250	4802	0	23914	Yes	12	kr 991,80	kr 2 000,00	kr 2 991,80
9	4802	9556	14358	6500	6500	7858	0	26970			kr 1 622,98	kr 0,00	kr 1 622,98
10	7858	0	7858	4700	4700	3158	0	22270	Yes	14	kr 652,25	kr 2 000,00	kr 2 652,25
11	3158	9556	12714	6250	6250	6464	0	25576			kr 1 335,06	kr 0,00	kr 1 335,06
12	6464	9556	16020	6500	6500	9520	0	19076	Yes	16	kr 1 966,25	kr 2 000,00	kr 3 966,25
13	9520	0	9520	5600	5600	3920	0	23032	Yes	17	kr 809,63	kr 2 000,00	kr 2 809,63
14	3920	9556	13476	2500	2500	10976	0	30088			kr 2 266,97	kr 0,00	kr 2 266,97
15	10976	0	10976	4700	4700	6276	0	25388			kr 1 296,24	kr 0,00	kr 1 296,24
16	6276	9556	15832	3750	3750	12082	0	21638	Yes	20	kr 2 495,40	kr 2 000,00	kr 4 495,40
17	12082	9556	21638	6500	6500	15138	0	24694			kr 3 126,58	kr 0,00	kr 3 126,58
18	15138	0	15138	3750	3750	11388	0	20944	Yes	22	kr 2 352,06	kr 2 000,00	kr 4 352,06
19	11388	0	11388	3750	3750	7638	0	26750			kr 1 577,54	kr 0,00	kr 1 577,54
20	7638	9556	17194	3750	3750	13444	0	23000	Yes	24	kr 2 776,70	kr 2 000,00	kr 4 776,70
......													
50	11178	0	11178	2500	2500	8678	0	27790			kr 1 792,34	kr 0,00	kr 1 792,34
51	8678	9556	18234	2500	2500	15734	0	25290			kr 3 249,68	kr 0,00	kr 3 249,68
52	15734	0	15734	4700	4700	11034	0	20590	Yes	56	kr 2 278,95	kr 2 000,00	kr 4 278,95
Total							0				kr 108 019,62	kr 52 000,00	kr 160 019,62

C.4 (T, S)

(T, S)													
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	Ending inventory + order	Place order?	Order size, Q	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	3750	3750	24540	0	24540	Yes	5000	5	kr 5 068,45	kr 2 000,00	kr 7 068,45
2	24540	0	24540	6500	6500	18040	0	23040				kr 3 725,95	kr -	kr 3 725,95
3	18040	0	18040	6250	6250	11790	0	16790	Yes	12750	7	kr 2 435,09	kr 2 000,00	kr 4 435,09
4	11790	0	11790	3750	3750	8040	0	25790				kr 1 660,57	kr -	kr 1 660,57
5	8040	5000	13040	3750	3750	9290	0	22040	Yes	7500	9	kr 1 918,74	kr 2 000,00	kr 3 918,74
6	9290	0	9290	3750	3750	5540	0	25790				kr 1 144,22	kr -	kr 1 144,22
7	5540	12750	18290	6250	6250	12040	0	19540	Yes	10000	11	kr 2 486,72	kr 2 000,00	kr 4 486,72
8	12040	0	12040	4700	4700	7340	0	24840				kr 1 515,99	kr -	kr 1 515,99
9	7340	7500	14840	3750	3750	11090	0	21090	Yes	8450	13	kr 2 290,51	kr 2 000,00	kr 4 290,51
10	11090	0	11090	5600	5600	5490	0	23940				kr 1 133,90	kr -	kr 1 133,90
11	5490	10000	15490	6250	6250	9240	0	17690	Yes	11850	15	kr 1 908,42	kr 2 000,00	kr 3 908,42
12	9240	0	9240	4250	4250	4990	0	25290				kr 1 030,63	kr -	kr 1 030,63
13	4990	8450	13440	3750	3750	9690	0	21540	Yes	8000	17	kr 2 001,36	kr 2 000,00	kr 4 001,36
14	9690	0	9690	3750	3750	5940	0	25790				kr 1 226,84	kr -	kr 1 226,84
15	5940	11850	17790	5600	5600	12190	0	20190	Yes	9350	19	kr 2 517,70	kr 2 000,00	kr 4 517,70
16	12190	0	12190	3750	3750	8440	0	25790				kr 1 743,18	kr -	kr 1 743,18
17	8440	8000	16440	4700	4700	11740	0	21090	Yes	8450	21	kr 2 424,76	kr 2 000,00	kr 4 424,76
18	11740	0	11740	6250	6250	5490	0	23290				kr 1 133,90	kr -	kr 1 133,90
19	5490	9350	14840	4700	4700	10140	0	18590	Yes	10950	23	kr 2 094,30	kr 2 000,00	kr 4 094,30
20	10140	0	10140	5600	5600	4540	0	23940				kr 937,68	kr -	kr 937,68
							.....							
50	13440	0	13440	6250	6250	7190	0	23290				kr 1 485,01	kr -	kr 1 485,01
51	7190	9850	17040	6500	6500	10540	0	16790	Yes	12750	55	kr 2 176,92	kr 2 000,00	kr 4 176,92
52	10540	0	10540	5600	5600	4940	0	23940				kr 1 020,30	kr -	kr 1 020,30
Total							0					kr 93 599,10	kr 52 000,00	kr 145 599,10

C.5 (r, S)

(r, S)														
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	End inv + order	Place order?	Order size, Q_k	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	4700	4700	23590	0	23590	Yes	5950	5	kr 4 872,24	kr 2 000,00	kr 6 872,24
2	23590	0	23590	3750	3750	19840	0	25790				kr 4 097,72	kr -	kr 4 097,72
3	19840	0	19840	6250	6250	13590	0	19540	Yes	10000	7	kr 2 806,86	kr 2 000,00	kr 4 806,86
4	13590	0	13590	3750	3750	9840	0	25790				kr 2 032,34	kr -	kr 2 032,34
5	9840	5950	15790	6250	6250	9540	0	19540	Yes	10000	9	kr 1 970,38	kr 2 000,00	kr 3 970,38
6	9540	0	9540	5600	5600	3940	0	23940	Yes	5600	10	kr 813,76	kr 2 000,00	kr 2 813,76
7	3940	10000	13940	3750	3750	10190	0	25790				kr 2 104,63	kr -	kr 2 104,63
8	10190	0	10190	5600	5600	4590	0	20190	Yes	9350	12	kr 948,01	kr 2 000,00	kr 2 948,01
9	4590	10000	14590	3750	3750	10840	0	25790				kr 2 238,88	kr -	kr 2 238,88
10	10840	5600	16440	2500	2500	13940	0	23290	Yes	6250	14	kr 2 879,15	kr 2 000,00	kr 4 879,15
11	13940	0	13940	3750	3750	10190	0	25790				kr 2 104,63	kr -	kr 2 104,63
12	10190	9350	19540	6250	6250	13290	0	19540	Yes	10000	16	kr 2 744,90	kr 2 000,00	kr 4 744,90
13	13290	0	13290	4250	4250	9040	0	25290				kr 1 867,11	kr -	kr 1 867,11
14	9040	6250	15290	3750	3750	11540	0	21540	Yes	8000	18	kr 2 383,45	kr 2 000,00	kr 4 383,45
15	11540	0	11540	4250	4250	7290	0	25290				kr 1 505,67	kr -	kr 1 505,67
16	7290	10000	17290	3750	3750	13540	0	21540	Yes	8000	20	kr 2 796,53	kr 2 000,00	kr 4 796,53
17	13540	0	13540	3750	3750	9790	0	25790				kr 2 022,01	kr -	kr 2 022,01
18	9790	8000	17790	6500	6500	11290	0	19290	Yes	10250	22	kr 2 331,82	kr 2 000,00	kr 4 331,82
19	11290	0	11290	4700	4700	6590	0	24840				kr 1 361,09	kr -	kr 1 361,09
20	6590	8000	14590	6250	6250	8340	0	18590	Yes	10950	24	kr 1 722,53	kr 2 000,00	kr 3 722,53
							......							
50	12090	5600	17690	2500	2500	15190	0	23290	Yes	6250	54	kr 3 137,32	kr 2 000,00	kr 5 137,32
51	15190	0	15190	3750	3750	11440	0	25790				kr 2 362,80	kr -	kr 2 362,80
52	11440	8100	19540	3750	3750	15790	0	22040	Yes	7500	56	kr 3 261,24	kr 2 000,00	kr 5 261,24
Total							410					kr 94 185,67	kr 66 000,00	kr 160 185,67

C.6 (r_k, Q)

(r_k, Q)														
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	End inv + previous order(s)	Replenish-ment level r_k	Place order?	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	2500	2500	25790	0	25790	16103			kr 5 326,63	kr -	kr 5 326,63
2	25790	0	25790	3750	3750	22040	0	22040	18551			kr 4 552,11	kr -	kr 4 552,11
3	22040	0	22040	4700	4700	17340	0	17340	18520	Yes	7	kr 3 581,38	kr 2 000,00	kr 5 581,38
4	17340	0	17340	2500	2500	14840	0	24396	22249			kr 3 065,03	kr -	kr 3 065,03
5	14840	0	14840	4250	4250	10590	0	20146	24102	Yes	9	kr 2 187,24	kr 2 000,00	kr 4 187,24
6	10590	0	10590	6250	6250	4340	0	23452	21623			kr 896,38	kr -	kr 896,38
7	4340	9556	13896	4700	4700	9196	0	18752	20632	Yes	11	kr 1 899,33	kr 2 000,00	kr 3 899,33
8	9196	0	9196	6250	6250	2946	0	22058	21170			kr 608,46	kr -	kr 608,46
9	2946	9556	12502	6250	6250	6252	0	15808	19067	Yes	13	kr 1 291,28	kr 2 000,00	kr 3 291,28
10	6252	0	6252	3750	3750	2502	0	21614	17819			kr 516,76	kr -	kr 516,76
11	2502	9556	12058	3750	3750	8308	0	17864	18685	Yes	15	kr 1 715,92	kr 2 000,00	kr 3 715,92
12	8308	0	8308	6500	6500	1808	0	20920	16022			kr 373,42	kr -	kr 373,42
13	1808	9556	11364	4250	4250	7114	0	16670	16574			kr 1 469,31	kr -	kr 1 469,31
14	7114	0	7114	2500	2500	4614	0	14170	18642	Yes	18	kr 952,97	kr 2 000,00	kr 2 952,97
15	4614	9556	14170	4700	4700	9470	0	19026	18576			kr 1 955,92	kr -	kr 1 955,92
16	9470	0	9470	3750	3750	5720	0	15276	19170	Yes	20	kr 1 181,40	kr 2 000,00	kr 3 181,40
17	5720	0	5720	4700	4700	1020	0	20132	20981	Yes	21	kr 210,67	kr 2 000,00	kr 2 210,67
18	1020	9556	10576	4700	4700	5876	0	24988	21916			kr 1 213,62	kr -	kr 1 213,62
19	5876	0	5876	4700	4700	1176	0	20288	23775	Yes	23	kr 242,89	kr 2 000,00	kr 2 242,89
20	1176	9556	10732	4250	4250	6482	0	25594	25552			kr 1 338,78	kr -	kr 1 338,78
.....														
50	3784	9556	13340	3750	3750	9590	0	19146	24666	Yes	54	kr 1 980,70	kr 2 000,00	kr 3 980,70
51	9590	0	9590	6500	6500	3090	0	22202	24418	Yes	55	kr 638,20	kr 2 000,00	kr 2 638,20
52	3090	9556	12646	4250	4250	8396	0	27508	26969			kr 1 734,10	kr -	kr 1 734,10
Total							0					kr 70 765,86	kr 56 000,00	kr 126 765,86

C.7 (T, S_k)

(T, S_k)															
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	Ending inventory + order	Maximum level, S_k	Place order?	Order size, Q	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	3750	3750	24540	0	24540	25975	Yes	1435	5	kr 5 068,45	kr 2 000,00	kr 7 068,45
2	24540	0	24540	6250	6250	18290	0	19725	25410	0			kr 3 777,59	kr -	kr 3 777,59
3	18290	0	18290	4250	4250	14040	0	15475	25437	Yes	9962	7	kr 2 899,80	kr 2 000,00	kr 4 899,80
4	14040	0	14040	6500	6500	7540	0	18937	23002				kr 1 557,30	kr -	kr 1 557,30
5	7540	1435	8975	4250	4250	4725	0	14687	25653	Yes	10966	9	kr 975,89	kr 2 000,00	kr 2 975,89
6	4725	0	4725	3750	3750	975	0	21903	25801				kr 201,38	kr -	kr 201,38
7	975	9962	10937	6250	6250	4687	0	15653	25204	Yes	9551	11	kr 968,05	kr 2 000,00	kr 2 968,05
8	4687	0	4687	3750	3750	937	0	21454	25722				kr 193,53	kr -	kr 193,53
9	937	10966	11903	4250	4250	7653	0	17204	24912	Yes	7708	13	kr 1 580,64	kr 2 000,00	kr 3 580,64
10	7653	0	7653	6500	6500	1153	0	18412	24212				kr 238,14	kr -	kr 238,14
11	1153	9551	10704	4250	4250	6454	0	14162	25749	Yes	11587	15	kr 1 333,00	kr 2 000,00	kr 3 333,00
12	6454	0	6454	5600	5600	854	0	20149	27179				kr 176,38	kr -	kr 176,38
13	854	7708	8562	4250	4250	4312	0	15899	25597	Yes	9698	17	kr 890,59	kr 2 000,00	kr 2 890,59
14	4312	0	4312	3750	3750	562	0	21847	24084				kr 116,07	kr -	kr 116,07
15	562	11587	12149	5600	5600	6549	0	16247	22295	Yes	6048	19	kr 1 352,62	kr 2 000,00	kr 3 352,62
16	6549	0	6549	6250	6250	299	0	16045	22508				kr 61,76	kr -	kr 61,76
17	299	9698	9997	6500	6500	3497	0	9545	21749	Yes	12204	21	kr 722,27	kr 2 000,00	kr 2 722,27
18	3497	0	3497	2500	2500	997	0	19249	25683				kr 205,92	kr -	kr 205,92
19	997	6048	7045	2500	2500	4545	0	16749	28812	Yes	12063	23	kr 938,72	kr 2 000,00	kr 2 938,72
20	4545	0	4545	3750	3750	795	0	25062	30733				kr 164,20	kr -	kr 164,20
								.....							
50	7255	0	7255	6500	6500	755	0	21031	26958				kr 155,94	kr -	kr 155,94
51	755	10372	11127	3750	3750	7377	0	17281	29134	Yes	11853	55	kr 1 523,63	kr 2 000,00	kr 3 523,63
52	7377	0	7377	6500	6500	877	0	22634	26348				kr 181,13	kr -	kr 181,13
Total							0						kr 48 578,26	kr 52 000,00	kr 100 578,26

C.8 (r_k, S_k)

(r_k, S_k)															
Week	Beginning Inventory	Units Received	Available Inventory	Demand	Demand filled	Ending inventory	Stock out	End inv + previous order(s)	Replenish-ment level r_k	Maximum level, S_k	Place order?	Order size Q_k	Arrive on day	Holding cost	Order cost	Total cost
1	28290	0	28290	5600	5600	22690	0	22690	20179	22601				kr 4 686,36	kr -	kr 4 686,36
2	22690	0	22690	6500	6500	16190	0	16190	16247	20222	Yes	4032	6	kr 3 343,86	kr 2 000,00	kr 5 343,86
3	16190	0	16190	6500	6500	9690	0	13722	13686	20192				kr 2 001,36	kr -	kr 2 001,36
4	9690	0	9690	3750	3750	5940	0	9972	16769	23041	Yes	13069	8	kr 1 226,84	kr 2 000,00	kr 3 226,84
5	5940	0	5940	2500	2500	3440	0	20541	20603	24614	Yes	4073	9	kr 710,49	kr 2 000,00	kr 2 710,49
6	3440	4032	7472	2500	2500	4972	0	22114	22509	28351	Yes	6237	10	kr 1 026,91	kr 2 000,00	kr 3 026,91
7	4972	0	4972	4250	4250	722	0	24101	24205	30578	Yes	6477	11	kr 149,12	kr 2 000,00	kr 2 149,12
8	722	13069	13791	6500	6500	7291	0	24078	24011	29724				kr 1 505,87	kr -	kr 1 505,87
9	7291	4073	11364	6500	6500	4864	0	17578	23220	26868	Yes	9290	13	kr 1 004,60	kr 2 000,00	kr 3 004,60
10	4864	6237	11101	4250	4250	6851	0	22618	22743	26333	Yes	3715	14	kr 1 415,00	kr 2 000,00	kr 3 415,00
11	6851	6477	13328	6250	6250	7078	0	20083	20265	26441	Yes	6358	15	kr 1 461,88	kr 2 000,00	kr 3 461,88
12	7078	0	7078	6250	6250	828	0	20191	20400	26505	Yes	6314	16	kr 171,01	kr 2 000,00	kr 2 171,01
13	828	9290	10118	5600	5600	4518	0	20905	20880	24473				kr 933,14	kr -	kr 933,14
14	4518	3715	8233	3750	3750	4483	0	17155	20740	26337	Yes	9182	18	kr 925,91	kr 2 000,00	kr 2 925,91
15	4483	6358	10841	3750	3750	7091	0	22587	22797	28912	Yes	6325	19	kr 1 464,56	kr 2 000,00	kr 3 464,56
16	7091	6314	13405	6250	6250	7155	0	22662	22647	27354				kr 1 477,78	kr -	kr 1 477,78
17	7155	0	7155	6250	6250	905	0	16412	21137	25889	Yes	9477	21	kr 186,92	kr 2 000,00	kr 2 186,92
18	905	9182	10087	3750	3750	6337	0	22139	22066	28107				kr 1 308,83	kr -	kr 1 308,83
19	6337	6325	12662	5600	5600	7062	0	16539	22641	29120	Yes	12581	23	kr 1 458,57	kr 2 000,00	kr 3 458,57
20	7062	0	7062	6250	6250	812	0	22870	23073	28381	Yes	5511	24	kr 167,71	kr 2 000,00	kr 2 167,71
								.....								
50	4511	0	4511	3750	3750	761	0	20254	20125	23787				kr 157,18	kr -	kr 157,18
51	761	9932	10693	6250	6250	4443	0	14004	17709	23906	Yes	9902	55	kr 917,65	kr 2 000,00	kr 2 917,65
52	4443	0	4443	3750	3750	693	0	20156	20204	26470	Yes	6314	56	kr 143,13	kr 2 000,00	kr 2 143,13
Total							0							kr 52 765,41	kr 62 000,00	kr 114 765,41

C.9 What-if simulation

Run	Holding cost	Order cost	Total cost	Stock out
1	kr 102 574,44	kr 54 000,00	kr 156 574,44	0
2	kr 102 643,01	kr 54 000,00	kr 156 643,01	0
3	kr 108 750,76	kr 52 000,00	kr 160 750,76	0
4	kr 120 752,30	kr 50 000,00	kr 170 752,30	0
5	kr 94 747,87	kr 56 000,00	kr 150 747,87	0
6	kr 97 755,48	kr 54 000,00	kr 151 755,48	0
7	kr 85 221,07	kr 58 000,00	kr 143 221,07	0
8	kr 109 802,04	kr 52 000,00	kr 161 802,04	0
9	kr 102 514,54	kr 56 000,00	kr 158 514,54	0
10	kr 101 749,93	kr 56 000,00	kr 157 749,93	0
11	kr 109 576,50	kr 52 000,00	kr 161 576,50	526
12	kr 105 221,43	kr 52 000,00	kr 157 221,43	0
13	kr 105 738,60	kr 54 000,00	kr 159 738,60	0
14	kr 113 348,72	kr 52 000,00	kr 165 348,72	0
15	kr 88 098,98	kr 58 000,00	kr 146 098,98	0
16	kr 84 756,36	kr 60 000,00	kr 144 756,36	0
17	kr 109 255,95	kr 54 000,00	kr 163 255,95	0
18	kr 98 287,94	kr 56 000,00	kr 154 287,94	0
19	kr 121 137,29	kr 50 000,00	kr 171 137,29	0
20	kr 96 031,71	kr 56 000,00	kr 152 031,71	218
21	kr 103 284,10	kr 54 000,00	kr 157 284,10	0
22	kr 88 551,30	kr 58 000,00	kr 146 551,30	0
23	kr 106 928,27	kr 52 000,00	kr 158 928,27	0
24	kr 106 623,00	kr 54 000,00	kr 160 623,00	0
25	kr 103 385,31	kr 54 000,00	kr 157 385,31	0
26	kr 102 089,48	kr 54 000,00	kr 156 089,48	50
27	kr 103 422,07	kr 56 000,00	kr 159 422,07	0
28	kr 112 582,46	kr 54 000,00	kr 166 582,46	0
29	kr 101 384,36	kr 56 000,00	kr 157 384,36	0
30	kr 108 728,46	kr 54 000,00	kr 162 728,46	0

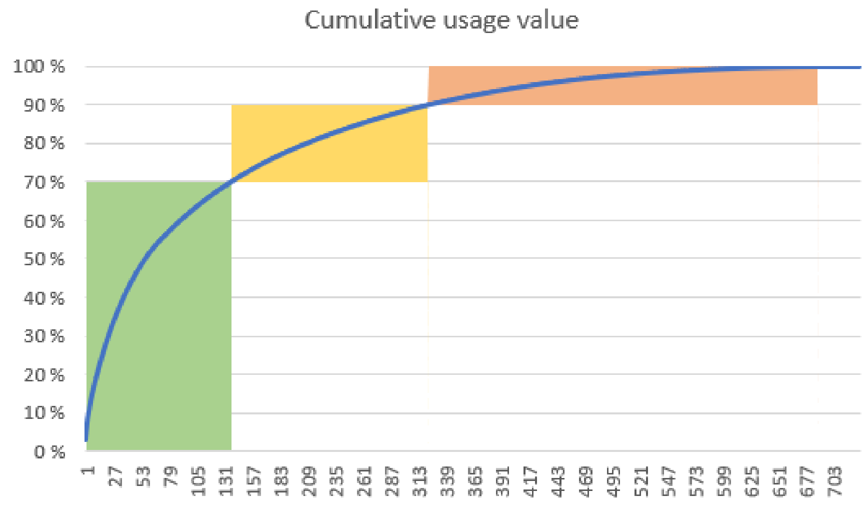
D Material classification - Case Company B MTS

D.1 ABC-XYZ

Materials				
	A	B	C	Total
X	7	0	0	7
Y	72	13	10	95
Z	58	172	356	586
Total	137	185	366	688
Percentage				
	A	B	C	Total
X	1,017 %	0,000 %	0,000 %	1,02 %
Y	10,465 %	1,890 %	1,453 %	13,81 %
Z	8,430 %	25,000 %	51,744 %	85,17 %
Total	19,91 %	26,89 %	53,20 %	100,00 %

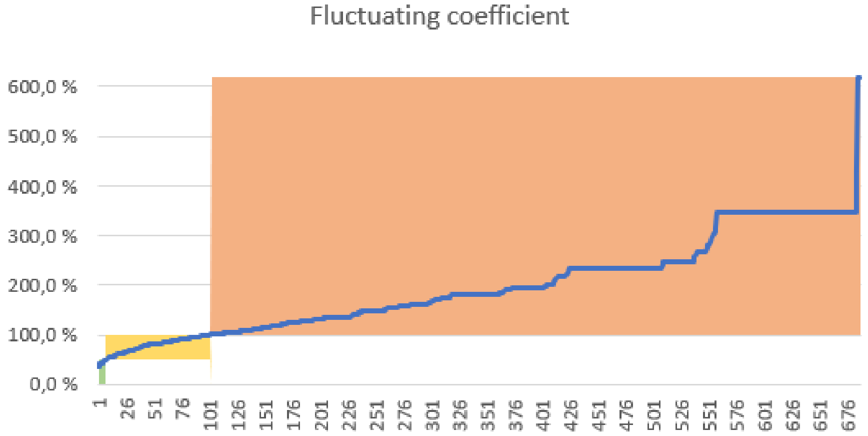
D.2 ABC data

ABC data				
ABC	No. Materials	Usage value	% of total volume	% of materials
A	137	69,86 %	71,84 %	18,82 %
B	185	20,12 %	16,06 %	25,41 %
C	366	10,02 %	12,10 %	50,27 %
NO DEMAND	40	0,00 %	0,00 %	5,49 %
Total	728	100,00 %	100,00 %	100,00 %



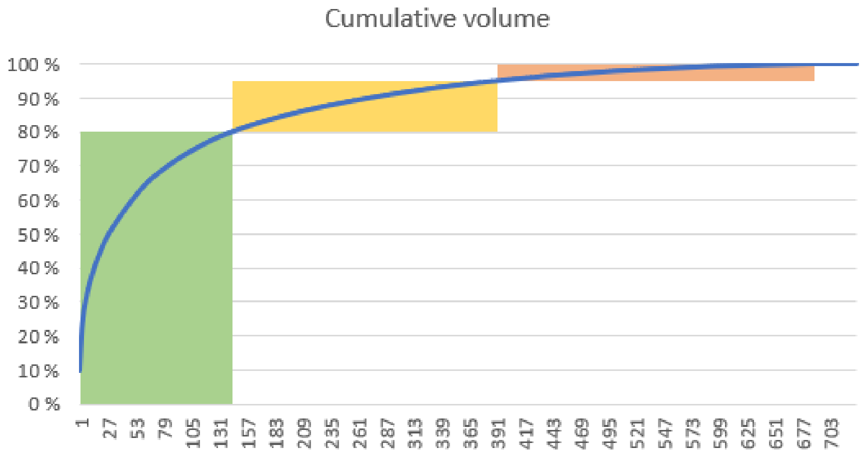
D.3 XYZ data

XYZ data				
XYZ	No. Materials	Average fluct. coefficient	% of total volume	% of materials
X	7	41,88 %	4,72 %	0,96 %
Y	95	79,97 %	47,75 %	13,05 %
Z	586	218,32 %	47,53 %	80,49 %
NO DEMAND	40	0,00 %	0,00 %	5,49 %
Total	728	186,57 %	100,00 %	100,00 %



D.4 HML data

HML data				
HML	No. Materials	Average volume	% of total volume	% of materials
H	143	73,11	79,92 %	19,64 %
M	248	7,94	15,05 %	34,07 %
L	297	2,22	5,03 %	40,80 %
NO DEMAND	40	0,00	0,00 %	5,49 %
Total	728	17,97	100,00 %	100,00 %



E Results from Monte Carlo simulation

E.1 Case Company A

GIL19289				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 5 708,97	kr 6 000,00	kr 11 708,97	218,3
(r, Q)	kr 6 177,00	kr 6 250,00	kr 12 427,00	3,2
(T, S)	kr 6 274,58	kr 6 000,00	kr 12 274,58	55,3
(r, S)	kr 6 287,84	kr 6 200,00	kr 12 487,84	3,9
(r_k, Q)	kr 5 784,11	kr 6 150,00	kr 11 934,11	0,2
(T, S_k)	kr 5 904,62	kr 6 000,00	kr 11 904,62	0,0
(r_k, S_k)	kr 5 556,21	kr 6 000,00	kr 11 556,21	298,4

SÆRBÆ_P161				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 26 844,10	kr 14 000,00	kr 40 844,10	0,7
(r, Q)	kr 20 743,57	kr 10 500,00	kr 31 243,57	0,6
(T, S)	kr 30 605,26	kr 14 000,00	kr 44 605,26	0,5
(r, S)	kr 25 621,34	kr 7 233,33	kr 32 854,67	1,1
(r_k, Q)	kr 28 237,59	kr 10 850,00	kr 39 087,59	1,0
(T, S_k)	kr 24 623,05	kr 14 000,00	kr 38 623,05	0,0
(r_k, S_k)	kr 24 782,72	kr 15 283,33	kr 40 066,05	0,8

TFU96X96				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 1 773,50	kr 1 500,00	kr 3 273,50	1,2
(r, Q)	kr 1 793,34	kr 1 766,67	kr 3 560,01	0,1
(T, S)	kr 2 166,27	kr 1 500,00	kr 3 666,27	0,2
(r, S)	kr 2 066,04	kr 1 500,00	kr 3 566,04	0,1
(r_k, Q)	kr 1 651,43	kr 1 583,33	kr 3 234,76	0,0
(T, S_k)	kr 1 445,66	kr 1 500,00	kr 2 945,66	2,3
(r_k, S_k)	kr 1 473,52	kr 2 000,00	kr 3 473,52	0,0

FSK45X70PAN				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 357,96	kr 300,00	kr 657,96	5,1
(r, Q)	kr 322,06	kr 320,00	kr 642,06	0,1
(T, S)	kr 439,33	kr 300,00	kr 739,33	0,0
(r, S)	kr 443,46	kr 300,00	kr 743,46	0,8
(r_k, Q)	kr 321,91	kr 300,00	kr 621,91	0,0
(T, S_k)	kr 285,93	kr 300,00	kr 585,93	0,0
(r_k, S_k)	kr 288,23	kr 300,00	kr 588,23	0,0

E.2 Case Company B

320-20095				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 20 483,94	kr 7 000,00	kr 27 483,94	0,00
(r, Q)	kr 11 458,30	kr 6 033,33	kr 17 491,63	0,00
(r, S)	kr 11 294,78	kr 6 033,33	kr 17 328,11	0,00
(T, S)	kr 12 482,58	kr 7 000,00	kr 19 482,58	0,00
(r_k, Q)	kr 9 409,43	kr 5 933,33	kr 15 342,77	0,00
(T, S_k)	kr 8 905,14	kr 7 000,00	kr 15 905,14	0,00
(r_k, S_k)	kr 7 844,40	kr 7 833,33	kr 15 677,73	0,00

200-70100				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 27 475,55	kr 18 900,00	kr 46 375,55	188,37
(r, Q)	kr 35 366,85	kr 22 950,00	kr 58 316,85	28,97
(r, S)	kr 39 502,23	kr 18 450,00	kr 57 952,23	29,40
(T, S)	kr 37 501,84	kr 18 900,00	kr 56 401,84	63,27
(r_k, Q)	kr 28 618,64	kr 23 850,00	kr 52 468,64	8,63
(T, S_k)	kr 31 991,45	kr 18 900,00	kr 50 891,45	5,87
(r_k, S_k)	kr 29 163,25	kr 22 050,00	kr 51 213,25	6,67

200-23905				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 28 243,53	kr 18 770,00	kr 47 013,53	177,30
(r, Q)	kr 31 341,39	kr 11 400,00	kr 42 741,39	0,07
(r, S)	kr 36 937,84	kr 14 650,00	kr 51 587,84	10,57
(T, S)	kr 37 626,16	kr 18 770,00	kr 56 396,16	63,27
(r_k, Q)	kr 35 903,31	kr 11 600,00	kr 47 503,31	0,00
(T, S_k)	kr 32 271,48	kr 18 770,00	kr 51 041,48	5,87
(r_k, S_k)	kr 29 381,78	kr 22 380,00	kr 51 761,78	2,80

360-21370				
Replenishment methods	Holding cost	Order cost	Total cost	Stock out
(T, Q)	kr 1 896,17	kr 1 200,00	kr 3 096,17	0,00
(r, Q)	kr 1 373,65	kr 940,00	kr 2 313,65	1,00
(r, S)	kr 1 435,48	kr 900,00	kr 2 335,48	0,00
(T, S)	kr 1 593,60	kr 1 200,00	kr 2 793,60	0,00
(r_k, Q)	kr 1 143,94	kr 920,00	kr 2 063,94	0,00
(T, S_k)	kr 1 041,35	kr 1 200,00	kr 2 241,35	0,00
(r_k, S_k)	kr 928,40	kr 1 170,00	kr 2 098,40	0,00

F Probability distribution

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9279	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9463	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998