The benefits of multi-echelon inventory control in a reseller of office supplies environment

Brugmans, G.H.

Eindhoven, Netherlands, October 2019

The benefits of multi-echelon inventory control in a reseller of office supplies environment

By

Brugmans, G.H.

Student number 0904042

In partial fulfilment of the requirements for the degree of

Master of Science in Operations management and logistics

Supervisors:

Dr. V.J.C. Lurkin, Eindhoven University of Technology

Prof. Dr. A.G. de Kok, Eindhoven University of Technology

L.G.M. Kauffeld, Office Depot Europe

Eindhoven University of Technology (TU/E). School of Industrial Engineering (IE).
Series Master's Thesis Operations Management and Logistics.

Subject headings: Supply chain management, multi-echelon inventory control, forecasting, seasonality, lead time variance, safety lead time, supply chain costs, customer service level

Abstract

This research concerns quantifying the benefits of multi-echelon inventory control in a reseller of office supplies environment. The supply chain at the reseller of office supplies is a multi-echelon one, which can be controlled either locally or centrally. The currently implemented installation stock policies with information sharing need to be preserved. However, the policy parameters are optimised based on a centralized multi-echelon inventory control approach. On top of that, the current control policy is analysed to find improvement potentials.

The current inventory control policy is explained in detail and afterwards adapted to multi-echelon inventory control. A simulation tool is developed to retrieve the supply chain performance, i.e. inventory holding costs, major order costs and minor order costs, and the customer service level measured in terms of aggregate unit fill rate, for each scenario.

The analysis of the current inventory control policy leads to the recommendation of using actual lead times instead of agreed vendor lead times. Agreed lead times deviate too much from the actual lead times, which forces the system into undesirable behaviour. Forecast information sharing between the CDC and LDCs leads to the same stock value and a disservice reduction of 46,6% compared to the scenario without information sharing.

The policy parameters are optimised with multi-echelon inventory control using ChainScope. The safety lead time concept is introduced to incrementally improve this scenario, but more benefits could be gained by optimising the safety lead time in future research. The multi-echelon inventory control scenario dominates the current control scenario; the stock value decreases with 2,3% accompanied with a 13,4% decrease in disservice.

Preface

Mariahout, October 2019

This research is the last step in my career as a student. It is the final requirement to obtain a master of science degree in Operations Management and Logistics. With a background in industrial engineering, I have had a wonderful time as a student. In this preface I want to thank everyone which have supported me in the last few years.

At first, I would like to thank my first supervisor Virginie Lurkin. Your support during the master thesis process has been very helpful for me. You always gave me critical feedback, which contributes to new insights and the quality of the final result. You have always had time to help me in difficult parts of the master thesis and I really appreciate your energy and dedication to the project. I would also want to thank Ton de Kok, my second TU/e supervisor. Your professional insights in the field of multi-echelon inventory control have supported in challenging me for the highest possible result. Additionally, your software tool ChainScope was very useful and produces interesting results for the company.

Another thanks to Laurens Kauffeld, my company supervisor at Office Depot Europe. Your comments and ideas gave me a critical point of view to my own work. Besides that, I want to thank the supply chain optimisation team (Rick op het Veld, Lesly van Heumen and Sil Heijnen), who always helped me with questions, data collection and new insights. A special thanks to Rick op het Veld, which was my company buddy and was always able to support me.

Moreover, I want to thank my fellow students for the great moments in the last few years. I am convinced that the combination of strengths lead to outstanding project results. A special thanks to Lisa van Lierop, we have always joined in project groups, studied together and we were great travel partners. You have also provided me with useful feedback regarding my master thesis project.

Finally, I want to thank family and friends for supporting me with relaxing activities. My friends have always been there to drink a beer and let me think about other, not study related, topics. I would like to thank my parents and sister for making me the person I am today.

Stan Brugmans

Executive summary

This research is about the benefits of multi-echelon inventory control over an installation stock control policy with information sharing. The research is performed at Office Depot Europe, a reseller of office supplies which serves 29 European countries. The management team wants to know how much the company could save after centrally optimising the policy parameters over the entire supply chain. The performance is measured in terms of service level (aggregate unit fill rate) and supply chain costs (inventory holding costs, major order costs and minor order costs). First a short answer to the main research question is provided and afterwards the main research question is discussed in detail with the sub-questions.

Main research question: *How can multi-echelon inventory control be used to minimize supply chain costs while maintaining the desired end customer service level in a reseller environment?*

In this research ChainScope is used to centrally optimise the control parameters of the already implemented installation stock control policy with information sharing. The software tool optimises the safety stock values, which are translated to the control parameters. The lead time input parameter is improved iteratively to enhance the performance of multi-echelon inventory control. In general, the stock value reduces (2,3%) and moves from centrally to locally. The service level is increased compared to the current control scenario. The answers to the sub-questions below give more insights to the main research question.

What is the demand distribution at the local distribution centres including the impact of seasonality and correlation?

To draw conclusions about the demand distribution and seasonality, sufficient data needs to be available. This means that only items which have three years (2016, 2017 and 2018) of complete data are included in this analysis. At first, all other variability causing factors as seasonality, trend and outliers, are excluded. Own-brand items which are delivered indirectly have an average trend of -0.48 per week and face seasonality mainly at the beginning of the year. Outliers are excluded based on a method described by Montgomery and Runger (2010). The Pearson correlation test proves that demand patterns of the same item in different warehouses show correlation.

Previous literature has shown that the gamma, normal and Poisson distribution are investigated most. The research gives a few reasons why the Poisson distribution could be excluded from the analysis, which means the data is only fitted to the normal and gamma distribution. For each item, the chi-square goodness of fit test, as described by Montgomory and Runger (2010), is used to check which distribution fits best. The distribution which scores lowest on the chi-square goodness of fit statistic is rated as the best fitting distribution. Note that the distribution fit does not always needs to be significant.

The analysis concludes that for 88,9% of the items in the LDC the gamma distribution outperforms the normal distribution. The demand pattern in the CDC, which is initiated by the purchase orders of the LDCs and business partners, also fits better to the gamma distribution (78,5 % of the items). In the remainder of this research it is assumed that the demand is gamma distributed.

What is the lead time distribution of the suppliers to the central distribution centre as well as the lead time distribution between the central distribution centre and the local distribution centres?

The same analysis is applied for the lead time distribution of the supplier to the CDC and the intercompany lead time between the CDC and LDCs. During the lead time distribution fit, the variance caused by the European harbour waiting time is excluded from the analysis, because this is (partly) in control of the company.

Again, the gamma distribution outperforms the normal distribution, but not as clear as for the demand distribution. The vendor to CDC lead times fit better to the gamma distribution in 56,9% of the cases, whereas for the CDC to LDC lead times this percentage is 64,0%. However, on average the chi-square goodness of fit statistic has a higher decrease when switching from the normal to the gamma distribution than the other way around. Those two observations lead to the conclusion that the lead times are also gamma distributed in the remainder of the research.

What would be the performance of the current system when the current replenishment policy is applied correctly?

A few years ago, the current LDC inventory control policy is developed in the master thesis of Op ‘t Veld (2016). After the master thesis of Op ‘t Veld (2016), the replenishment policy is adjusted to the needs of the company, which makes it look like an (R,s,S,nQ)-policy (Heijnen, 2019). The CDC uses a periodic review dynamic base-stock policy (R,S), where the base-stock level is adjusted with the forecast.

The CDC uses the agreed vendor lead times to determine the base-stock level. In this research this is compared with the scenario where the actual lead times are used. The scenario with actual lead time outperforms the agreed lead time scenario, since the service level is increased with 1% with a small inventory increase. To apply the policy correctly, in the remainder of the research it is assumed that the actual lead times need to be used.

The results above are generated with stationary simulated demand based on a gamma distribution with the forecast average and standard deviation. To point out the value of the manual adjustments of planners, simulation results are generated with actual demand. Compared to the simulated demand scenario, the stock value remains almost the same, but disservice increases with 742,3 %. This means that planners are important to cover demand peaks and other external influences.

What is the value of information sharing within the current replenishment policy?

The current replenishment policy in the CDC receives forecasts for the upcoming periods from the LDCs. The research has also investigated what would happen if the CDC needs to calculate the forecast by themselves. Instead of having access to daily demand information, only the periodic purchase order history of the LDCs and business partners is available.

The resulting simulation shows that the disservice of the information sharing scenario outperforms the disservice of the scenario without information sharing by a reduction of 46,6%, while the stock value remains almost the same. This confirms that information sharing adds value in a reseller of office supplies environment. Future research could investigate if the stock value decrease weights against the extra costs due to information sharing and if sharing more than only the forecasts would result in higher benefits.

Which multi-echelon inventory control strategies exist and can be used?

Multi-echelon control techniques are investigated intensively in previous research. A company requirement is to preserve the current replenishment policies and optimise the policy parameters over the entire supply chain. However, the literature has never combined the two policies implemented at the company. Therefore, ChainScope (a tool developed by A.G. de Kok) is used, which optimises safety stock levels independent of the implemented policy. The resulting values can be translated to the policy parameters.

In previous literature, two optimisation options are discussed often, i.e. cost minimization with penalty costs or cost minimization with a service level constraint. The most difficult part of the first option is computing the penalty cost value which demonstrates desirable system behaviour. ChainScope uses the second optimisation option, where a target service level on item level needs to be met against lowest costs.

What is the performance with multi-echelon inventory control?

The performance of the optimised multi-echelon control parameters is simulated and reported. At first, the actual lead times are used as input in the optimisation model. However, the software tool treats those lead times as fixed. The simulation results show a major stock decrease compared to the current policy, but the service level also drops to about 95%. To generate desirable results, safety lead time is added.

For the LDCs, the replenishment policy is flexible, which allows an analysis with the conclusion to include 4,3% added safety lead time to each item in a LDC. An expert opinion, verified by a lead time analysis, leads to the decision to add 10 days on vendor to CDC lead times. As expected, this added lead time concept increased stock value and the service level also raised with more than 3%.

A detailed analysis of the simulation result shows a major service level difference between slow movers and fast movers. This implies that the safety lead time needs to vary between slow and fast movers. The variable safety lead time scenario uplifts the service level again, while keeping the stock value constant. Afterwards, the scenario is compared with the current installation stock policy, but could be improved in future research by optimising the safety lead times.

What can be gained by changing the current installation stock policy parameters based on multi-echelon inventory control?

The incremental improved multi-echelon control scenario is finally compared to the current installation stock policy. The switch results in a stock decrease of 2,3% combined with a disservice decrease of 13,4 %. When the service level of the multi-echelon inventory control scenario would also be reduced to service level of the installation stock control policy, the stock decrease would definitely be higher than 2,3%.

In general, the new policy moves the stock from centrally to locally. This makes the LDCs more aware of their forecast accuracy, as they can actually see the over- or understock in their distribution centre. The research also shows differences between the number of LDCs where an item is sold and whether the item is a slow or a fast mover.

The results of this research conclude that the company could gain by implementing multi-echelon inventory control. However, the implementation needs an intense collaboration between the LDCs and the CDC. Before actually implementing multi-echelon control, the feasibility of this collaboration needs to be investigated.

Table of contents

List of figures

List of tables

List of equations

List of variables and abbreviations

a	The constant in the regression model
$\alpha_{E[DL]}$	Alpha parameter of the gamma distribution representing the demand during lead time
$\alpha_{E[DL]+E[U]}$	Alpha parameter of the gamma distribution representing the demand during lead time including the undershoot
$\beta_{E[DL]}$	Bèta parameter of the gamma distribution representing the demand during lead time
$\beta_{E[DL]+E[U]}$	Bèta parameter of the gamma distribution representing the demand during lead time including the undershoot
b	The trend factor in the regression model
Benelux	Belgium, the Netherlands and Luxembourg
Buyperiod	The number of periods to buy for the CDC
Dach Benelux	Germany, Austria, Switzerland, the Netherlands, Belgium and Luxembourg
$C_{cycle\ stock,\ Qboxround}$	Cycle costs of the optimal order quantity rounded on boxes
$C_{cycle\ stock,\ Qlayerround}$	Cycle costs of the optimal order quantity rounded on layers
$C_{cycle\ stock,\ Qopt+E[U]}$	Cycle costs of the unrounded optimal order quantity
$C_{cycle\ stock,\ Qpalletround}$	Cycle costs of the optimal order quantity rounded on pallets
$C_{minororder}$	Minor order costs
$C_{stockholding}$	Stock holding costs percentage
CV	Coefficient of variance
CDC	Central Distribution Centre
D_i	Actual demand in week i
E[D]	Expected daily demand
$E[D_L]$	Expected demand during lead time
$E[D_L + U]$	Expected demand during lead time including the undershoot
E_i	The expected number of observation in class i based on the hypothesized probability distribution
EOQ	Economic order quantity
E[U]	Expected undershoot
EU7	United Kingdom & Ireland, Germany, Switzerland, Austria and the Benelux
$FCcdc_a$	The forecast of the CDC in cycle a
IP	Intellectual property
IOP	Item order point (reorder level s)
ITM	Inventory Transaction Model
k	The number of bins or classes for the chi-square goodness of fit test
LDC	Local Distribution Centre
ME	Multi-echelon
MIN	Replenishment order minimum control parameter
MUL	Replenishment order multiple control parameter
n	The number of data points
O_i	The actual number of observations in class i
ORL	Order-up-to level at the LDCs

ORL_{CDC}	Order-up-to level at the CDC
p	Item price in Euros
$Q_{boxround}$	Optimal order quantity rounded to boxes
Q_{EOQ}	Economic order quantity
$Q_{layerround}$	Optimal order quantity rounded to layers
Q_{opt}	Optimal order quantity
$Q_{palletround}$	Optimal order quantity rounded to pallets
Q_{review}	Order quantity based on the demand during review period
Roundingvalue	Rounded optimal order quantity
R,s,S	Periodic review (R), reorder level (s) and order-up-to level (S)
r_{xy}	Sample Pearson correlation coefficient
s	Reorder level (IOP)
SBS	Synchronized Base Stock
SME	Small and Medium-sized Enterprises
s_{max}	Maximum reorder level used in the iterations to determine the optimal s
s_{min}	Minimum reorder level used in the iterations to determine the optimal s
S_{xx}	Sum of squares of the difference between the mean x value and each x
S_{xy}	Sum of the product of the difference between the mean x value and x with the difference between the mean y value and y
$\sigma(D_L)$	Standard deviation of the demand during lead time
$\sigma(D_L+U)$	Standard deviation of the demand during lead time including the undershoot
σ(LT)	Standard deviation of the lead time
σ(U)	Standard deviation of the undershoot
$\sigma_{weekly\ demand}$	Standard deviation of the weekly demand
μ(LT)	Average lead time
$\mu_{weekly\ demand}$	Average of the weekly demand
V_{min}	Vendor minimum
V_{mul}	Vendor multiple
X_0^2	Chi-square goodness of fit test statistic
$\hat{Y}$	The predicted value of Y

Simulation variables

$Balance_{i,0,t}$	Inventory position of item i at the CDC at the end of period t
$Balance_{i,j,t}$	Inventory position of item i at warehouse j at the end of period t
$BO_{i,0,t}$	Backorders of item i at the CDC at the end of period t
$BO_{i,j,t}$	Backorders of item i at warehouse j at the end of period t
$BPorders_{i,t}$	Business partner demand of item i at the end of period t
$D_{i,0,t}$	Demand of item i at the CDC at the end of period t
$D_{i,j,t}$	Demand of item i at warehouse j at the end of period t
$Incomingorder_{i,0,t}$	Incoming order of item i in the CDC at the end of period t
$Incomingorder_{i,j,t}$	Inbound replenishment order of item i in warehouse j at the end of period t
$IOP_{i,j,t}$	Reorder level of item i at warehouse j during period t
$LT_{i,0,t}$	Replenishment lead time of item i at the CDC at the end of period t
$LT_{i,j,t}$	Replenishment lead time of item i at warehouse j at the end of period t

$OHS_{i,0,t}$	Physical stock of item i at the CDC at the end of period t
$OHS_{i,0,value}$	Average on-hand stock value of item i in the CDC
$OHS_{i,j,t}$	On hand stock of item i at warehouse j at the end of period t (can be negative in case of backorders)
$OHS_{i,j,value}$	Average on-hand stock value of item i in warehouse j
$OHSactual_{i,0,t}$	Actual on-hand stock of item i in the CDC at the end of period t
$Orderday_{0,t}$	Binary variable indication whether day t in the CDC is an order day
$Orderday_{j,t}$	Binary variable indicating whether day t in warehouse j is an order day
$OpenBPorders_{i,t}$	Open business partner orders of item i at the CDC at the end of period t
$Openpos_{i,j,t}$	Open purchase orders of item i of warehouse j at the CDC at the end of period t
$ORL_{i,j,t}$	Order-up-to level of item i at warehouse j during period t
$ORL_{i,0,x}$	Order-up-to level of item i at the CDC during order cycle x
$Price_{i,0}$	The cost-price of item i in the CDC
$Price_{i,j}$	The cost-price of item i in warehouse j
$MIN_{i,0,t}$	Minimum replenishment quantity of item i at the CDC during period t
$MIN_{i,j,t}$	Minimum replenishment quantity of item i at warehouse j during period t
$MUL_{i,0,t}$	Replenishment order multiple of item i at the CDC during period t
$MUL_{i,j,t}$	Replenishment order multiple of item i at warehouse j during period t
$NetBO_{i,j,t}$	Net backorders of item i at warehouse j at the end of period t
$NetopenBPorders_{i,t}$	Net open business partner replenishment orders of item i at the end of period t
$NetopenPO_{i,j,t}$	Net open purchase order of item i of warehouse j at the CDC at the end of period t
$ReleasedBP_{i,t}$	Business partner order of item i sent to the business partner at the end of period t
$Releasedorder_{i,j,t}$	Replenishment order of item i sent from the CDC to warehouse j at the end of period t
$Reserved_{i,j,t}$	Reserved CDC stock of item i for warehouse j at the end of period t
$ReservedBP_{i,j,t}$	Reserved CDC stock of item i for the business partners at the end of period t
$Service_{i,0}$	Service level of item i at the CDC
$Service_{i,j}$	Service level of item i at warehouse j
$SOQ_{i,0,t}$	Suggested replenishment quantity of item i at the CDC at the end of period t
$SOQ_{i,j,t}$	Suggested replenishment quantity of item i at warehouse j at the end of period t
$SS_{i,0,x}$	Safety stock of item i at the CDC during order cycle x
$FC_{i,0,x}$	Forecast for item i at the CDC in order cycle x
$\#_{orderlines}$	Total number of replenishment order lines per year (both CDC and LDC)
$\#_{orders}$	Total number of replenishment orders per year (both CDC and LDC)

Simulation sets:

I	Unique items in local warehouses
B	Items for business partners
J	Warehouses
Y	Items for business partners & items in local warehouses

T	Time periods
X	CDC order cycles

1 Introduction

The supply chain of companies becomes more complex over time, with companies operating globally and serving a large customer market. This increases the need for advanced inventory control and replenishment policies. Supply chains can have multi-echelon characteristics and can be controlled with installation stock policies or integrated policies, which will be discussed later. In this research the benefits of a multi-echelon inventory control in an installation stock policy with information sharing is quantified in a reseller of office supplies environment.

In the first part of this report, some general information is given about Office Depot Europe, the company which owns the problem and where the thesis is written. Chapter 2 gives the problem definition, methodology and scope of the research. In chapter 3 demand and lead time information is given, including their distributions. Chapter 4 describes the current replenishment policies, which are translated to multi-echelon inventory control in chapter 5. In chapter 6 the simulation results are presented and discussed. Chapter 7 and 8 close the research with a conclusion and discussion.

1.1 Company fact and figures

Office Depot Europe has annual sales of approximately 1,1 billion euros in 2018. There are about 5.500 active employees, who are distributed across 13 different countries. In general, the company serves the business-to-business market. However, there are approximately 160 retail stores in France and Sweden, which contribute to 14% of the revenue.

The business-to-business market can be separated into 'Office Depot' and 'Viking' customers. Office Depot customers are characterized by relatively large customers which order their products (office supplies) on a contract basis. This means that they have a sales agent, which takes care of the relationship between the customer and Office Depot. The prices and products offered to that kind of customers are pre-defined in contracts. On the other hand, 'Viking customers' order their products on the website with consistent and transparent prices. Viking Customer can represent SMEs (Small and Medium-sized Enterprises) and private customers. The last type of customers are the ones which buy the items in the retail stores in France and Sweden.

The purpose of Office Depot is to highlight their deep office supply expertise, to offer solutions and supplies, to focus on customer experience and the desire to place online first. For 2018-2019, the company has eight objectives. One of them is directly related to the research and is defined as "to grow cash through a focus on inventory".

1.2 Company history

Office depot inc. is founded in Florida in 1986, with sales of about 2 million dollars. Office Depot expanded to Europe in 1990 in the United Kingdom. The company decided to merge with Viking Direct in 1998, which increased the total sales to 9 billion dollars.

In that time, sales grew fast as they reached 15 billion dollar a year worldwide during the 20th anniversary in 2006.

Finally, in 2017 a major change occurred as the European operations are separated from Office Depot. Aurelius has bought this European part of the organization, called Office Depot Europe. Aurelius group is a private equity firm with offices across Europe, the United States and Asia.

Nowadays, Office Depot Europe is still owned by Aurelius group and has annual sales of 1,1 billion euros. After the acquisition by Aurelius, the operations in France are separated from the rest of Europe.

1.3 Sales regions

Office Depot Europe is currently active in 29 different European countries. Those countries are divided over three groups named EU7, growth countries and France. The EU7 group consists of the United Kingdom & Ireland, Germany, Switzerland, Austria and the Benelux (Belgium, the Netherlands and Luxembourg). The growth countries are Spain, Portugal, Italy, Czech Republic and Sweden. To serve more countries, Office Depot Europe collaborates with business partners. Today there are 4 business partners which all have their own territory. They serve the customers in Bosnia, Bulgaria, Croatia, Denmark, Estonia, Finland, Hungary, Latvia, Lithuania, Macedonia, Montenegro, Norway, Poland, Romania, Serbia and Slovenia. In Figure 1.1 below an overview of the active sales regions is given. The distribution centre structure to serve all those regions is explained later.

Figure 1.1: Overview of the European countries where Office Depot is active

1.4 Supply chain characteristics and distribution centres in scope

Office Depot sells both own-brand products as products purchased at an external vendor (which delivers directly to the Local Distribution Centre (LDC)). The supply chain of the own-brand products is important for this research. This supply chain has a central distribution centre (CDC) in combination with several LDCs. This means that the supply chain consists of two echelons. Moreover, two different flows can be distinguished, i.e. the CDC direct flow and the CDC indirect flow. The CDC direct flow does not use the central distribution centre, as products are delivered directly from the vendor to the local distribution centres. The CDC indirect flow uses the central distribution centre as an extra storage point in the supply chain. France and Sweden form an exception, since they have retail stores. This means that the local distribution centre delivers products to the stores, where customers buy it. For this reason, in those two countries there is a three-echelon supply chain structure.

Office Depot sells products for which they have IP rights, known as “own-brand products”. Those products are mainly produced in Asia and afterwards transported to Europe by sea. For now, Office Depot is not interested in the third echelon (retail stores), so this is considered out of scope. The supply chain can be identified as a two-echelon supply chain, since there is a central distribution centre and various local distribution centres. Especially the indirect delivery can be identified as the two-echelon supply chain. Figure 1.2 shows an overview of the indirect supply chain. Different vendors produce the own-brand products and deliver them to the far-east consolidation centre. An important note is that the consolidation centre is only used for combining orders into a shipment and does not hold any stock. The products arrive at the central distribution centre by sea and/or road. Afterwards, the items are distributed to the local distribution centres and business partners by means of road transport. Finally, the products are delivered to the customers (where the delivery is outsourced).

In the remainder of this master thesis, the multi-echelon supply chain of Office Depot is defined as the part from the vendor (via the CDC and LDCs or the business partners) to the customers. Therefore, the multi-echelon supply chain structure of Office Depot has the characteristics of a divergent supply chain. This means that each stock point in the supply chain has at most 1 predecessor. (De Kok, 2003)

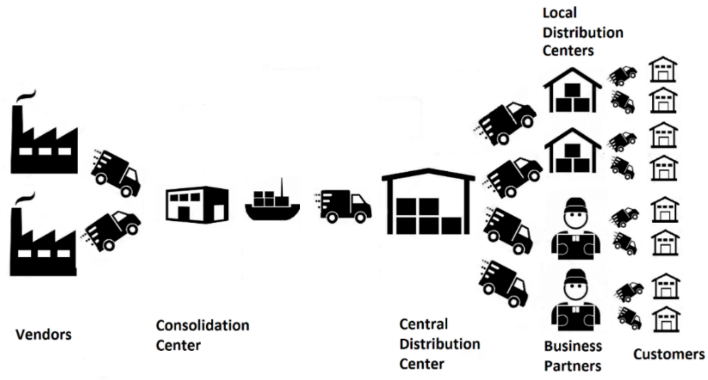

Figure 1.2: Supply chain structure CDC indirect

Office Depot has a central distribution centre located in Zwolle (the Netherlands). On top of that, there are 11 local distribution centres located in many European countries. The exact locations of those warehouses are displayed in Figure 1.3.

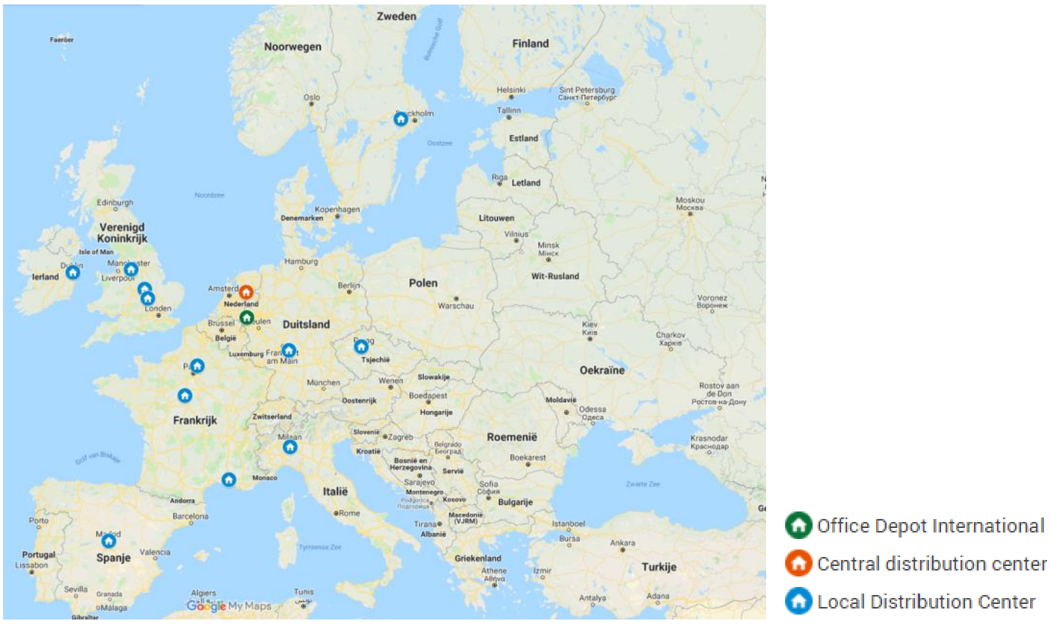

Figure 1.3: Overview of the European Office Depot locations

However, a few distribution centres operate in a special way. The distribution centre in Northampton only handles furniture and items which are too large or heavy to handle in another distribution centre. Office Depot still orders items for Northampton, but the handling itself is outsourced to an external party. The LDC located in Senlis (France) also handles only furniture. On top of that, the France operations are separated from the rest of the European operations. The distribution centre in Dublin only has a few direct deliveries and the remaining demand in Ireland is met via the distribution centre in Ashton. Because of the above-mentioned reasons, the warehouses in Northampton, France and Dublin are considered out of scope.

1.5 Product split and item selection

Office Depot sells products and services which help their customer to work better, whatever their workplace is. The product assortment is divided into 10 categories, which are given in Table 1.1 below.

Table 1.1: Product categories

Main group	**Product categories**
Facility management	Cleaning, hygiene and workwear
	Food and catering
	Furniture and presentations
Office administration	Filing and solutions
	GOS and mailing
	Writing and machines
Printing & Technology	Paper, label and envelopes
	Ink and toner
	Printers and technology
Others	Others

Office Depot has a few own brands which are distributed across all product categories. Those brands be Office Depot, Niceday, Foray, Realspace, Workpro, Highmark and Ativa which can only by purchased at Office Depot and are therefore categorized as own-brand products. In the remaining part of this research, the focus will be on those own-brand items.

The planning and inventory department is divided into 6 categories, based on product types (see Figure 1.4) Category 1, 2 and 3 represent the three main groups explained above (except 'Others'). Another category is called 'retained', which contains a customer-specific assortment. The last category is called 'vital', which has a little overlap with 'retained', but in this category the products are even more specific for a customer.

Figure 1.4: Division of the planning and inventory department

For the distribution centres within scope, the number of unique products in combination with the number of unique items which are delivered indirectly are presented in Table 1.2. Those numbers only represent the own-brand items. The assortment of Office Depot can change over time, but the numbers are retrieved on March 11, 2019. Dach Benelux is an often-used term which represent Germany, Austria, Switzerland, the Netherlands, Belgium and Luxembourg.

To execute a proper analysis, sufficient data needs to be available. Since developing and running a simulation tool is part of this research, a settle period is necessary to generate useful results. For this reason, only the items which have a complete data set between week 20 2017 and week 18 2019 are included. Moreover, when the resulting data has more than 5 zeros at the beginning (week 20 – week

24 in 2017) or at the end (week 15 – week 18 in 2019) of the set, the item is assumed to be a new item (phase-in) or will be excluded from the assortment soon (phase-out). Therefore, those items are not included in this research. As can be seen in Table 1.2, about 35% of the items are excluded, because they have either missing data or the item is introduced after week 20 2017.

Table 1.2: Distribution centres with the number of own-brand products

Country	**Distribution centre**	**Warehouse code**	**Number of unique products**	**Number of unique products delivered indirectly**	**Number of unique items delivered indirectly with sufficient data**
United Kingdom	Leicester	L	1.239	250	120 (48,0 %)
	Ashton	R	1.239	250	118 (47,2 %)
Italy	Siziano	M	483	445	337 (75,7 %)
Czech Republic	Hostivice	1	405	378	328 (86,8%)
Sweden	Strägnäs	009	505	495	350 (70,7 %)
Spain	Madrid	E	679	715	455 (63,6 %)
DACH Benelux	Großostheim	F	1.302	539	295 (54,7 %)
Total			**5.852**	**3.072**	**2.003 (65,2 %)**

The 2.003 item-warehouse combinations consist of 899 unique item codes. This means that an item can be sold in one or more distribution centres. The division of the number of distribution centres per unique item can be found in Table 1.3.

Note that items can have more distribution centres, but due to data cleaning they are excluded for this research. Therefore, it makes sense to hold items with only one distribution centre on stock in the CDC. On top of that, business partners are also delivered from the CDC. Table 1.4 gives the number of delivery locations when the business partners are included.

In this chapter general information about Office Depot Europe is given. Besides that, the distribution centres in scope are specified, including the number of items. In the next chapter the company problem is discussed and the research methodology is given.

Table 1.3: The number of distribution centres per unique item

Number of distribution centres	**Number of unique items**	**Number of item-warehouse combinations**
1	389	389
2	154	308
3	184	552
4	135	540
5	17	85
6	11	66
7	9	63
Total	**899**	**2.003**

Table 1.4: The number of distribution centres and business partners per unique item

Number of distribution centres	**Number of unique items**	**Number of item-warehouse and item-business partners combinations**
1	330	330
2	167	334
3	132	396
4	151	604
5	95	475
6	12	72
7	7	49
8	5	40
Total	**899**	**2.300**

2 Problem definition and methodology

The first part of this chapter explains the company problem and afterwards the research methodology to solve the problem is discussed.

2.1 Need for multi-echelon inventory control

The need for multi-echelon planning has risen around 1950. According to Clark (1958), past literature only has sought for optimal policies for relatively simple situations: one stocking point with one single item. However, this approach is very limited for the complex real-world supply systems, i.e. a supply chain with more stocking locations, which replenish each other. Due to a lack of a conceptual approach and many dimensions involved, past attempts to model such complex real-world supply systems have faltered. (Clark, 1958)

Muli-echelon inventory systems occur frequently in supply chains, since products need to be distributed over large geographical areas. Local distribution centres are needed to assure a high service level. To replenish those local warehouses, a central distribution centre is used (De Kok, 2003). According to Vargas Suavita (2012), the need for multi-echelon planning is defined as: "The motivation for using a multi-echelon inventory system rather than a single-echelon approach in each location, is that single-echelon approaches can lead to a poor coordination, delays and/or information distortion between suppliers and customers, and all these aspects are translated into the so-called bullwhip effect or the increase in demand distortion that moves upstream towards the manufacturers, causing inefficient use of resources and high transportation and inventory holding costs (De Kok, 2003)".

De Kok (2003) defines the goal of multi-echelon planning as: "The overall goal is, in general, to minimize the costs for ordering, for capital tied up in the supply chain, and for not providing adequate customer service". During the last two decades, the possibilities to control multi-echelon inventory systems have increased due to the research progress and information technology developments (De kok, 2003).

2.2 Research gap

De Kok et al. (2018) gives an overview of 394 papers about multi-echelon inventory control. This paper classifies all papers on the supply chain characteristics and replenishment policies. However, there is no paper which meets all criteria within the reseller of office supplies environment. Moreover, after an extensive literature review, the conclusion is drawn that the combination of replenishment policies used by Office Depot Europe is never investigated in multi-echelon inventory control papers.

The research gap can be identified as the multi-echelon inventory control strategy where the current replenishment policies are combined. The LDCs use a internally developed ITM-model, which combines the EOQ sensitivity analysis of Durlinger (1998), the (R,s,S) tool of De Kok (2010) and the P(s,S) policy of Viswanathan (1997) (Op 't Veld, 2016). In the last few years, this model is adapted, which makes it look like an (R,s,S,nQ)-policy (Heijnen, 2019). For the central distribution centre replenishments, a periodic review base stock (R,S) policy is used. The current policies are explained in more detail in chapter 4. There is no paper which addresses the value of multi-echelon inventory control over local stock control with a combination of those two policies.

In the literature two options for the optimisation function are given, i.e. cost minimization with penalty costs or cost minimization with service level constraints. The most difficult part of the first option is computing the penalty cost value which demonstrates desirable system behaviour. This research focuses on cost minimization with service level constraints.

This report adds value to the research within the field of multi-echelon inventory control. The value of multi-echelon inventory control will be addressed, while the two current control policies are combined (which is never investigated). Furthermore, a case study using simulation is developed within a reseller of office supplies environment.

2.3 Management issue and question

As mentioned before, the demand planning and inventory management of the central distribution centre and the local distribution centres are mostly separated. To reduce inventory and supply chain costs, the management wants to find out what the advantages of implementing multi-echelon control are.

To summarize, Office Depot faces the following management dilemma and management question:

Management dilemma: The inventory levels and supply chain costs of the own-brand products which follow the CDC indirect flow are too high.

Management question: How can multi-echelon inventory control be used to minimize supply chain costs while maintaining the desired end customer service level in a reseller environment?

The management question is translated to multiple research questions which assist in solving the management dilemma.

2.4 Main research questions and sub-questions

The main research question is equal to the management question described in the previous paragraph, which is formulated below.

Main research question: How can multi-echelon inventory control be used to minimize supply chain costs while maintaining the desired end customer service level in a reseller environment?

A few sub-questions related to the main research question can be formulated.

1. What is the demand distribution at the local distribution centres including the impact of seasonality and correlation?
2. What is the lead time distribution of the suppliers to the central distribution centre as well as the lead time distribution between the central distribution centre and the local distribution centres?
3. What would be the performance of the current system when the current replenishment policy is applied correctly?
4. What is the value of information sharing within the current replenishment policy?
5. Which multi-echelon inventory control strategies exist and can be used?
6. What is the performance with multi-echelon inventory control?
7. What can be gained by changing the current installation stock policy parameters based on multi-echelon inventory control?

2.5 Supply chain performance measures

The main objective of the master thesis is the comparison of multi-echelon inventory control compared to the current installation stock policy with information sharing. Therefore, the performance of the current situation is measured.

However, planners do not always stick to the policy guidelines and give their own twist to the replenishment policy. To give an idea about the improvements of changing to multi-echelon inventory control, the performance of the current policy when planners follow the guidelines exactly is analysed. To do this, the current policy is described and modelled in detail.

The next step is to take a look at the existing theories of multi-echelon control and find a proper policy to implement. As mentioned before, no paper which combines the two current replenishment policies exists. Therefore, another model is discussed which optimises the safety stock levels across the supply chain. A simulation model will be developed to test the performance of the current control model. Afterwards, the scenario in which parameters are based on multi-echelon stock control will be compared to the current installation stock policy to find the improvement potential.

The current performance measures of the supply chain of Office Depot are supply chain costs and service level, which are explained below.

The supply chain costs are the total costs in the supply chain to make it possible to deliver products to the final customers. Supply chain costs consist of three components, i.e. inventory holding costs, minor order costs and major order costs. Those performance measures are explained more extensively in chapter 5.

The other important performance measure is the service level perceived by the end customer. This can be defined as the unit fill rate, line fill rate and order fill rate. The unit fill rate is the percentage of units ordered which can be directly delivered to the customer on time. The same definition is true for the line fill rate and order fill rate, where the term units will be replaced by either order lines or orders. The company measures the service level in terms of line fill rate, but due to data accessibility issues, in this research service level is defined as unit fill rate. Eventually, the service level is measured on aggregate level, i.e. the service level is calculated over the cumulative demand and backorders over all items.

2.6 Methodology

In this section the methodology which is used to solve the research questions is discussed. The problem-solving cycle is used, which is based on the regulative cycle of van Strien (1997). This section elaborates on this methodology and the entire chapter follows the methods described in chapter 6 of van Aken et al. (2007).

2.6.1 Problem solving cycle

To solve a business problem, the problem-solving cycle is often used. An overview of this cycle is given in Figure 2.1. This research will contain the problem definition, analysis and diagnosis and solution design steps. The last two steps, intervention and learning and evaluation, is out of scope for the project.

At first, the company can face a lot of problems, which can be interrelated or stand-alone problems. The problem mess is a combination of all problems faced by project owners. Throughout the whole problem solving cycle, it is important to keep the problem mess in mind, such that the steps within the cycle always contribute to the overall goal.

The problem mess found in the orientation phase should result in a problem definition. The goal of the problem definition is to describe that part of the problem mess which will be investigated during the research. The chosen problem has to be in line with the company objectives, mission and strategy. Therefore, it is important to keep an eye on management decisions which change the company strategy, mission or objective. The problem definitions need to be splitted into a number of sub-assignments, which together form an answer to the main research question. Those parts are already described earlier in this chapter.

The analysis and diagnosis step in combination with solution design step uses the conceptual project design, discussed in van Aken et al. (2007). In the next session, a detailed explanation of this approach is given.

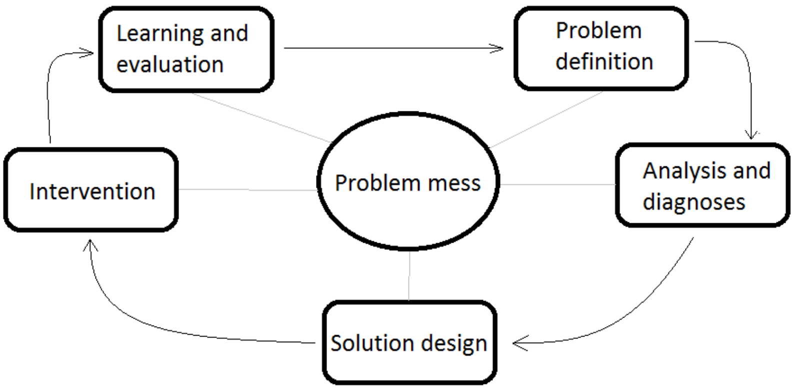

Figure 2.1:The problem-solving cycle (van Aken, 2007)

2.6.2 Conceptual project design

When the problem definition is clear, one can start executing the analysis and diagnoses step followed by the solution design step. The conceptual project design as proposed by van Aken et al. (2007) is used as a guideline for those two steps. The main idea behind this logic is to create a link between theory and practice to come up with a diagnosis and possible solution directions. In Figure 2.2 below, a graphical representation of the design (customized to the project) is presented. The subject of analysis can be found in the right box and the theoretical directions are represented in the box on the left.

The topic 'inventory systems' is needed to learn more about the existing inventory management systems. This serves as a basis for the master thesis and afterwards the multi-echelon inventory control strategies can be investigated. To conclude anything about the saving potential of multi-echelon control, this part is analysed in detail. Often, those models assume a particular demand or lead time distribution. Therefore, literature to identify those distributions is gathered. Eventually, since the demand can contain seasonality patterns, theory about the effects of seasonality is collected. Another important reason to find the demand and lead time distribution is to generate realistic simulation results.

The subject of analysis and the theoretical perspectives will lead to a diagnosis and solution design, which will be specified further after the theoretical background is found. In those steps, the current installation stock policy as well as the multi-echelon inventory control is explained and developed, after which the simulation results are generated.

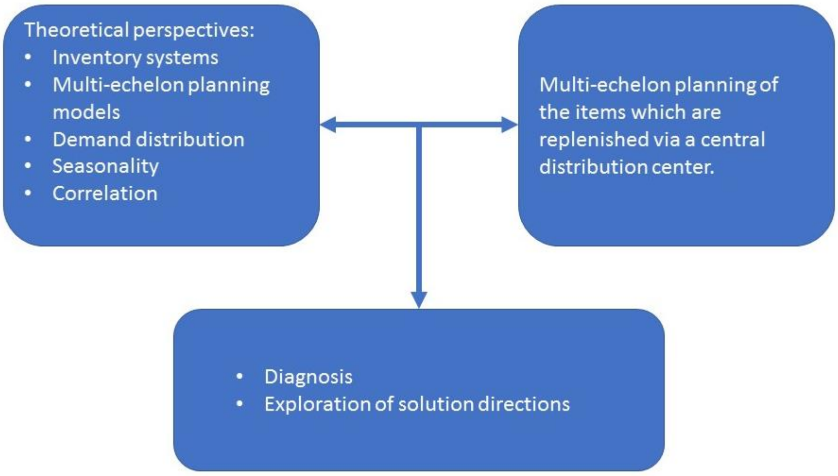

Figure 2.2: Conceptual project design

2.7 Scope

In this section, the scope of the project is defined in terms of region, product groups and other important input parameters. An overview of the scope is given in Table 2.1. Some topics are already discussed in the first chapter.

The replenishment strategy is compared for the own-brand items which are delivered via the CDC. This means that the current division of direct and indirect deliveries is considered as fixed. The review of the decision whether an item should be delivered directly or indirectly is out of scope, but could be an interesting follow-up assignment.

The regions which are considered are all distribution centres which are replenished via the CDC, including the business partners. Office Depot is interested in the CDC to LDC flow, which means the retail stores are considered out of scope. Therefore, the third echelon is not important anymore, which leaves the supply chain for this research as a two-echelon one. On top of that, chapter 1 mentions a few reasons to exclude the warehouses in France, Northampton and Dublin.

The safety stock calculation in combination with the reorder level computation need to be part of the research. Those are important, since they have a direct relationship to the performance measures and will change when the parameters are based on multi-echelon inventory control.

The accuracy of the forecast methods is out of scope for this research, since this single topic is large enough to cover another research on his own and hence not achievable within the amount of time.

Moreover, Office Depot is considering a CDC location change. Since the focus of the research needs to stay on multi-echelon inventory control, the assumption is made that the CDC will stay in Zwolle (or at least stays in Europe). With this assumption the exact location with the cost parameters is known, which is crucial for a proper analysis.

To actually implement the solution, a major change of the information systems and system structure could be required. This is not part of the research, because the aim is only to analyse the potential of multi-echelon inventory control instead of actually implementing it.

Table 2.1: Overview of the scope

	Within scope	**Out of scope**
Items	Own-brand items which are replenished indirectly	Other than own-brand items or own-brand items which are replenished directly or have too less data
Region	All regional distribution centres in the United Kingdom, Italy, Czech Republic, Sweden, Spain and Germany	Retail stores and the distribution centres in France, Northampton and Dublin
Review of the replenishment method	Within scope	
Forecast method		Out of scope
CDC location change		Out of scope
Information systems		Out of scope

This chapter defined the research questions which will be answered, including the scope of the research. The next chapter fits the demand and lead time pattern to a data distribution and gives some insights regarding seasonality, trend and correlation.

3 General demand and lead time analysis

In this chapter the demand pattern and historic lead times are analysed. The first part gives insights into the demand characteristic and distribution, whereas the second part determines the lead time distribution of the vendors to the CDC and the intercompany CDC to LDC lead time distribution.

3.1 Demand analysis

The demand distribution is often an assumption for an inventory control policy. Therefore, the demand distribution is determined for every item-warehouse combination. In the upcoming paragraph, variability pooling is described as a potential benefit of a multi-echelon supply chain. To determine the demand distribution, other factors (i.e. trend, seasonality and outliers), that cause variance, are excluded. Afterwards, the demand distribution and the correlation between LDCs can be calculated. Computing the trend and seasonality only makes sense when the considered time period is sufficiently long. For this reason, only the item-warehouse combinations which have at least three years of data (2016, 2017 and 2018) are included in the analysis.

3.1.1 Variability pooling

One benefit of a multi-echelon supply chain could be variability pooling. This means that the combined variability of the total demand is less than the average variability of the demand at the single local warehouses. The coefficient of variation is used, because it calculates the variance with respect to the mean. This makes it possible to compare items with different averages. The formula for the coefficient of variation is formulated in Equation 3.1.

$$CV = \frac{\sigma_{weekly\ demand}}{\mu_{weekly\ demand}}$$

Equation 3.1: Coefficient of variation

There are 403 items which are delivered indirectly for at least 2 warehouses. For those items, the coefficient of variation of the total demand is compared with the average coefficient of variation of the single local distribution centre demands. In 97,8 % of the comparisons, the coefficient of variation for the total demand is lower than the average coefficient of variation. The average coefficient of variation of the total demand is 0,86, whereas the average coefficient of variation of the single demands is 1,24. This means that the coefficient of variation can be reduced with 30,6%. Those results show that the company could gain from a multi-echelon supply chain.

3.1.2 Trend, seasonality and outliers

To measure the trend within an item demand pattern, the regression analysis method described by Nahmias and Cheng (2005) is used. In this method we believe that the relationship between X and Y is linear and can be defined with Equation 3.2.

$$\hat{Y} = a + bX$$

Equation 3.2: Regression model as described by Nahmias and Cheng (2005)

Where Ŷ is the predicted value of Y, a is the constant and b is the trend factor. The values of the factors a and b are determined such that the sum of squared distances between the actual data points and the regression line is minimized. For this research, only the trend factor is important, so those calculations are explained below with Equation 3.3, Equation 3.4 and Equation 3.5.

$$b = \frac{S_{xy}}{S_{xx}}$$

Equation 3.3: Trend factor

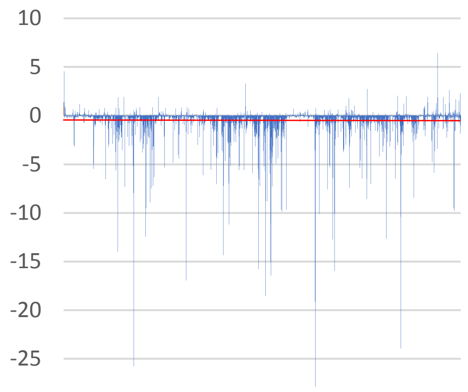

Figure 3.1: Trend per item-warehouse combination

Where

$$S_{xy} = n\sum_{i=1}^{n} iD_i - \frac{n(n+1)}{2}\sum_{i=1}^{n} D_i$$

Equation 3.4: Trend factor part 1

$$S_{xx} = \frac{n^2(n+1)(2n+1)}{6} - \frac{n^2(n+1)^2}{4}$$

Equation 3.5: Trend factor part 2

The trend of all item-warehouse combinations is calculated and plotted in Figure 3.1. The red line indicates the average trend of -0,48 per week. The calculated trend for each item-warehouse combination is removed from the sales data since this variance cannot be explained by the demand distribution. The next step is to calculate the seasonality for every item-warehouse combination.

After removing the trend from the data, seasonality has to be removed. Nahmias and Cheng (2005) define a method to calculate the seasonal factors for stationary series. The considered seasonal periods have a length of 4 weeks. This means that one year will be divided into 13 buckets of 4 weeks. The first step is to calculate the average sales per bucket over the total data set (which contains 3 years with 13 buckets). Afterwards, for each bucket the actual bucket sales are divided by this average bucket sales. Since the research will use three years of data, there will also be three buckets which represent the same period of the year. The average of those three buckets will be specified as the seasonal factor. To give an example, the seasonal factors of the total demand are given in Figure 3.2.

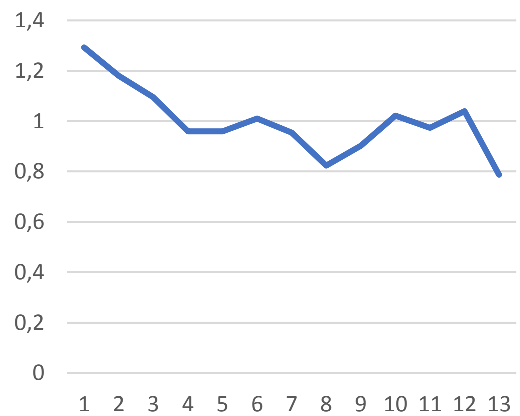

Figure 3.2: Seasonal factors of the total demand

Montgomery and Runger (2010) provide a method to the detect outliers. To find the appropriate demand distribution, outliers are excluded from the dataset. Montgomery and Runger (2010) define the interquartile range as the distance between the lowest 25 percent of the data points and the highest 25 percent of the data points. To find the interquartile range, the data points are ranked from low to high. For example, when the data set has 100 data points, the interquartile range is found by subtracting the 25th data point from the 75th. Outliers are defined as data points which are more than 1,5 times the interquartile range below the 25th data point or above the 75th data point.

3.1.3 Distribution fitting method

To determine which data distribution has the best fit with the actual demand, the chi-square goodness of fit test is used. This test, as described by Montgomory and Runger (2010), first divides the data set into k bins or class intervals. Afterwards, for each bin the actual number of observations are counted (O) and the expected number of observations (E) is calculated based on the hypothesized probability distribution. Finally, the test statistic can be calculated with Equation 3.6.

$$\chi_0^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i}$$

Equation 3.6: Chi-square goodness of fit test statistic

The lower a certain distribution scores on the test statistic, the better the fit. The software package Python is used to execute the calculations. The computation of the test statistic is a predefined function in Python. Moreover, the software chooses the optimal number of bins for a given data set.

Previous research has investigated a few demand distributions very intensively. This research is going to focus on those common used distributions, which are the normal, gamma and poisson distribution.

Axsäter (2015) mentions that a sum of many independent data points tends to a normal distribution (central limit theorem). Since the total weekly demand at the warehouses is generated by many independent customers, the weekly aggregated demand could be normally distributed. A normal distribution always has at least a small probability of a negative value. Since the customer demand cannot be negative, another distribution is also considered. The best alternative given by Axsäter (2015) is the gamma distribution.

Furthermore, Axsäter (2015) also states that a compound Poisson process will approximate the normal distribution when the time period is sufficiently long. On top of that, Montgomery and Runger (2010) state that the Poisson distribution is approximated by the normal distribution when the average demand is higher than 5. After removing the trend, seasonality and outliers from the dataset, 83,5% of the item-warehouse combination have an average demand of higher than 5. This large fraction, combined with the statement of Montgomery and Runger (2010) and Axsäter (2015), leads to the decision of only fitting the normal and gamma distribution.

3.1.4 Distribution fitting results

As mentioned in the previous section, only the normal and gamma distribution is fitted for all own-brand items which are delivered indirectly to the local distribution centres and have complete data for 2016, 2017 and 2018. As the data would not always fit perfectly, the distribution which scores lowest on the chi-square test statistic is considered as the best fit.

Table 3.1: Distribution fitting results LDC

Distribution	**Number of times the fit is better than the other one**	**Percentage**
Gamma	1.570	88,9 %
Normal	197	11,1%

The results of the distribution fit can be found in Table 3.1. As can be seen, the gamma distribution outperforms the normal distribution for 88,9 % of the items. It is important to note that the data has not always a significant fit with the particular distribution. However, since only the most common used distributions are tested, one can conclude that the gamma distribution fits better than the normal distribution. Therefore, in the remainder of this report it is assumed that the demand at the local distribution centres is gamma distributed.

3.1.5 Correlation

The demand of a single item at different distribution centres can be correlated. To investigate whether this happens, the Pearson correlation test is used. This test is described by Montgomery and Runger (2010), which defines the sample correlation coefficient with Equation 3.7.

$$r_{xy} = \frac{\sum_{i=1}^{n} y_i(x_i - \bar{x})}{\left[\sum_{i=1}^{n}(y_i - \bar{y})^2 \sum_{i=1}^{n}(x_i - \bar{x})^2\right]^{1/2}}$$

Equation 3.7: Sample correlation coefficient

Where x and y are two data sets of a single item at different distribution centres. $\bar{x}$ and $\bar{y}$ are the averages of those data sets.

Table 3.2: Results of the Pearson correlation test

	Number of combinations	Percentage
Positive significant	426	19,3%
Negative significant	14	0,6%
Not significant	1.763	80,0%

The Pearson correlation test is executed for every warehouse combination which sell the same item and is delivered indirectly. The results can be found in Table 3.2 and show that in most cases no significant correlation is found. On top of that, when a significant correlation is found, a positive correlation is likely. This insight is only used to show the forecast difficulty at the reseller in office supplies.

3.1.6 Demand distribution at the central distribution centre

The same procedure is used to test the distribution of LDC and business partner purchase orders at the CDC. Since the CDC orders in periods of 4 weeks, the data is gathered in periods of 4 weeks. As mentioned before, the trend, seasonality and outliers are removed from the dataset. The distribution is fitted only over the items which have complete data for three years. The chi-square test is used to test whether the data better fits to a normal or gamma distribution.

Table 3.3: Distribution fitting results CDC

Distribution	Number of times the fit is better than the other one	Percentage
Gamma	585	78,5%
Normal	160	21,5%

Table 3.3 shows the results of the chi-square goodness of fit test for the CDC. The gamma distribution performs better for 78,5 % of the items, so in the remainder of this report a gamma distribution for all items will be assumed.

3.2 Lead time analysis

To replenish the local distribution centres and the central distribution centre, lead time is taken into account. The lead time is defined by the number of days between the order placement until the order is received. Since there are two echelons, there are also two lead times components, i.e. from vendor to the CDC and from the CDC to LDCs. In this chapter those lead times are described and explained.

3.2.1 Vendor to CDC lead time

The CDC is replenished by the external vendors. Currently, there are 60 vendors for own-brand items. A distinction can be made by far-east vendors and European vendors. The data for the far-east vendors is more complete than for European vendors. European vendors only have stored the order date and delivery date, while far-east vendors do have more time stamps as mentioned in Table 3.4. The composition of the lead time is presented in Figure 3.3. Furthermore, to give an idea about this composition, the average fraction of time spend in each stage can be found in Figure 3.4 and Table 3.5.

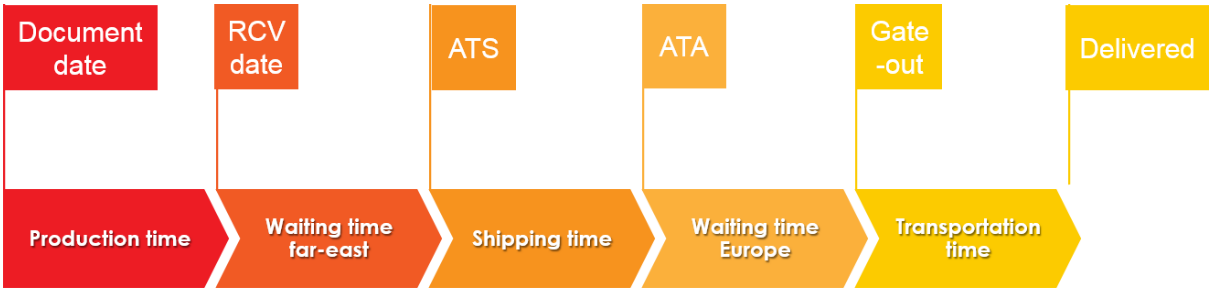

Figure 3.3: Composition of the far-east lead times

Table 3.4: Available data far-east vendor

Time stamp	**Explanation**
Document date	Order receiving date
RCV date	Far east harbour arrival date
ATS	Actual time of shipment
ATA	Actual time of arrival in Europe
Gate-out	Date on which the container leaves the European harbour
Delivered	Delivery date in the CDC

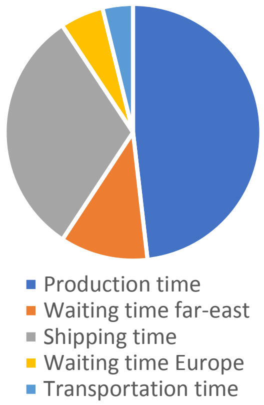

Figure 3.4: Lead time split (far-east vendors)

The statistics for the lead times are gathered on vendor level and the distribution of the lead times is also determined on vendor level. However, the company has control over the sequence in which the containers arrive at the CDC. This means that they can choose which container will wait in the European terminal and which one will be released. Therefore, the lead time variance due to the waiting time in the European harbour is excluded while fitting the distribution.

Table 3.5: Average fraction of time spend in each stage

Lead time component	**Average in workdays**	**Standard deviation**
Production time	31,66	8,05
Waiting time far-east	6,98	2,84
Shipping time	20,00	2,23
Waiting time Europe	3,59	2,18
Transportation time	2,43	1,73
Total lead time	64,96	9,10
Total lead time without waiting time Europe	61,64	9,43

For the European vendors, only the document and delivery date is available. The lead time is defined as the number of workdays between those two moments.

The lead times from the vendors to the CDC are fitted to the gamma and normal distribution. The distribution is fitted per vendor and afterwards the lead time of every item within that vendor is assumed to be equal. The results of the distribution test can be found in Table 3.6.

Table 3.6: Distribution test vendor to CDC

Distribution	**Number of times the fit is better than the other one**	**Percentage**
Gamma	818	56,9%
Normal	620	43,1%

For the cases the gamma distribution scores lower than the normal distribution, the weighted average decrease in the chi-square measure compared to the normal distribution is 21,4%, compared to a decrease of 10,0% the other way around. This means that the weighted average chi-square reduction when the gamma distribution 'wins' is more than twice as big as when the normal distribution 'wins'. Together with the results in Table 3.6, this leads to the assumption of gamma distributed vendor to CDC lead times.

3.2.2 Central distribution centre to local distribution centre lead time

The local distribution centres are replenished from the central distribution centre. This section explains the lead time distribution for this part of the supply chain. As the local distribution centres have a fixed order date and an agreed fixed receiving date, the lead time should be fixed as well. This means that the local distribution centres work with a weekly cycle, where they have fixed order days. However, the actual lead time can deviate from the agreed lead time. This section analyses the lead times and fits the actual data against the normal and gamma distribution.

The lead times are gathered per LDC to CDC combination. The data fit is tested for every warehouse-CDC combination. Afterwards, the same distribution is assumed for every item in the warehouse. The items with their best fitting distribution are counted and displayed in Table 3.7.

Table 3.7: CDC to LDC lead times

Distribution	**Number of times the fit is better than the other one**	**Percentage**
Gamma	1.711	64,0%
Normal	963	36,0%

On top of those results, when the gamma distribution has a better score, the weighted average decrease in the chi-square measure is 85,1%. On the other hand, when the normal distribution fits better, the weighted average reduction of the chi-square measure is 20,0%. The combination of the number of times the gamma is preferred over the normal distribution and the fact that the weighted average reduction is much bigger for the gamma distribution, leads to the assumption of gamma distributed lead times from CDC to LDC.

The warehouses in the Czech Republic and Sweden do not have stored their lead time information. This means that those lead times need to be estimated. In consultation with the company, it is agreed that the average of Spain and Italy will be a good representation for the two missing countries.

4 Current installation stock replenishment policy at Office Depot Europe

The current replenishment policy at Office Depot is an installation stock one with information sharing between the CDC and the local distribution centres. However, the local replenishment method of a few countries is not known or visible. Therefore, it is assumed that all distribution centres use the internally developed inventory transaction model (ITM). As this is currently not the case, the method is simulated for all distribution centres. This will be the baseline for the comparison with multi-echelon control described in chapter 5. In the second part of this chapter, the current (R,S)-policy in the CDC is discussed.

4.1 Local distribution centre replenishment method

As mentioned above, every LDC is assumed to use the ITM-model, which is developed in the master thesis of Op 't Veld (2016). This model is developed a few years ago, because the product availability was too low, the inventory value was too high and the number of inbound delivery lines was too high. The ITM-model combines the EOQ sensitivity analysis of Durlinger (1998), the (R,s,S) tool of De Kok (2010) and the P(s,S) policy of Viswanathan (1997) (Op ‘t Veld, 2016). After the master thesis of Op ‘t Veld (2016), the replenishment policy is adjusted to the needs of the company, which makes it look like an (R,s,S,nQ)-policy (Heijnen, 2019). This is an installation stock policy, since a LDC only need information about its own distribution centre.

4.1.1 ITM input

One characteristic of the ITM model is the static forecasting method. Every local distribution centre calculates the forecast for the upcoming 4 weeks by averaging the demands during the last 13 weeks. Weekly demand which deviates more than two times the standard deviation from the average are excluded from the forecast. On top of that, weeks 1, 51 and 52 will not be used either, since the demand during those weeks is not representative compared to the surrounding weeks. The standard deviation of the forecast is calculated over the same weeks as used for the average. This method is classified as the horizontal moving average forecasting technique, as described by Thomopoulos (2015) in Equation 4.1.

$$forecast = \frac{[x(1)+..+x(N)]}{N}$$

Equation 4.1: Horizontal moving average forecasting

Where x(1), .. , x(N) are the demand entries and N is the most recent demand point. Remember that outliers will be removed, which affects the number of entries.

To prevent the replenishment policy from high parameter fluctuations and overstock, the forecast coefficient of variation is capped on 2,5. This means the standard deviation of items which have a standard deviation of more than 250% is equated with 250% of the average.

The ITM-model uses a target service level to determine the optimal parameters. The overall target for items at Office Depot is a service level of 99,1%. However, the company strives for a higher service level for a few items, which are targeted on 99,5%.

The actual lead times from the CDC to the LDCs are gathered over the year 2018. For each LDC, the average is calculated and the standard deviation of the transportation and handling time equals 20% of the average. The actual lead times can deviate more due to a lack of CDC stock. Since ITM does not want to take this variance component into account, the standard deviation is fixed at 20% of the average.

The carton, layer and pallet quantities are gathered from the system and checked for correctness. The retrieved values are compared with the feedback from the warehouse. All prices are displayed in Euros.

The review periods for the local distribution centres are fixed, since all local distribution centres order once a week on a fixed day. This means that the review period of all LDCs equals five workdays.

The supply chain costs of Office Depot can be divided into inventory holding costs, minor order costs and major order costs. The inventory holding costs can be computed as 24,5% of the item price. The minor order costs are valued at € 5,50 per order line, while the major order costs are valued at € 20,00 per order.

4.1.2 Calculation of the optimal order quantity in ITM

The first part of the ITM-model calculates the optimal order quantity Q_{opt}. Q_{opt} can be based on the EOQ (Economic Order Quantity) formula (Equation 4.2) or the review period formula, which equals the demand during review period (Equation 4.3). The optimal order quantity is the maximum of the EOQ and the demand during review period (Equation 4.4).

$$Q_{EOQ} = \left\lceil \sqrt{\frac{2 * C_{minororder} * E[D] * 260}{p * C_{stockholding}}} \right\rceil$$

Equation 4.2: Economic order quantity

$$Q_{review} = \lceil E[D] * RP \rceil$$

Equation 4.3: Order quantity based on review period

$$Q_{opt} = \max\left(Q_{EOQ}, Q_{review}\right)$$

Equation 4.4: Optimal order quantity

The Q_{opt} given in Equation 4.4 equals the difference between s (IOP) and S (ORL) in the R,s,S-model. However, the actual ordered quantity will not equal the optimal order quantity. The ordered quantity will be at least the Q_{opt}, which is the difference between the IOP and ORL, plus the expected undershoot. Expected undershoot is defined as the expected number of units the inventory position is below the IOP when an order is placed. The expected undershoot depends on the length of the review period and the demand characteristics and is formulated in Equation 4.5.

$$E[U] = \frac{\frac{(\sigma(D)^2 * RP + E[D]^2 * RP^2) * 0.5}{E[D]}}{RP}$$

Equation 4.5: Expected undershoot

The standard deviation of the replenishment order quantity only depends on the standard deviation of the undershoot, which can be computed with Equation 4.6.

$$\sigma(U) = \sqrt{\left(1 + \frac{\left(\frac{\sigma(D)}{E[D]}\right)^2}{RP}\right) * \left(1 + 2 * \frac{\left(\frac{\sigma(D)}{E[D]}\right)^2}{RP}\right) * \frac{(E[D] * RP)^2}{3} - E[U]^2}$$

Equation 4.6: Standard deviation of the undershoot

4.1.3 Order rounding

The optimal order quantity will be rounded to force the system into desired behaviour for warehouse operations. This means that orders are rounded to either entire pallets, entire layers, entire boxes or single units. Q_{opt} is only rounded when the resulting added cycle costs (called cost variance) due to rounding is below 10%. The cycle cost of the unrounded optimal order quantity is calculated with the formula in Equation 4.7.

$$C_{cycle\ stock,Q_{opt}+E[U]} = \left(\frac{Q_{opt+E[U]}}{2} * p * C_{stockholding}\right) + \left(\frac{E[D] * 260}{Q_{opt+E[U]}} * C_{minororder}\right)$$

Equation 4.7: Cycle costs of the unrounded optimal order quantity

The optimal order quantity will be rounded to pallets, boxes or layers with the formulas in Equation 4.8, Equation 4.9 and Equation 4.10.

$$Q_{palletround} = \left\lceil \frac{Q_{opt+E[U]}}{Q_{pallet}} \right\rceil * Q_{pallet}$$

Equation 4.8: Optimal order quantity rounded to pallets

$$Q_{layerround} = \left\lceil \frac{Q_{opt+E[U]}}{Q_{layer}} \right\rceil * Q_{layer}$$

Equation 4.9: Optimal order quantity rounded to layers

$$Q_{boxround} = \left\lceil \frac{Q_{opt+E[U]}}{Q_{box}} \right\rceil * Q_{box}$$

Equation 4.10: Optimal order quantity rounded to boxes

The rounding values are based on the decision tree described in Equation 4.11, Equation 4.12 and Equation 4.13.

$$Roundingvalue = \begin{cases} Q_{pallet} & if\ (\frac{C_{cycle\ stock,Q_{palletround}}}{C_{cycle\ stock,Q_{opt+E[U]}}} - 1 < 0.1) \\ Roundingvalue^{a} & otherwise \end{cases}$$

Equation 4.11: Order quantity rounding value

$$Roundingvalue^{a} = \begin{cases} Q_{layer} & if\ (\frac{C_{cycle\ stock,Q_{layerround}}}{C_{cycle\ stock,Q_{opt+E[U]}}} - 1 < 0.1) \\ Roundingvalue^{b} & otherwise \end{cases}$$

Equation 4.12: Order quantity rounding value (a)

$$Roundingvalue^{b} = \begin{cases} Q_{box} & if\ (\frac{C_{cycle\ stock,Q_{boxround}}}{C_{cycle\ stock,Q_{opt+E[U]}}} - 1 < 0.1) \\ 1 & otherwise \end{cases}$$

Equation 4.13: Order quantity rounding value (b)

It is important to note that the optimal reorder level will be based on the unrounded order quantity.

4.1.4 Service level calculation

The service level for items in the local distribution centres in the current inventory control policy can be calculated using Equation 4.14.

$$P_2 = 1 - \frac{(E[D_L] + E[U]) * \left(1 - F\left(s; \alpha_{E[D_L]+E[U]}; \beta_{E[D_L]+E[U]}\right)\right) - s * \left(1 - F\left(s; \alpha_{E[D_L]+E[U]} - 1; \beta_{E[D_L]+E[U]}\right)\right)}{Q_{opt} + E[U]} + \frac{E[D_L] * \left(1 - F\left(s + Q_{opt}; \alpha_{E[D_L]}; \beta_{E[D_L]}\right)\right) - s * (1 - F\left(s + Q_{opt}; \alpha_{E[D_L]-1}; \beta_{E[D_L]}\right))}{Q_{opt} + E[U]}$$

Equation 4.14: Service level for items in the local distribution centres

The expected demand during lead time can be calculated with Equation 4.15, while the standard deviation of demand during lead time is calculated with Equation 4.16. The expected demand during lead time including the expected undershoot is computed with Equation 4.17, with the standard deviation formulated in Equation 4.18.

$$E[D_L] = E[D] * E[LT]$$

Equation 4.15: Expected demand during lead time

$$\sigma(D_L) = \sqrt{E[LT] * \sigma(D)^2 + E[D]^2 * \sigma(LT)^2}$$

Equation 4.16: Standard deviation of the demand during lead time

$$E[D_L + U] = E[D_L] + E[U]$$

Equation 4.17: Expected demand during lead time including the expected undershoot

$$\sigma(D_L + U) = \sqrt{\sigma(U)^2 + \sigma(D_L)^2}$$

Equation 4.18: Standard deviation of the demand during lead time including the undershoot

Since the expected demand during lead time and the undershoot are gamma distributed, the combination of the two is also assumed to be gamma distributed. The parameters of the distribution can be calculated by means of Equation 4.19, Equation 4.20, Equation 4.21 and Equation 4.22.

$$\alpha_{E[D_L]} = \frac{E[D_L]^2}{\sigma(D_L)^2}$$

Equation 4.19: Alpha parameter of the gamma distribution representing the demand during lead time

$$\beta_{E[D_L]} = \left(\frac{\sigma(D_L)}{E[D_L]}\right)^2 * E[D_L]$$

Equation 4.20: Bèta parameter of the gamma distribution representing the demand during lead time

$$\alpha_{E[D_L]+E[U]} = \frac{E[D_L + U]^2}{\sigma(D_L + U)^2}$$

Equation 4.21: Alpha parameter of the gamma distribution representing the demand during lead time including undershoot

$$\beta_{E[D_L]+E[U]} = \left(\frac{\sigma(D_L + U)}{E[D_L + U]}\right)^2 * E[D_L + U]$$

Equation 4.22: Bèta parameter of the gamma distribution representing the demand during lead time including undershoot

4.1.5 Calculation of the optimal reorder level

The calculation of the reorder level which yields a service level as close as possible to the target service level is obtained by executing a few iterations. The model is built such that only 14 iterations need to be executed, instead of testing all possible reorder levels. The reorder level of the iteration will be calculated with the variables s_{min} and s_{max}, which can change every iteration (as showed in Equation 4.23).

$s = \frac{s_{max}+s_{min}}{2}$ with starting values $s_{max} = 10 * E[D_L]$ and $s_{min} = 0$

Equation 4.23: Reorder level which belongs to the iteration

The fill rate which belongs to the reorder level of Equation 4.23 is calculated with Equation 4.14. If the target fill rate is lower than the fill rate calculated with the reorder level above, the new iteration will use the old s as s_{max}. On the other side, when the target fill rate is higher than the calculated fill rate, the old s will be used as s_{min} in the new iteration. After multiple iterations, s_{min} and s_{max} get close to each other, which leads to the optimal reorder level.

4.1.6 Output parameters ITM-model

The ITM-model produces four important control parameters, i.e. MIN, MUL, IOP and ORL. In the upcoming section the calculation of those values is explained. The output parameters will be used in the simulation tool as described in the next chapter.

The replenishment order minimum is calculated as the maximum between the vendor minimum and the rounding quantity proposed by ITM (Equation 4.24).

$$MIN = \max\ (V_{Min}, Roundingvalue)$$

Equation 4.24: Replenishment order minimum

The replenishment order multiple is calculated in the same way as the order minimum, where the vendor minimum is replaced by the vendor multiple (Equation 4.25).

$$MUL = \max(V_{Mul}, Roundingvalue)$$

Equation 4.25: Replenishment order multiple

The final reorder level is the rounded average of s_{max} and s_{min} with the only restriction that this value needs to be at least 1 (Equation 4.26). This restriction is needed, since otherwise the website will always flag the item as out of stock.

$$IOP = \max\left(1, \left[\frac{s_{min} + s_{max}}{2}\right]\right)$$

Equation 4.26: Item order point (reorder level)

The order-up-to level is the sum of the IOP and the optimal order quantity (Equation 4.27). Note that the inventory position is raised to the ORL or above the ORL, which means that the actual replenishment order quantities are not equal to the optimal order quantity.

$$ORL = IOP + \ Q_{opt}$$

Equation 4.27: Order-up-to level

4.2 Central distribution centre replenishment policy

The central distribution centre uses a periodic review order-up-to (R,S) policy. This policy also contains most characteristics of an installation stock policy, except the forecast information sharing component described in this chapter. The inventory position is reviewed every 20 workdays, where the planners decide whether a replenishment order needs to be placed. All customers (LDCs and business partners) send their forecast for the upcoming periods to the CDC, such that the replenishment order can be based on the forecast of the customers. For this research it is assumed that the LDCs and business partners use the horizontal moving average forecasting technique as described in chapter 4.1.1. The CDC forecast is completed by summing all local and business partner forecasts.

Afterwards the number of cycles for which the planner has to buy (buyperiod) is determined. This depends on the agreed lead time (in workdays), review period and safety stock (in workdays) and can be computed with Equation 4.28. The length of the order cycle equals 20 workdays.

$$buyperiod = \frac{Agreed\ lead\ time\ (in\ workdays) + Safety\ stock\ (in\ workdays) + RP\ (in\ workdays)}{Ordercyclelength}$$

Equation 4.28: Number of periods to buy

The base stock level (ORL) can be determined by summing the forecasts over the number of periods to buy as formulated in Equation 4.29.

$$ORL_{CDC} = \left(\sum_{a=1}^{\lfloor buyperiod \rfloor} FCcdc_a \right) + (buyperiod - \lfloor buyperiod \rfloor) * FCcdc_{\lceil buyperiod \rceil}$$

Equation 4.29: Base stock level at the CDC

Where a fraction of the last forecast is added when the number of periods to buy is not an integer number.

The installation stock policy explained in this chapter can be adjusted with multi-echelon inventory control. According to Axsäter & Juntti (1996), the installation stock reorder point policies are dominated by the multi-echelon stock reorder point policies in serial and assembly systems. For distribution systems, either the installation stock policy or multi-echelon stock policies are beneficial. The aim of the next chapter is to define the adjusted policy parameters for the currently implemented installation stock policy based on multi-echelon inventory control which fits to the structure of a reseller of office supplies.

5 Multi-echelon inventory control

In the literature, the specific combination of replenishment policies described in the previous chapter is never investigated. The multi-echelon inventory control techniques described in the literature often assume another combination of replenishment policies, which forms an obstacle for the implementation in a reseller in office supplies environment. Regarding the optimisation function, two options are investigated often.

The first option minimizes the total cost, while including penalty costs for a backorder. For example, Cachon (2001) uses this optimisation function, where the total costs consist of LDC holding costs, CDC holding costs and penalty costs. The most difficult part of this option is computing the penalty cost value which demonstrates desirable system behaviour.

The second optimisation function option minimizes costs while a service level constraint needs to be met. An example of a paper which uses this policy is Tempelmeier (1993). The main idea is to minimize the inventory costs by changing the warehouse (CDC) reorder point and afterwards optimising the depot (LDC) reorder point, while ensuring the service level at least equals the target.

The literature also makes a distinction between installation stock policies and echelon stock policies. The first one only needs inventory information of its own location and the second one requires inventory access of the entire supply chain. The company wants to preserve the installation stock policy; hence the echelon stock policy is not investigated further. It is important to note that, for divergent multi-echelon systems, the optimal control policy is unknown.

As mentioned before, there is no paper which combines the two policies which are used within the reseller of office supplies environment. Therefore, the software tool called ChainScope is used to determine safety stock values. Afterwards, the policy parameters are derived from the safety stock parameters. The tool uses the second optimisation function, i.e. minimizing costs while meeting a service level constraint, and is explained further in the next paragraphs.

Note that the difference between the current policy and the changed policy only covers the parameter calculation. In the multi-echelon control scenario, the parameters are optimised centrally, whereas in the current control policy they will be optimised decentralized. Therefore, multi-echelon control does not change the implemented replenishment policy, but only adjusts the policy parameters.

In the remainder of this research the current situation is the installation stock control policy and the parameters are adjusted in the multi-echelon control scenario.

This chapter describes the multi-echelon inventory control tool used and in the last part the simulation tool and the test scenarios are given.

5.1 ChainScope

This software tool, developed by prof dr. A.G. de Kok, optimises the safety stock levels on item level per warehouse. Based on those results, the control parameters which belong to the used policy can be computed, which is explained in the next paragraph. ChainScope uses the synchronised base stock policy (SBS) as described by De Kok & Fransoo (2003) in case of shortage. This policy releases feasible work orders and more information can be retrieved in De Kok & Fransoo (2003) and the results of Diks and De Kok (1999).

Important item input parameters of ChainScope are the expected lead time, added value, release cost, yield, lot size and review period. ChainScope assumes that lead times are fixed, while in reality this is not true. The consequence of this assumption is quantified in chapter 6. The added value equals the extra transportation and handling costs by transferring the item to the next echelon. Release cost is defined as the cost of releasing one replenishment order (which are equal to the cost per order line defined in chapter 4). It is assumed that the yield of every item equals 1, which means no items are lost or damaged. The lot-size field is used to enter the expected order size, which forces ChainScope in the right behaviour. For the local distribution centre, the expected order size is Q_{opt}, including expected undershoot, rounded to minimums and multiples. For the central distribution centre, the expected order quantity equals the expected demand during review period rounded to minimums and multiples.

ChainScope also needs customer input to specify the demand pattern and customer characteristics. The forecasted demand and forecasted standard deviation calculated in chapter 4 serve as input for expected demand and expected standard deviation. It is assumed that the customer lead time equals 0, i.e. when the LDC has stock, the customer order is fulfilled directly. The target fill rate in ChainScope equals the target fill rate used in the ITM-models of chapter 4.

5.2 ChainScope output interpretation

As mentioned in the previous section, ChainScope returns safety stock levels which have a high supply chain performance independent of the replenishment policy used. The safety stock values can be translated to the policy parameters, which is explained in this paragraph.

As the optimal order quantity for the LDC does not change, the ORL can still be calculated by Equation 4.27 (using the new IOP).

The reorder levels of the LDCs will change after the ChainScope optimisation, because the safety stock levels are recalculated. The next step is to translate the safety stock level to the optimal reorder level (IOP). Tempelmeier (1993) formulates an equation which calculates the safety stock in a reorder level policy (Equation 5.1).

$$SS = IOP - E[U] - E[D_L]$$

Equation 5.1: Safety stock as defined by Tempelmeier (1993)

This equation can be translated to an equation which calculates the IOP based the safety stock. This new control parameter will be used in the current installation stock policy and is formulated in Equation 5.2.

$$IOP = SS + E[U] + E[D_L]$$

Equation 5.2: Reorder level calculation based on Tempelmeier (1993)

Where E[U] and $E[D_L]$ can be computed using Equation 4.5 and Equation 4.15. Note that ChainScope rounds the lead time to the nearest integer. The rounded lead time will be used to calculate the expected demand during lead time.

The current base-stock level calculation of the CDC uses the forecasts and the safety stock (in time units) as formulated in Equation 4.29. The output of ChainScope gives the safety stock level in units, which means that the calculation of the 'new' base-stock level can be adjusted to Equation 5.3 and Equation 5.4.

$$ORL_{CDC} = \left(\sum_{a=1}^{\lfloor buyperiod \rfloor} FCcdc_a \right) + (buyperiod - \lfloor buyperiod \rfloor) * FCcdc_{\lceil buyperiod \rceil} + SS_{\lceil buyperiod \rceil}$$

Equation 5.3: Adjusted base stock level calculation of the CDC

Where

$$Buyperiod = \frac{Agreed\ lead\ time\ (in\ workdays) + review\ period (in\ workdays)}{Ordercyclelength}$$

Equation 5.4: Adjusted number of periods to buy for the CDC

5.3 Simulation tool

To test the performance of different control parameters, a simulation tool is developed to measure the supply chain performance. The open source tool Spyder is used to build it, which is based on the programming language Python. The simulation tool distinguishes between the central distribution centre and the local distribution centres. In this section the logic behind the simulation tool and the assumptions which belong to the logic are discussed. The first part describes the input and assumptions of the simulation tool, followed by the simulation logic and output interpretation.

5.3.1 Simulation input and assumptions

The simulation tool needs input parameters to imitate the system behaviour. Table 5.1 gives all input parameters for the LDCs and Table 5.2 gives the input parameters for the CDC.

Table 5.1: Simulation input parameters LDC

Parameter	**Description**
IOP	Item order point per item
Order-up-to-level	Order up to level per item
Minimum	Replenishment order minimum per item
Multiple	Replenishment order multiple per item
Average lead time	Average replenishment lead time from CDC to LDC per item in workdays
Lead time variance	Replenishment lead time variance from CDC to LDC per item in workdays
Review period	Review period per warehouse
Cost price	Cost price (including CDC uplift) per item in Euros
Demand	Daily demand per day per item

Table 5.2: Simulation input parameters CDC

Parameter	**Description**
Average lead time	Average replenishment lead time from vendor to CDC per item in workdays
Lead time variance	Replenishment lead time variance from vendor to CDC per item in workdays
Cost price	Landed cost price per item in Euros
Safety stock	Safety stock per item in workdays or units
Minimum	Replenishment order minimum
Multiple	Replenishment order multiple
Forecast	Demand forecast (LDC orders) per item per review period
Demand business partners	Daily business partner demand per day per item

The main assumptions for this simulation tool are:

- Lead times are simulated based on a gamma distribution, given the actual mean and variance.
- Replenishment orders cannot overtake each other due to lead time variance. For example, when the calculated delivery date of an order is earlier than the calculated delivery date of the previous order, both orders are delivered on the delivery date of the previous order.
- Weekly demand at the LDCs is reformulated to daily demand by dividing the weekly demand equally over 5 weekdays.
- Inventory shortage at the CDC is divided proportionally over the open orders (which allows partial delivery). This means that inventory shortage is allocated based on LDC demand, i.e. the LDC with the highest demand receive the highest backorders. Van der Heijden et al. (1997) mentions that the drawback of this policy is the unknown effect on customer service level. The paper mentions a few other allocation policies, but in consultation with the company planners, the proportional allocation fits best to the current processes. Partial delivery to customers is also allowed.
- Replenishment orders arriving at the LDC or CDC, can leave the stock point on the next day at the earliest.
- Replenishment orders are placed at the beginning of the day.
- When the CDC receives stock and an open purchase order of the LDC at the CDC can be fulfilled, stock will be reserved until the next truck drives from the CDC to the LDC. The fulfilled backorders to the business partners are shipped directly.
- Transhipments are not allowed.
- The CDC forecast for a period is calculated by summing the horizontal moving average (13 weeks) forecasts of the LDCs and business partners for every order cycle (20 days).
- Input parameters are recalculated every 4 weeks, except parameters which deal with lead times, review periods or prices.
- Starting inventory position of the simulation is 0 for every item in every warehouse.
- All warehouses have infinite capacity.
- The first 150 days in the simulation are used to settle the model and afterwards the results are measured over one year (260 days). The length of the settlement period is determined with an example of the simulation output in Figure 5.1. In this example the stock settles after 105 days, but since other situations could behave a little bit different, a buffer is added.
- Safety stock is not allowed to be negative.

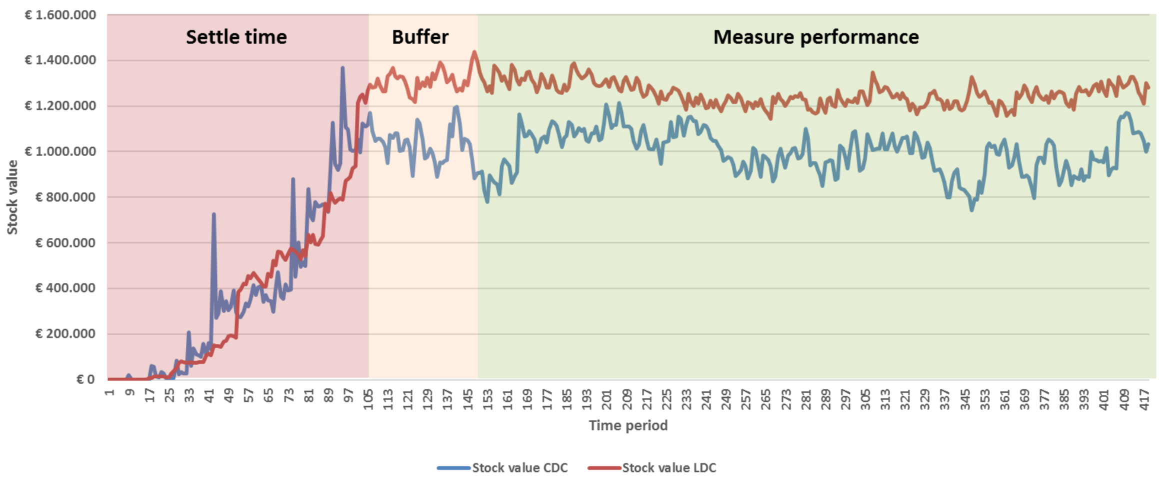

Figure 5.1: Length of the simulation settle period

5.3.2 Simulation logic

This part gives the formulas which form the backbone of the simulation tool. The formulas for the local distribution centres are formulated first, followed by the formulas for the central distribution centre. The simulation variables are defined in the list of variables at the beginning of the report.

The starting point of the simulation is the inventory position at the LDC, which can be formulated as the sum of the on-hand stock and outstanding replenishment orders minus the customer backorders at that specific distribution centre. The long settle period is chosen to settle the inventory position to a stable level. The LDC is allowed to place orders once a week only at their order day (weekday). When the current day in the simulation tool is not an order day, the demand of that day will be subtracted from the inventory position. On the other hand, when the current day is an order day, another process will start. This mechanism can be found in Equation 5.5.

$$Balance_{i,j,t} = \begin{cases} Balance^{a}_{i,j,t} & if\ Orderday_{j,t} = 1 \\ Balance_{i,j,t-1} - D_{i,j,t} & if\ Orderday_{j,t} = 0 \end{cases} \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.5: Balance equation at the LDC

When the local distribution centre is allowed to order, the next question is whether the LDC actually wants to place an order and what the order quantity has to be. When the balance of the previous period is smaller than the reorder level, a replenishment order must be placed. The order quantity will be the difference between the inventory position of the previous period and the order-up-to level, rounded up to order multiples. This value needs to be at least the order minimum. This replenishment order mechanism, including the inventory position adjustment, is formulated in Equation 5.6.

$$Balance^{a}_{i,j,t} = \begin{cases} Balance_{i,j,t-1} - D_{i,j,t} + \max\left(MIN_{i,j,t}, \left\lceil \frac{ORL_{i,j,t} - Balance_{i,j,t-1}}{MUL_{i,j,t}} \right\rceil * MUL_{i,j,t}\right) & if\ Balance_{i,j,t-1} < IOP_{i,j,t} \\ Balance_{i,j,t-1} - D_{i,j,t} & if\ Balance_{i,j,t-1} \geq IOP_{i,j,t} \end{cases}$$

Equation 5.6: Balance equation at the LDC (a)

The actual replenishment order quantity can be derived from the inventory position equations and demand by means of Equation 5.7. The demand at the CDC is the summation of all LDC replenishment orders and the business partner orders, as indicated with Equation 5.8.

$$SOQ_{i,j,t} = \max\left(Balance_{i,j,t} - Balance_{i,j,t-1} + D_{i,j,t}, 0\right) \qquad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.7: Suggested order quantity of the LDCs at the CDC

$$D_{i,0,t} = BPorders_{i,t} + \sum_{j \in J} SOQ_{i,j,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.8: Demand at the CDC

Since the supply chain is a two-echelon supply chain, the deliveries to the LDC depend on the stock in the CDC. When a replenishment order cannot be delivered in full, an open purchase order will be recorded. Equation 5.9, Equation 5.10, Equation 5.11 and Equation 5.12 show the calculation of the open purchase order quantities. Equation 5.13 gives an expression of all open purchase orders of the LDCs and the open business partner orders.

$$Openpos_{i,j,t} = \begin{cases} Openpos^{a}_{i,j,t} & if\ OHS_{i,0,t-1} > 0 \\ Openpos_{i,j,t-1} + SOQ_{i,j,t} & if\ OHS_{i,0,t-1} \leq 0 \end{cases} \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.9: Open purchase orders of the LDCs

$$Openpos_{i,j,t}^{a} = \begin{cases} Openpos_{i,j,t}^{b} & if\ \left((OHS_{i,0,t-1} - BO_{i,0,t-1}) < D_{i,0,t}\right) \cap (SOQ_{i,j,t} > 0) \\ Openpos_{i,j,t}^{c} & Otherwise \end{cases}$$

Equation 5.10: Open purchase orders of the LDCs (a)

$$Openpos_{i,j,t}^{b} = \begin{cases} Openpos_{i,j,t-1} + SOQ_{i,j,t} - \max\left(\frac{SOQ_{i,j,t}}{D_{i,0,t}} * (OHS_{i,0,t-1} - BO_{i,0,t-1}), 0\right) - \min\left(Openpos_{i,j,t-1}, \frac{Openpos_{i,j,t-1}}{BO_{i,0,t-1}} * OHS_{i,0,t-1}\right) & if\ BO_{i,0,t-1} > 0 \\ Openpos_{i,j,t-1} + SOQ_{i,j,t} - \max\left(\frac{SOQ_{i,j,t}}{D_{i,0,t}} * (OHS_{i,0,t-1} - BO_{i,0,t-1}), 0\right) & Otherwise \end{cases}$$

Equation 5.11: Open purchase orders of the LDCs (b)

$$Openpos_{i,j,t}^{c} = \begin{cases} Openpos_{i,j,t-1} - \min\left(Openpos_{i,j,t-1}, \frac{Openpos_{i,j,t-1}}{BO_{i,0,t-1}} * OHS_{i,0,t-1}\right) & if\ BO_{i,0,t-1} > 0 \\ Openpos_{i,j,t-1} & Otherwise \end{cases}$$

Equation 5.12: Open purchase orders of the LDCs (c)

$$BO_{i,0,t} = OpenBPorders_{i,t} + \sum_{j \in J} Openpos_{i,j,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.13: Total open purchase orders and open business partner orders

Since the business partners also order their products at the CDC, they can also have open purchase orders. The formulas are comparable to the open purchase order formula of the LDCs and can be found in Equation 5.14, Equation 5.15, Equation 5.16 and Equation 5.17.

$$OpenposBPorders_{i,t} = \begin{cases} OpenBPorders_{i,t}^{a} & if\ OHS_{i,0,t-1} > 0 \\ OpenBPorders_{i,t-1} + BPorders_{i,t} & if\ OHS_{i,0,t-1} \leq 0 \end{cases} \quad \forall i \in I, \forall t \in T$$

Equation 5.14: Open purchase orders of the business partners

$$OpenBPorders_{i,t}^{a} = \begin{cases} OpenBPorders_{i,t}^{b} & if\ \left((OHS_{i,0,t-1} - BO_{i,0,t-1}) < D_{i,0,t}\right) \cap (BPorders_{i,t} > 0) \\ OpenBPorders_{i,t}^{c} & \end{cases}$$

Equation 5.15: Open purchase orders of the business partners (a)

$$OpenBPorders_{i,t}^{b} = \begin{cases} OpenBPorders_{i,,t-1} + BPorders_{i,t} - \max\left(\frac{BPorders_{i,t}}{D_{i,0,t}} * (OHS_{i,0,t-1} - BO_{i,0,t-1}), 0\right) - \min\left(OpenBPorders_{i,t-1}, \frac{OpenBPorders_{i,t-1}}{BO_{i,0,t-1}} * OHS_{i,0,t-1}\right) & if\ BO_{i,0,t-1} > 0 \\ OpenBPorders_{i,t-1} + BPorders_{i,t} - \max\left(\frac{BPorders_{i,t}}{D_{i,0,t}} * (OHS_{i,0,t-1} - BO_{i,0,t-1}), 0\right) & Otherwise \end{cases}$$

Equation 5.16: Open purchase orders of the business partners (b)

$$OpenBPorders_{i,t}^{c} = \begin{cases} OpenBPorders_{i,t-1} - \min\left(OpenBPorders_{i,t-1}, \frac{OpenBPorders_{i,t-1}}{BO_{i,0,t-1}} * OHS_{i,0,t-1}\right) & if\ BO_{i,0,t-1} > 0 \\ OpenBPorders_{i,t-1} & Otherwise \end{cases}$$

Equation 5.17: Open purchase orders of the business partners (c)

As mentioned in the assumptions above, stock will be reserved for a LDC. This means that the CDC keeps it in stock until a shipment to the LDC is released. This occurs once a week for every LDC. Since the LDC orders on a fixed weekday (once per week) and stock is reserved/released on every weekday, LDC orders and stock reserve/release moments are not synchronized. It is assumed that orders originating from the business partners are released immediately after reservation. The stock reservation and stock release mechanism can be found in Equation 5.18, Equation 5.19, Equation 5.20 and Equation 5.21.

$$Reserved_{i,j,t} = SOQ_{i,j,t} + Openpos_{i,j,t-1} - Openpos_{i,j,t} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.18: Reserved stock for the LDCs

$$ReservedBP_{i,t} = BPorders_{i,t} + OpenBPorders_{i,t-1} - OpenBPorders_{i,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.19: Reserved stock for the business partners

$$Releasedorder_{i,j,t} = \begin{cases} \sum_{a=0}^{4} Reserved_{i,j,t-a} & if\ Orderday_{j,t} = 1 \\ 0 & otherwise \end{cases} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.20: Released stock for the LDCs

$$ReleasedBP_{i,t} = ReservedBP_{i,t}$$

Equation 5.21: Released stock for the business partners

Replenishment orders which are released from the CDC, arrive at the LDC after the transportation lead time. As showed in chapter 3, this lead time is gamma distributed with an average (μ(LT)) and standard deviation (σ(LT)). For every delivery, the lead time is simulated based on the gamma distribution with parameters alpha and beta (Equation 5.22 and Equation 5.23) and is rounded to integer values with a minimum value of 1 day. When the calculated receiving date of the replenishment order is earlier than all previous orders, the order is shipped together with the order with the latest receiving date.

$$\alpha(LT) = \frac{\mu(LT)^2}{\sigma(LT)^2}$$

Equation 5.22: Alpha parameter of the gamma distribution representing the lead time

$$\beta(LT) = \left(\frac{\sigma(LT)}{\mu(LT)}\right)^2 * \mu(LT)$$

Equation 5.23: Bèta parameter of the gamma distribution representing the lead time

The incoming order will arrive after the simulated lead time, measured from the moment of the order release. In mathematical terms, this will look like Equation 5.24. Afterwards, the on-hand stock of the LDC will be calculated with Equation 5.25. Note that this on-hand stock formula allows negative values, which means that the LDC faces open backorders (which can be measured with Equation 5.26).

$$Incomingorder_{i,j,t+LT_{i,j,t}} = Releasedorder_{i,j,t} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.24: Receiving replenishment orders at the LDC

$$OHS_{i,j,t} = OHS_{i,j,t-1} + Incomingorder_{i,j,t} - D_{i,j,t} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.25: On-hand stock (in units) in the LDC

$$BO_{i,j,t} = \begin{cases} -OHS_{i,j,t} & if\ OHS_{i,j,t} < 0 \\ 0 & otherwise \end{cases} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.26: Open backorders (in units) in the LDC

In the upcoming part of this chapter, the equations which belong to the CDC are explained. The CDC also starts with an inventory position formula, which is the sum of the on-hand stock and outstanding replenishment orders minus open LDC orders and open business partner orders. The CDC is permitted to raise the inventory position only on CDC order days. A CDC order day occurs once every 20 days. Similar as for the LDCs, the calculation of the inventory position depends on whether the moment in time is an order day. (Equation 5.27)

$$Balance_{i,0,t} = \begin{cases} Balance^{a}_{i,0,t} & if\ Orderday_{0,t} = 1 \\ Balance^{b}_{i,0,t} & if\ Orderday_{0,t} = 0 \end{cases} \quad \forall i \in I, \forall t \in T$$

Equation 5.27: Balance equation at the CDC

When the time period is not an order day, the balance has to be adjusted with the CDC demand of that period (as indicated by Equation 5.28).

$$Balance^{b}_{i,0,t} = Balance_{i,0,t-1} - D_{i,0,t}$$

Equation 5.28: Balance equation at the CDC (b)

When the current time period is an order day, different steps need to be executed. The order-up-to level of that item in the CDC is calculated. This depends on the expected lead time and the safety stock of the CDC. The order-up-to level of an item in the CDC can be calculated with Equation 5.29 and Equation 5.30.

$$ORL_{i,0,x} = \sum_{a=0}^{\lfloor Buyperiod_{i,0,x} \rfloor - 1} FC_{i,0,x+a} + \left(Buyperiod_{i,0,x} - \lfloor Buyperiod_{i,0,x} \rfloor\right) * FC_{i,0,x+\lfloor Buyperiod_{i,0,x} \rfloor} \quad \forall i \in I, \forall x \in X$$

Equation 5.29: Order-up-to level at the CDC

Where

$$Buyperiod_{i,0,x} = \frac{SS_{i,0,x} + LT_{i,0,t}}{Ordercyclelength} + 1 \quad \forall i \in I, \forall x \in X$$

Equation 5.30: Number of periods to buy at the CDC

Note that the calculation of the order up to level and the buyperiod change under multi-echelon control, as described in Equation 5.3 and Equation 5.4. The order-up-to level can be used to calculate the value of the new inventory position when an order is placed. The order quantity is the difference between the previous balance and the order-up-to level, rounded to integer multiples. The quantity needs to be at least the order minimum. This mechanism is described by Equation 5.31.

$$Balance^{a}_{i,0,t} = \begin{cases} Balance_{i,0,t-1} + \max\left(MIN_{i,0,t}, \left\lceil \frac{ORL_{i,0,x} - Balance_{i,0,t-1}}{MUL_{i,0,t}} \right\rceil * MUL_{i,0,t}\right) - D_{i,0,t} & if ORL_{i,0,x} > Balance_{i,0,t-1} \\ Balance_{i,0,t-1} - D_{i,0,t} & otherwise \end{cases}$$

Equation 5.31: Balance equation at the CDC (a)

The suggested replenishment order quantity by the CDC can be calculated with the balance equations and the demand as indicated with Equation 5.32.

$$SOQ_{i,0,t} = \max\left(Balance_{i,0,t} - Balance_{i,0,t-1} + D_{i,0,t}, 0\right) \quad \forall i \in I, \forall t \in T$$

Equation 5.32: Suggested replenishment order quantity at the CDC

The lead time for replenishment orders to the CDC is simulated similarly as for the LDCs. The lead time is calculated for every shipment of a vendor. The alpha and beta of the gamma distribution are computed with Equation 5.22 and Equation 5.23. In the simulation tool, a random value within this gamma distribution is generated and rounded to integer values with a minimum value of 1 day. The replenishment order arrives after the simulated lead time, which can be found in Equation 5.33.

$$Incomingorder_{i,0,t+LT_{i,0,t}} = SOQ_{i,0,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.33: Receiving replenishment orders at the CDC

The projected stock in the CDC can be computed with the previous physical stock, incoming orders and reserved LDC orders (Equation 5.34). In contrast to the LDC on-hand stock, this value can only be 0 or positive, since the CDC does not release or reserve more orders than the projected physical stock. This formula is slightly adjusted to calculate the actual stock on-hand in the next paragraph.

$$OHS_{i,0,t} = OHS_{i,0,t-1} + Incomingorder_{i,0,t} - ReservedBP_{i,t} - \sum_{j \in J} Reserved_{i,j,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.34: Projected on-hand stock (in units) at the CDC

5.3.3 Output interpretation and validation

The most important output parameters are the on-hand stock value at the LDC and CDC, the service level in the LDC and the number of replenishment order lines at the LDCs and CDC. As mentioned before, the first 150 days are used as settle period. Afterwards, 260 days are used to measure the performance parameters.

The on-hand stock value for every item in the LDC can be computed by multiplying the average stock level (in units) with the cost price per unit (Equation 5.35).

$$OHS_{i,j,value} = \frac{1}{260} \sum_{t=151}^{410} OHS_{i,j,t} * Price_{i,j} \quad \forall i \in I, \forall j \in J$$

Equation 5.35: On-hand stock value at the LDC

The computation of the on-hand stock level in the CDC is a little bit more difficult. The simulation tool adjusts the stock level directly after reserving stock for an order. However, stock is actually affected after releasing the order. Another variable is created to measure the actual on-hand stock value, which is formulated in Equation 5.36.

$$OHSactual_{i,0,t} = OHSactual_{i,0,t-1} + Incomingorder_{i,0,t} - ReleasedBP_{i,t} - \sum_{j \in J} Releasedorder_{i,j,t} \quad \forall i \in I, \forall t \in T$$

Equation 5.36: On-hand stock (in units) at the CDC for the stock value calculation

With the actual stock-level in units, the average on-hand stock value can be calculated with Equation 5.37.

$$OHS_{i,0,value} = \frac{1}{260}\sum_{t=151}^{410} OHSactual_{i,0,t} * Price_{i,0} \quad \forall i \in I$$

Equation 5.37: On-hand stock value in the CDC

The open purchase orders and the open backorders are measure cumulatively, i.e. when a LDC faces new backorders, those are added to the previous outstanding backorders. To measure the number of backorders or open purchase orders, the net open backorders or purchase orders are defined. Equation 5.38, Equation 5.39 and Equation 5.40 provide those computations.

$$NetBO_{i,j,t} = \begin{cases} 0 \quad if\ BO_{i,j,t} = 0 \\ MIN\left(BO_{i,j,t}, D_{i,j,t}\right) \quad otherwise \end{cases} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.38: Net backorders at the LDC

$$NetopenPO_{i,j,t} = \begin{cases} 0 \quad if\ Openpos_{i,j,t} = 0 \\ MIN\left(Openpos_{i,j,t}, SOQ_{i,j,t}\right) \quad otherwise \end{cases} \quad \forall i \in I, \forall j \in J, \forall t \in T$$

Equation 5.39: Net open LDC purchase orders

$$NetopenBPorders_{i,t} \begin{cases} 0 \quad if\ OpenBPorders_{i,t} = 0 \\ MIN\left(OpenBPorders_{i,t}, BPorders_{i,t}\right) \quad otherwise \end{cases} \quad \forall i \in I, \forall t \in T$$

Equation 5.40: Net open business partner orders

With the equations above, all input variables for the service level calculation are ready. The aggregate service level for each item at the LDC and CDC can be computed using Equation 5.41 and Equation 5.42.

$$Service_{i,j} = 1 - \frac{\sum_{t=151}^{410} NetBO_{i,j,t}}{\sum_{t=151}^{410} Demand_{i,j,t}} \quad \forall i \in I, \forall j \in J$$

Equation 5.41: Service level at the LDC

$$Service_{i,0} = 1 - \frac{\sum_{t=151}^{410}\left(NetopenBPorder_{i,t} + \sum_{j \in J} NetopenPO_{i,j,t}\right)}{\sum_{t=151}^{410}\left(BPorders_{i,t} + \sum_{j \in J} SOQ_{i,j,t}\right)} \quad \forall i \in I$$

Equation 5.42: Service level at the CDC

The performance of the model is based on supply chain costs and service level. The supply chain costs consist of major order costs, minor order costs and inventory holding costs. The minor order costs are valued at € 5,50 per order line, while the major order costs are valued at € 20,00 per order. The inventory holding costs can be calculated as 24,5% of the average inventory value. The total supply chain cost can be computed using Equation 5.43.

$$\begin{aligned} Supply\ chain\ costs \\ = C_{minororder} * \#_{orderlines} + C_{majororder} * \#_{orders} + C_{stockholding} \\ * \left(\sum_{i \in I}\sum_{j \in J} OHS_{i,j,value} + \sum_{i \in I} OHS_{i,0,value}\right) \end{aligned}$$

Equation 5.43: Supply chain costs

Simulation validation

First of all, the simulation tool is validated extensively within the company, which confirms the tool reproduces the replenishment behaviour correctly. Afterwards, a few validation tests are executed and the results are presented in Table 5.3.

Additional to the company check, the simulation is validated with testing extreme parameters. For example, when the CDC safety stock is extremely high, the LDCs operate as a single-echelon policy. Besides that, the CDC service level is exactly 100%. With the same assumptions as in the ITM-model, the local service level deviates only 0,07% from the target and the LDC stock value deviates 0,2% from the expected value. On top of that, when the reorder level and order-up-to level in the LDCs is uplifted to extreme heights, the local service level equals 100%.

The CDC also operates as a single-echelon when the LDC demand is ordered directly at the CDC. The CDC stock value is validated, because it is the only performance measure which will be used in the results section. The CDC stock deviates 0,36% from the expected value (determined with the (R,S) inventory control policy).

Furthermore, when the reorder levels and order-up-to levels are set to 0 and all other parameters which could cause the inventory position to go above 0 are switched off, the service level at the LDCs equals 0,0%.

Finally, the simulation tool is compared with the ChainScope output to check the performance measures. Compared to the targets, the customer service level only deviates 0,04% and the LDC stock value deviates 0,27%. The simulation tool does not allow to compare the CDC stock value, since order moments and review periods are not synchronized and a few other ChainScope assumptions are not met.

The result above validates that the ChainScope output interpretation and the simulation logic makes sense. Therefore, this is a valid reason to continue with the formulas provided above.

Table 5.3: Simulation validation results

Number	**Test**	**Performance measure**	**Absolute deviation from target**	**Comment**
1	Extreme CDC safety stock	CDC service level	0,0 %	
2	Extreme CDC safety stock	LDC service level	0,07 %	
3	Extreme CDC safety stock	LDC stock value	0,20 %	
4	CDC as single-echelon (R,S)-policy	CDC stock	0,36 %	Based on a (R,S)-policy
5	ChainScope output	LDC service level	0,04 %	Parameters based on ChainScope safety stock output
6	ChainScope output	LDC stock value	0,27 %	Parameters based on ChainScope safety stock output
7	IOP, ORL, MIN, MUL on 0	LDC service level	0,0 %	

5.4 Scenarios to test and compare

In the analysis of the replenishment control strategy of the reseller in office supplies, a few situations are compared and analysed.

As mentioned in chapter 4, the size of the CDC replenishment orders is determined with the agreed vendor lead time. However, the actual lead time can deviate from this agreed lead time. Therefore, both situations are simulated. On top of that, the value of information sharing between the LDCs and the CDC is reviewed. Chen et al. (2000) point out that the bullwhip effect can be reduced, but not eliminated, by information sharing. The bullwhip effect means that variance of orders is amplified more upstream in the supply chain. The model, as proposed by the paper, does not include the complexity of multi-echelon supply chains. This means that other models need to be developed to optimise multi-echelon control parameters.

Afterwards, the multi-echelon control parameters need to be reviewed and compared with the current replenishment strategy. The actual lead times are used to determine the control parameters in the multi-echelon control scenario, so those are also used in the simulation tool. Afterwards, the multi-echelon control scenario is extended to the fixed and variable added lead time scenario, which will be explained later. An overview of the scenarios is given in Figure 5.2.

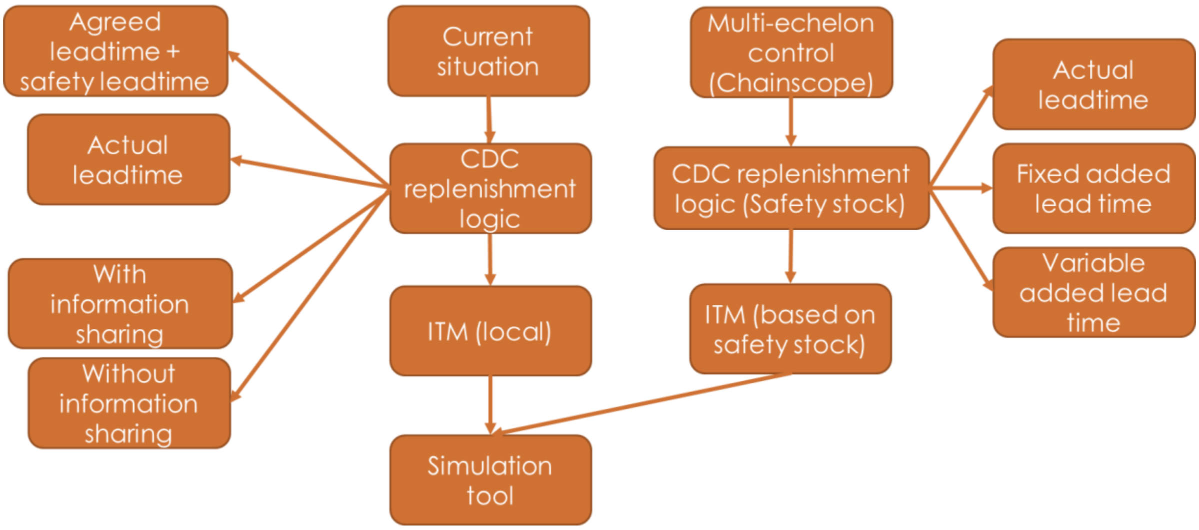

Figure 5.2: Overview of the simulation situations

The demand in the simulation tool can also have two options, i.e. actual demand (on a weekly basis over the last few years) or simulated demand (based on the cleaned forecast average and standard deviation, fitted to a gamma distribution). In the simulated demand scenario, the forecast changes every 20 workdays. Within those cycles (which can be found in Appendix B), the demand is assumed to be stationary. Since the policy parameters of the current local replenishment logic are based on the capped standard deviation (as described in chapter 4), the scenario with actual demand will probably have a lower performance than the scenario with simulated demand. In this last scenario, the demand will be simulated based on the average and capped standard deviation. A final overview of the situations to test and compare is given in Table 5.4.

Table 5.4: Overview of the simulation comparisons

	Scenario 1				**Scenario 2**			
#	**Control**	**Demand**	**Lead time**	**Information sharing**	**Control**	**Demand**	**Lead time**	**Information sharing**
1	Installation	Simulated	Actual	Yes	Installation	Simulated	Agreed	Yes
2	Installation	Simulated	Actual	Yes	Installation	Actual	Actual	Yes
3	Installation	Simulated	Actual	Yes	Installation	Simulated	Actual	No
4	Installation	Simulated	Actual	Yes	Multi	Simulated	Actual	Yes
5	Multi	Simulated	Actual	Yes	Multi	Simulated	Fixed added	Yes
6	Multi	Simulated	Fixed added	Yes	Multi	Simulated	Variable added	Yes
7	Installation	Simulated	Actual	Yes	Multi	Simulated	Variable added	Yes

As mentioned before, the supply chain costs and service level are the most important performance measures. Since the expected order sizes and the demand will not change in the multi-echelon control scenario, the major order costs and minor order costs do also not change much. Therefore, the supply chain costs change is caused by the inventory costs change. For this reason, all upcoming scenarios are compared on stock value and service level.

The reported values in the upcoming chapter are averages based on 10 simulation runs. As mentioned in chapter 4, the policy parameters are recalibrated every 20 days, which causes relatively high fluctuations within different runs. Because the simulation tool stays as close as possible to reality and the lack of computational power to do more than 10 runs, there is agreed to work with averages over 10 runs. The results of the simulations and comparisons are described in the next chapter.

6 Simulation and comparison results

In this chapter the simulation results and comparisons of the scenarios described in the previous chapter are discussed. When the name of a subchapter does not mention anything about information sharing, it is assumed that information sharing is applied. When information sharing is applied, only the forecasts of LDCs and business partners are shared.

6.1 Comparison 1: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with stationary simulated demand and agreed lead time

As mentioned before, the CDC uses the agreed vendor lead time to determine the size and timing of replenishment orders. However, the agreed lead time is not always in line with the actual calculated lead time. The first comparison compares the installation stock control policy with agreed and actual lead time.

An overview of the simulation results can be found in Figure 6.1, where

- First scenario: Installation stock control with stationary simulated demand and actual lead time.
- Second scenario: Installation stock control with stationary simulated demand and agreed lead time.

A detailed decomposition of the results can be found in Table A.1, Table A.2 and Table A.3 of Appendix A.

When switching from the first to the second scenario, both the local and central stock level decreases. However, this small decrease of 1,5% will not account for the increase in disservice of 85,4%. The service level in the scenario with actual lead time is higher, because the agreed lead times are not accurate. Moreover, the scenario using actual lead time results in a service level which is much closer to the target service level of 99,1%. This means that the replenishment logic produces better results when the CDC uses actual lead time (instead of the agreed lead time). The first recommendation to the reseller of office supplies is that lead times need to be recalculated more often, such that the most actual lead times are used in the replenishment policy. Since the replenishment logic performs better with actual lead times, the upcoming comparisons will also take the actual lead time as baseline.

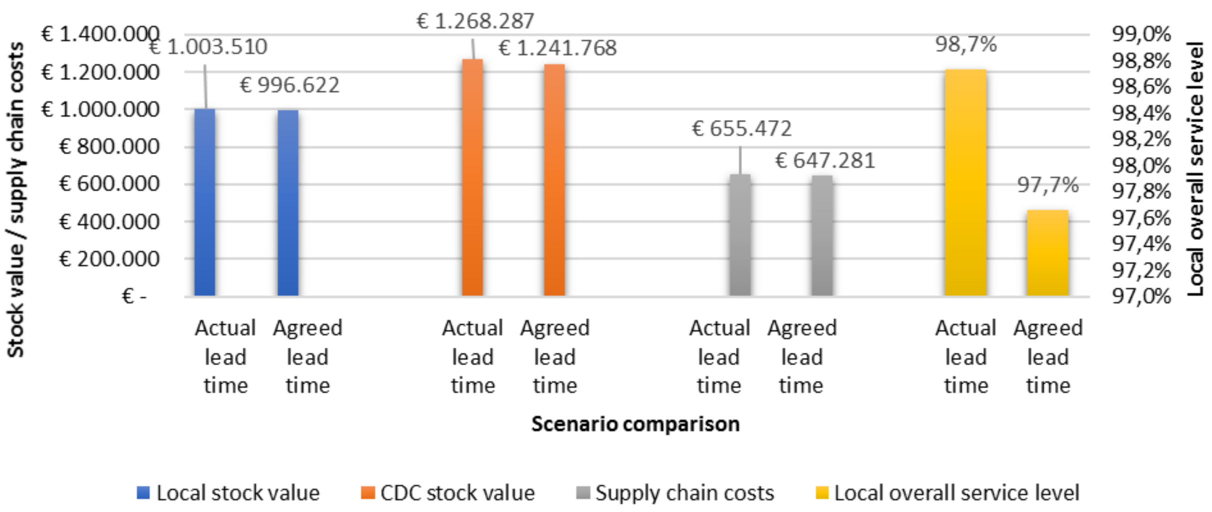

Figure 6.1: Comparison #1: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with stationary simulated demand and agreed lead time

6.2 Comparison 2: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with actual demand and actual lead time

The second comparison deals with the difference of simulated demand and actual demand. As mentioned before, in the current inventory control policy the standard deviation of the demand will be capped on 250% of the average to protect the supply chain against huge stock investments. This means the planner needs to react to demand fluctuations to make sure the service level can be met. This second comparison emphasizes the importance of this task by showing the situation where the planner does not adjust anything.

An overview of the simulation results can be found in Figure 6.2, where

- First scenario: Installation stock control with stationary simulated demand and actual lead time.
- Second scenario: Installation stock control with actual demand and actual lead time.

A detailed decomposition of the results can be found in Table A.4, Table A.5 and Table A.6 of Appendix A.

Simulating with actual demand leads to a higher stock value (an increase of 0,7 %) and the disservice increases with 742,3%. This means that the extra stock on hand does not contribute to the service level. In other words, the wrong items are on hand. Those results emphasize that, with the current replenishment policy, planners need to do an important job.

To achieve honest comparisons in the upcoming parts, the situation with simulated demand will be used as baseline. This choice is made, because the replenishment parameters are based on stationary gamma-distributed demand.

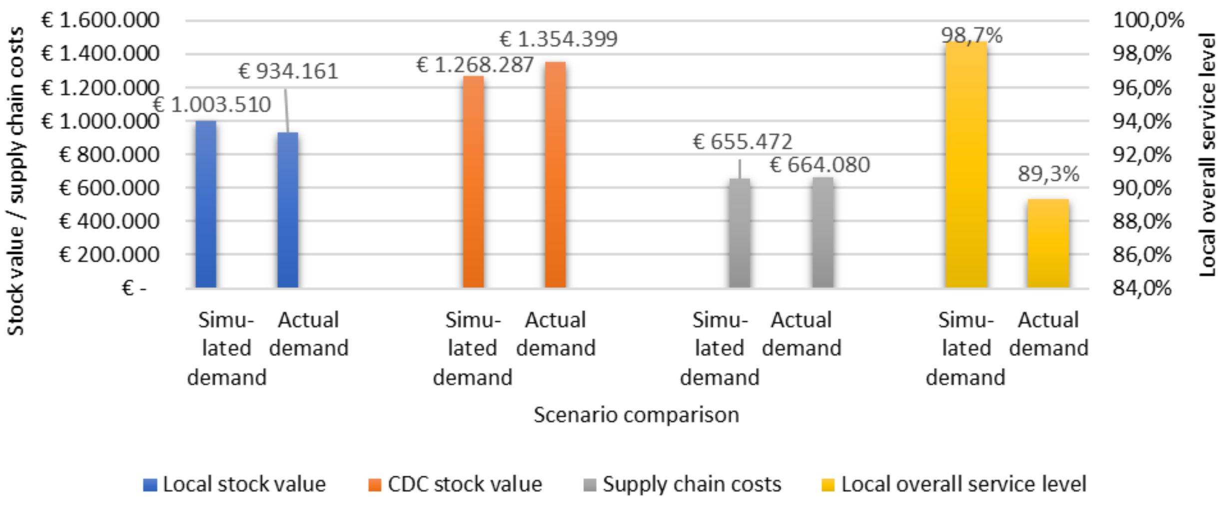

Figure 6.2: Comparison #2: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with actual demand and actual lead time

6.3 Comparison 3: Installation stock control with stationary simulated demand, actual lead time and information sharing vs. installation stock control with stationary simulated demand, actual lead time and without information sharing

The CDC base stock level is based on the forecasts for the upcoming periods. In this comparison the value of information sharing is pointed out. In the information sharing scenario, the CDC receives the forecasted sales on a daily basis in each warehouse. In the scenario without information sharing, the CDC needs to calculate the forecast with the available data. The only available data component they have are the historic LDC replenishment orders and business partner orders. Therefore, those orders are used to compute the horizontal moving-average forecast.

An overview of the simulation results can be found in Figure 6.3, where

- First scenario: Installation stock control with stationary simulated demand, actual lead time and information sharing.
- Second scenario: Installation stock control with stationary simulated demand, actual lead time and without information sharing.

A detailed decomposition of the results can be found in Table A.7, Table A.8 and Table A.9 of Appendix A.

The average stock levels and the supply chain costs are more or less the same for each scenario. On the other hand, the service level of the information sharing scenario dominates the non-information sharing scenario by more than 1 %. From another perspective, the disservice is reduced with 46,6 % due to information sharing. This result confirms that the reseller of office supplies adds value with sharing information. Future research could investigate if the stock value decrease weights against the extra costs due to information sharing and if sharing more than only the forecasts would result in more benefits. The CDC team needs to motivate the LDCs to send a forecast which is as accurate as possible, since this information can improve the supply chain performance. In the current supply chain setup, the LDCs are not obliged to buy the quantity they have forecasted. This could be a reason why the LDCs do not always care about their forecast accuracy.

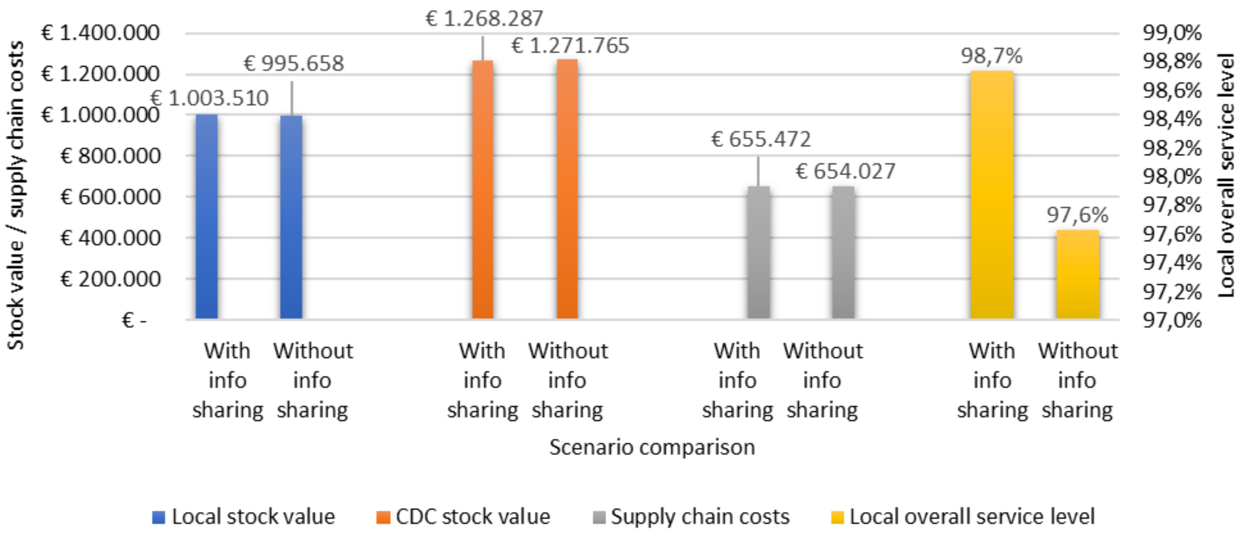

Figure 6.3: Comparison #3: Installation stock control with stationary simulated demand, actual lead time and information sharing vs. installation stock control with stationary simulated demand, actual lead time and without information sharing

6.4 Comparison 4: Installation stock control with stationary simulated demand and actual lead time vs. multi-echelon control with stationary simulated demand and actual lead time

In the next comparison, the value of multi-echelon stock control is analysed. The current policy with centrally optimised parameters (based on the output of ChainScope) is compared with the baseline (installation stock control with actual lead time and stationary simulated demand).

An overview of the simulation results can be found in Figure 6.4, where

- First scenario: Installation stock control with stationary simulated demand and actual lead time.
- Second scenario: Multi-echelon control with stationary simulated demand and actual lead time.

A detailed decomposition of the results can be found in Table A.10, Table A.11 and Table A.12 of Appendix A.

The most important difference between the two scenarios is the location of the stock. In the installation stock control policy, most stock is held in the CDC (most upstream location). On the other hand, in the multi-echelon inventory control scenario most stock is held locally (most downstream). In general, the total stock value and supply chain costs are lower, but the quality of the comparison is questionable. With the large disservice increase of 271,7%, the stock values are non-comparable.

There are different reasons why the service level of the reseller in office supplies in the multi-echelon inventory control scenario simulation will not equal the target service level, which are

- ChainScope assumes fixed lead time in the optimisation. In the simulation tool the lead is simulated based on actual average and standard deviation and is therefore not fixed.
- ChainScope rounds the lead time to the nearest integer, which could cause small deviations.
- The simulation tool has the characteristic that lead times cannot overtake each other, which means the average simulated lead time could be more than the actual average lead time.
- The current replenishment policy will not be changed, which means the control parameters (such as the reorder level) are recalibrated every 4 weeks. These recalibrations have a few disadvantages. First of all, the supply chain needs settlement time. Most items are ordered every week on a fixed order day and have a lead time with an average of 5 or 6 workdays, which means the supply chain needs 5-10 days to adjust to the new control parameters. This is relatively long, given the fact that after 20 days the system will be recalibrated again. Furthermore, the demand is simulated with a gamma distribution based on the average and standard deviation. However, these parameters also change every 4 weeks, which means that the average of 20 days simulated demand will not settle to the actual average.
- The optimised IOP and ORL are rounded to integer values with the restriction that it is at least 1. This means that the IOP and ORL used in the simulation are closely, but not exactly, steering on the target service level.
- As mentioned in chapter 5, ChainScope assumes the synchronized base stock policy in case of shortage, which is not implemented in the simulation tool.

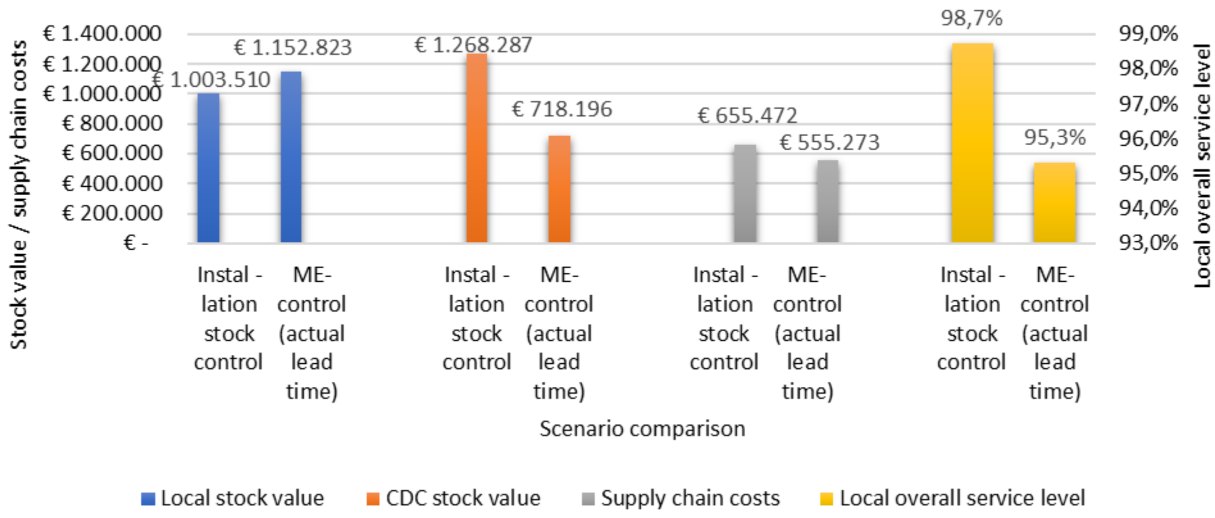

Figure 6.4: Comparison #4: Installation stock control with stationary simulated demand and actual lead time vs. multi-echelon control with stationary simulated demand and actual lead time

As can be seen in the list above, the service level deviation could be caused by another lead time interpretation. Since ChainScope does not allow for lead time variance, this can be compensated by adding safety lead time, i.e. inflating the lead time. The upcoming part explains what the safety lead time approach could be and afterwards the results are generated.

The lead time of suppliers is subject to variance due to consolidation and waiting time at the European arrival port. An expert opinion within the CDC planning department points out that adding 10 days safety lead time will account for this lead time variance. To verify this expect opinion, the number of workdays a container spends in those two stages is presented in Table 6.1, Table 6.2 and Table 6.3.

Table 6.1: Far east consolidation time

Consolidation time	**Percentage of order lines**
0-2 days	12,4 %
3-4 days	21,3 %
5-6 days	17,8 %
7-8 days	19,5 %
9-10 days	12,5 %
>10 days	16,5 %

Table 6.2: Waiting time European port

Waiting time port	**Percentage of order lines**
0-1 days	27,8 %
2-3 days	39,7 %
4-5 days	20,4 %
>5 days	12,1 %

Table 6.3: Total added time due to consolidation and port waiting time

Consolidation time + waiting time harbour	**Percentage of order lines**
0-3 days	5,2 %
4-6 days	22,1 %
7-9 days	27,5 %
10-12 days	21,5 %
13-15 days	12,9 %
>15 days	10,8 %

The three tables above show that adding 10 days safety lead time is an acceptable uplift.

The replenishment orders of the LDCs at the CDC can be delayed by CDC stock-outs and handling or transportation issues. ChainScope already incorporates the CDC stock-outs in the multi-echelon analysis, so the safety lead time should only cover the handling and transportation issues. To get an idea of the correct inflation factor, the currently implemented ITM-model is used as an analysis tool.

At first, results are generated using average lead time and lead time variance as input. This results in an optimal reorder level (IOP), which is saved. Afterwards, the lead time variance is switched off and the new average lead time which generates the same IOP as in the old situation is found. The difference between the new and old average lead time is called the safety lead time. The safety lead time is found by looking to the best fit by adding incremental steps of 0,5% each. On average, the safety lead time, which generates the same reorder level, equals 4,3 % of the average lead time.

Only one cycle is used to calculate the uplift, which forms a limitation of this analysis. Since the percentages can change in other cycles, the average of 4,3% days is added to the average lead time for each LDC.

Concluding, new ChainScope output will be generated with added safety lead time of 4,3 % on local items and 10 workdays on CDC items. The next paragraph discusses the results.

6.5 Comparison 5: Multi-echelon control with stationary simulated demand and actual lead time vs. multi-echelon control with stationary simulated demand and fixed added lead time

In the next comparison, the multi-echelon inventory control situation with actual lead time is compared with the multi-echelon inventory control situation with added lead time. In ChainScope and the simulation tool, the lead time of vendors to the CDC is increased with 10 workdays and the local lead time is increased with 4,3%.

An overview of the simulation results can be found in Figure 6.5, where

- First scenario: Multi-echelon control with stationary simulated demand and actual lead time.
- Second scenario: Multi-echelon control with stationary simulated demand and fixed added lead time.

A detailed comparison can be found in Table A.13, Table A.14 and Table A.15 of Appendix A.

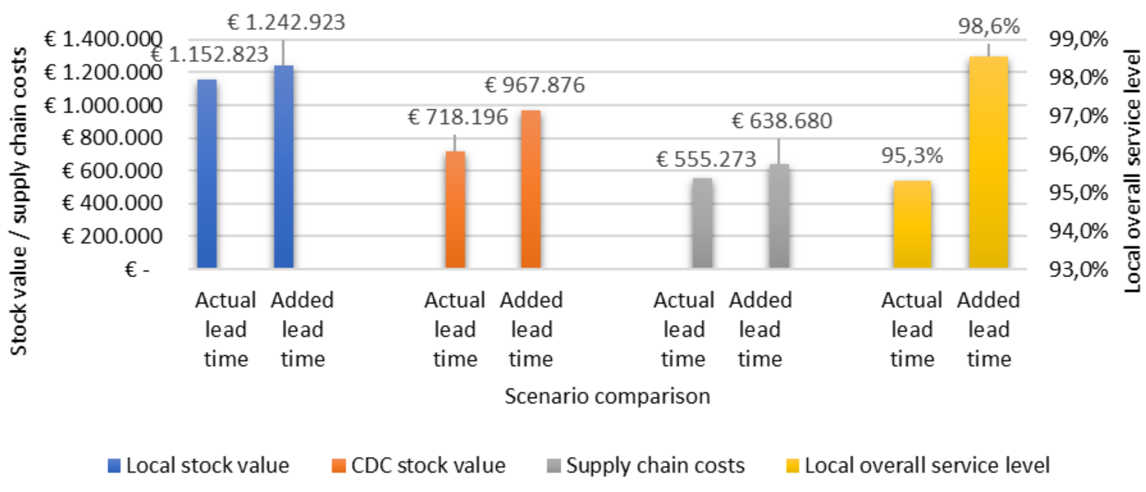

Figure 6.5: Comparison #5: Multi-echelon control with stationary simulated demand and actual lead time vs. multi-echelon control with stationary simulated demand and added lead time

As expected, the stock level at both the LDCs and the CDC is increased, which also leads to a higher service level. This means that the uplift (adding lead time) has the expected and desirable effect. In the section below, the simulation results are analysed further to find other factors which limit the supply chain performance.

As mentioned in the previous chapter, the local uplift is computed for every item-warehouse combination, but only the average uplift (4,3%) is used as added lead time. Table 6.4 below shows the simulation results in buckets of the actual best-fitted uplift.

Table 6.4: Added lead time buckets with the corresponding service levels and average daily demand

Set	**# of items**	**Service level**	**Average daily demand**
0,0 % -1,5 %	205	99,8 %	0,5
2,0 % - 3,5 %	792	99,6 %	6,1
4,0 % - 5,5 %	544	99,2 %	15,6
6,0 % - 7,5 %	276	98,4 %	59,5
8,0 % - 9,5 %	124	98,6 %	70,5
10,0 % - 11,5 %	32	98,1 %	73,8
12,0 % - 13,5 %	25	98,3 %	277,5
14,0 % - 16,5 %	5	96,8 %	1.089,9

The first column in the table represents the percentage of days which needs to be added to result in the same reorder level. Remember that in the previous analysis 4,3 % is added for every item. Table 6.4 shows that the items for which less than 4,3 % should be added perform higher than the target. On the other hand, items for which more than 4,3 % should be added perform lower than de target. Furthermore, the average daily demand increases when the safety lead time percentage increases.

Combining those two observations leads to the conclusion that fast movers need more than 4,3 % safety lead time. Since the service level performance measure compares total demand by total backorders, this conclusion will have a major impact on the fill rate.

Table 6.5: Variable added safety vendor lead time

Bucket		**Added lead time**
1	Slow movers	0 days
2	↓	1,5 days
3		3 days
4		4,5 days
5		6 days
6		7,5 days
7		9 days
8		10,5 days
9		12 days
10	Fast movers	13,5 days

Instead of changing the local lead time uplift, it would also be possible to change the vendor lead time uplift. This is a better choice, since the local lead time uplift is only calculated for one cycle and could be different in another cycle and it is expected that the long CDC lead times will have more effect. The total demand of the items in the CDC is summed and the items are divided over 10 equal buckets. Those buckets are increasing in average demand, i.e. the 10% lowest demand items are combined in bucket 1 and the 10th bucket is filled with the 10% highest demand items. Afterwards, the added CDC lead time will vary between 0 and 13,5 days as defined in Table 6.5, instead of adding 10 days for each item.

The variable added safety lead time scenario is compared with the fixed added safety lead time scenario in the next paragraph to test the effect.

6.6 Comparison 6: Multi-echelon inventory control with fixed added lead time vs. multi-echelon control with variable added lead time

The next comparison quantifies the added value of the variable safety lead time uplift over adding a fixed uplift (in the CDC).

An overview of the simulation results can be found in Figure 6.6, where

- First scenario: Multi-echelon inventory control policy with stationary simulated demand and fixed added lead time.
- Second scenario: Multi-echelon inventory control policy with stationary simulated demand and variable added lead time.

The detailed results can be found in Table A.16, Table A.17 and Table A.18 of Appendix A.

As expected, the CDC stock is uplifted. The variable safety lead time uplift dominates the fixed lead time uplift scenario. With a limited stock increase (0,4%), the disservice reduces with 23,8%. It is clear that fast movers need a higher uplift than slow movers. However, the safety lead time uplift is not optimised. The supply chain performance could be improved by optimising the safety lead time, but due to time constraints this is left to future research.

To find the potential of switching from the current installation stock control to multi-echelon inventory control, the simulations are compared in the next paragraph.

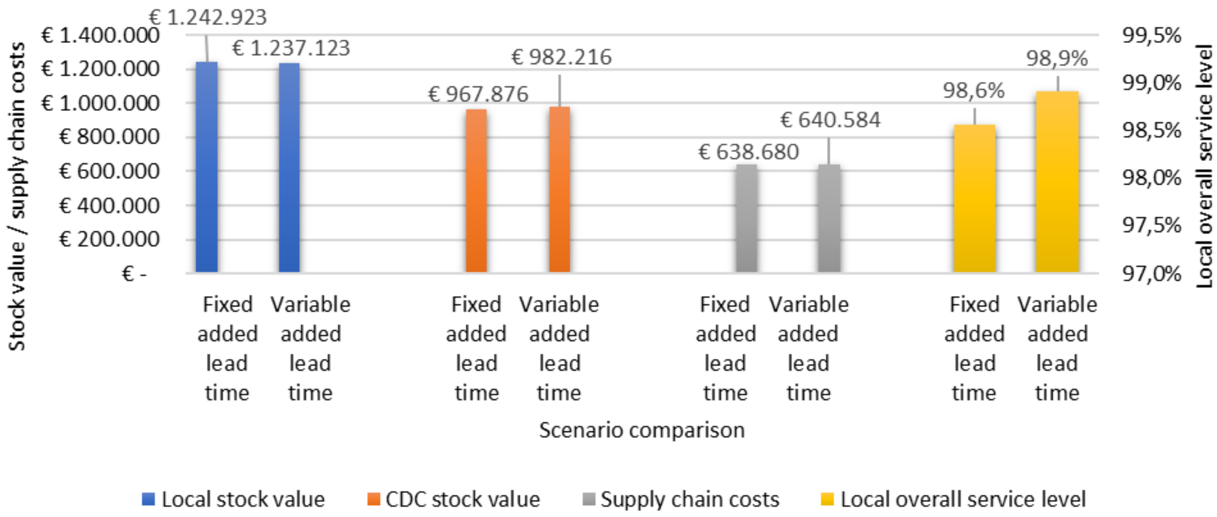

Figure 6.6: Comparison #6: Multi-echelon inventory control with fixed added lead time vs. multi-echelon inventory control with variable added lead time

6.7 Comparison 7: Installation stock control with stationary simulated demand and actual lead time vs. multi-echelon inventory control with stationary simulated demand and variable added lead time

This final comparison emphasizes the added value of multi-echelon inventory control over an installation stock policy.

An overview of the results can be found in Figure 6.7, where

- Scenario 1: Current installation stock control policy with stationary simulated demand and actual lead time.
- Scenario 2: Multi-echelon inventory control policy with stationary simulated demand and variable uplifted lead time.

The detailed results can be found in Table A.19, Table A.20 and Table A.21 of Appendix A.

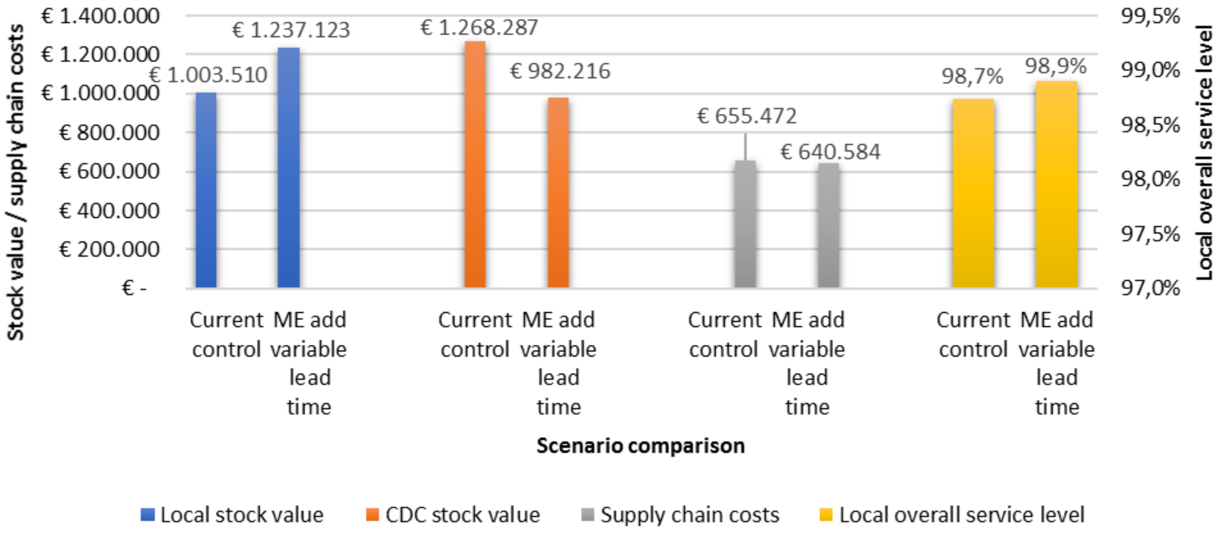

Figure 6.7: Comparison #7: Installation stock control policy with stationary simulated demand and actual lead time vs. multi-echelon inventory control with variable added lead time

The detailed results can be found in Table A.19, Table A.20 and Table A.21 of Appendix A.

Multi-echelon control results in a small (2,3%) stock decrease, and more importantly, the disservice decreases with 13,4%. The result is a win-win situation, since stock decreases and service level increases. When the service level of the multi-echelon inventory control scenario would also be reduced to 98,7%, the stock decrease would definitely be even higher than 2,3%.

While the total stock value stays almost the same, the biggest difference deals with the location of the stock since it moves from centrally to locally. This means that more stock is held in the local stock points, close to the customers. A disadvantage is that the supply chain becomes less flexible, since inventory is already assigned to a LDC.

There are also a few advantages of the stock movement. At first, the LDCs deliver a purchase forecast to the CDC and afterwards it is not compulsory to actually buy the amount of the forecast. When more stock is held locally, the LDC faces the consequences of a bad forecast by themselves. In the new situation they own the dead stock or face the consequences of understock caused by a bad forecast.

The analysis below elaborates further on the differences between the original installation stock control policy and multi-echelon inventory control. It will give some insights in the observed differences between item characteristics. Future research can be used to prove that the differences are actually caused by the characteristics.

The effect of the number of LDCs on the performance can be found in Table 6.6.

Table 6.6: Performance comparison related to the number of LDCs per item

Number of LDCs	**Number of unique items**	**Total stock value**		**Service level**	
		Current	**Multi-echelon inventory control**	**Current**	**Multi-echelon inventory control**
1	389	€ 462.576	€ 454.665	98,4 %	98,5 %
2	154	€ 472.578	€ 473.326	98,9 %	99,5 %
3	184	€ 374.261	€ 372.196	98,5 %	98,8 %
4	135	€ 726.883	€ 697.136	98,8 %	98,8 %
5	17	€ 107.016	€ 98.154	99,2 %	99,5 %
6	11	€ 77.604	€ 77.398	99,0 %	99,5 %
7	9	€ 50.879	€ 46.554	99,1 %	99,4 %

As can be seen in Table 6.6, the highest service level gain is achieved at the items which are sold in 2 and 6 LDCs. However, this is not a proof that 2 or 6 LDCs is optimal for the reseller in office supplies. There are a lot of other reasons which can play a role in the observed difference.

Another reason could be the average demand, as mentioned earlier in this chapter. In Table 6.7, the items are ranked from slow-movers to fast-movers and afterwards classified in 10 categories in the same way as earlier in this chapter (Table 6.5).

Table 6.7: Performance comparison per demand category

Demand category		**Average yearly demand**	**Total stock value**		**Service level**	
			Current	**Multi-echelon inventory control**	**Current**	**Multi-echelon inventory control**
1	Slow movers	60	€ 83.073	€ 90.681	98,2%	99,4%
2		231	€ 98.447	€ 105.725	98,8%	99,5%
3		503	€ 134.215	€ 137.610	98,7%	99,7%
4		974	€ 105.168	€ 102.495	98,7%	99,3%
5		1633	€ 133.861	€ 133.177	98,9%	99,7%
6		2775	€ 202.998	€ 206.454	98,8%	99,4%
7		4768	€ 273.283	€ 272.894	98,9%	99,7%
8		8316	€ 203.074	€ 200.154	98,8%	99,6%
9		16534	€ 300.518	€ 303.253	98,7%	99,4%
10	Fast movers	91540	€ 737.160	€ 666.896	98,7%	98,7%

As can be seen in Table 6.7, the customer service is improved for every category except for the fast mover category, where the service level stays the same. The stock level of the first 9 categories (where the service level improves) is increased a little bit, but this does not weigh against the large stock value benefit in the 10th bucket. Therefore, the highest stock value benefit can be gained in the fast mover category.

When the items which are delivered to a business partner are compared with the other items, some interesting insights are found. This analysis is applied to the multi-echelon inventory control scenario with variable added lead time and can be found in Table 6.8.

Table 6.8: Business partner effect on stock value and service level

Business partner item?	**Number of items**	**CDC stock value**	**LDC stock value**	**Total stock value**	**LDC service level**
Yes	297	€ 433.381	€ 547.285	€ 980.666	98,9 %
No	602	€ 548.836	€ 689.838	€ 1.238.673	99,0 %

The stock values are converted to fractional number in Table 6.9.

Table 6.9: Business partner effect on fractional stock levels

Business partner item?	**Number of items**	**CDC stock value**	**LDC stock value**	**Total stock value**
Yes	33,0 %	44,1 %	44,2 %	44,2 %
No	67,0 %	55,9 %	55,8 %	55,8 %

As can be seen in Table 6.8 and Table 6.9, about 33% of the items (which are delivered to business partners) account for 44 % of the stock. No robust and significant conclusions can be drawn from this analysis, since the differences can be caused by other components. However, it could be possible that the stock can be reduced when the business partner items are delivered in a different way. For example, the business partners could be delivered from a LDC instead of the CDC. This LDC probably already holds stock for the regular customers. This could reduce overall stock, since the company can limit the CDC safety stock. This major process change needs further investigation and is therefore recommended for future research.

The simulation output is also compared to the ChainScope output in Table 6.10 and the differences are discussed. The main differences are caused by

- The assumption that inbound replenishment orders can leave the stock point the next day at the earliest causes one extra day lead time. Since the stock value is measured at the end of the day, replenishment inbound orders are at least one day in stock. Concluding, this assumption inflates the stock value and decreases the service level.
- When the CDC can fulfil open purchase orders of the LDC, the stock is reserved until the next truck drives from the CDC to the LDC. This means that deliveries are delayed and increases the CDC stock value.
- The replenishment policy parameters in the company are recalculated every 20 workdays. The fluctuating demand causes system inefficiencies. For example, for items with a seasonal pattern, the reorder level drops after the period of high demand. This means that the CDC and LDC has stocked according to a high forecast and afterwards the demand is significantly reduced, which leads to overstock. This can also work out the other way around.

- The variable added safety lead time concept computes the policy parameters with a higher lead time than the actuals, which inflates the LDC and CDC stock. This will add between € 0 and € 337.756 in the CDC and between € 0 and € 18.377 in the LDCs.
- The safety stock in the simulation is not allowed to be negative, while ChainScope assumes it can be negative. This will add between € 0 and € 155.479 in the CDC.

Table 6.10: Comparison simulation output with ChainScope output

Performance measure	**Simulation output**	**ChainScope output**
LDC service Level	98,9 %	99,1 %
LDC average stock value	€ 1.237.123	€ 1.044.651
CDC average stock value	€ 982.216	€ 549.540

Finally, the scenario where negative safety stock values in the CDC were allowed is simulated. However, the company does not allow for negative safety stock, so this is only useful for extra insights. The results are displayed in Appendix C and the main conclusions are described below.

Compared to the current control policy, the multi-echelon control policy with negative safety stock values will result in an overall stock decrease of 8,2% with equal service levels. In general, the local stock value is increased and the central stock value is decreased. The central decrease is much higher than the local increase, which leads to the overall stock decrease.

7 Conclusion

This chapter concludes the research with an answer to the main research question. To remember, the main research question was formulated as

> *Main research question: How can multi-echelon inventory control be used to minimize supply chain costs while maintaining the desired end customer service level in a reseller environment?*

In this research multi-echelon inventory control is compared to the current installation stock policy with information sharing at a reseller in office supplies. The current control policies do need to stay the same, but the control parameters are allowed to change.

The company already improves the performance of the installation stock policy by sharing forecast information between the LDCs and the CDC. However, there is an open opportunity in the CDC base stock level calculation. The performance can be increased by changing the agreed lead time to the actual lead time. Moreover, safety stock levels are determined on vendor level with little variation between vendors and items. The installation stock policy safety stocks could be improved to give a performance boost, but this is left for future research.

Since previous research in multi-echelon inventory control has never combined the two policies implemented at the reseller of office supplies, the software package ChainScope is used to determine the optimal safety stock levels. Those values are translated to the policy parameters like reorder levels and base stock levels. The major difference deals with the positioning of stock, because in general stock moves from the CDC to the LDCs. On average this will decrease disservice (with 13,4%), while the stock level decreases (with 2,3%).

Those results are generated by iteratively improving the safety lead times in the multi-echelon control policy. Note that the safety lead times are not fully optimised, which means the potential of a multi-echelon control policy could be even higher. The optimisation of the safety lead times is left for future research.

The detailed comparison can be found in chapter 6 and Appendix A, whereas the multi-echelon control policy used is explained in chapter 5.

8 Discussion

In the last chapter, the recommendation to the company are discussed, including the limitations of this research and the future research opportunities.

8.1 Implementation recommendations

The outcomes of this research result in a few company recommendations and insights. At first, the current control policy is analysed, which leads to the first recommendation. The scenario which uses actual lead time instead of the currently used agreed lead time in the CDC has a higher performance. It is recommended to update the actual lead times more often and replicate those values in the CDC replenishment policy.

Comparison 3 in chapter 6 proves that the company adds value with sharing the forecasts. The information sharing scenario dominates the non-information sharing one. It is recommended to keep sharing forecast information and at the same time motivate the LDCs to forecast as accurate as possible. In this way the supply chain costs can be reduced and the service level to the final customers can be retained.

The last recommendation deals with the objective of this research, i.e. implementing multi-echelon inventory control. Instead of optimising the safety stock levels in each echelon separately, the company can gain from optimising all safety stocks in the supply chain centrally. This will result in a stock shift from centrally to locally, which also has the benefit that local distribution centres become more aware of the consequences of an inaccurate forecast. Concluding, the company can take advantages on multiple aspects.

However, it is recommended to discuss the new concept very clear to the employees. They can feel out of control and behave in the wrong way. The first implementation step would be informing the employees and create support in the entire organization. Moreover, when the multi-echelon inventory control strategy of this research is implemented, some warehouses need to shift to the ITM replenishment model. The company needs to investigate the costs and feasibility of this shift. Moreover, the information technology should support multi-echelon inventory control, which also needs to be investigated. Concluding, a substantial improvement potential is found in multi-echelon inventory control, but the feasibility and costs of the actual implementation need to be investigated.

8.2 Limitations

As described in the scope of this research, it was not possible to include all items in the analysis. The reason is that sufficient data needs to be available, so only 65% of the indirect delivered items could be included. This leads to the consequence that a CDC item has less successors in the supply chain, which limits the multi-echelon inventory control potential.

As described in chapter 6, the reseller in office supplies does not have a robust method to determine the safety lead time. Therefore, this added lead time is found iteratively. This means that the safety lead times used in the multi-echelon control optimisation are not optimised. The improvement potential could be even higher when an optimisation technique would be developed which generates optimal safety lead times. Due to time constraints, this opportunity is a direction for future research.

Another limitation is the simulation length used. The control parameters in the replenishment system of the company are updated every 4 weeks. Therefore, to run a simulation longer than 410 days, the input data for those days is also needed. It was not possible to extend the simulation length, since this results in more excluded items.

The service level within the company is measured in terms of line fill rate. However, in this research there was no access to the order line history, but only total weekly demand per item is available. Therefore, in this research the service level was measured in terms of unit fill rate instead of line fill rate.

The last limitation is the exclusion of Chinese New Year. The company needs to order more in the cycles before Chinese New Year, because the far east production will be limited during this period. This order restriction is not used in the optimisation, because the replenishment behaviour could not be replicated exactly.

8.3 Contribution to the literature

This research contributes to the literature, since it has never investigated centralized multi-echelon inventory control in a reseller environment which combines a (R,s,S,nQ)-policy with a (R,S)-policy with information sharing. ChainScope is used to calculate optimal policy parameters, which is never tested in a simulation tool for finite horizons. The finite horizon is created by recalibrating the system every 20 workdays, which many companies do. The master thesis also gives recommendations for future research, which are discussed in the next paragraph.

8.4 Future research

As mentioned in chapter 4, the current forecasting technique is horizontal moving average, which has a few limitations. As concluded in chapter 3, the demand pattern of items at the reseller in office supplies faces trend, seasonality and correlates between different LDCs. Horizontal moving average does not account for those patterns, which leaves a more accurate forecasting technique for future research. All simulation studies use the same forecast, which means the forecast error will have no effect on the scenario differences within this research.

Besides the forecasting technique, there are other opportunities for future research. Chapter 2 mentions that the choice between direct and indirect delivery is made on vendor level. The added value of multi-echelon inventory control could be changed by revising this choice and testing the impact on the replenishment policy. This means that revising the direct or indirect delivery choice could be a direction for future research.

Chapter 6 gives the impression that the company could gain from delivering the business partners from a LDC instead of the CDC. The biggest advantage can be gained by variability pooling, because more demand patterns could be combined. Besides that, the CDC can reduce safety stock since it is not in touch with a customer any more.

Finally, as mentioned in chapter 6, the benefits of multi-echelon inventory control can be amplified by the optimisation of the safety lead time. The optimal safety lead time should deviate on item level, but there seems to be a relationship between slow and fast movers. On average, fast movers need more safety lead time than slow movers. After the optimisation, the stock values could be reduced and the service level could be increased.

9 Bibliography

Axsäter, S. (2015). *Inventory control (Vol. 225).* Springer.

Axsäter, S., & Juntti, L. (1996). Comparison of echelon stock and installation stock policies for two-level inventory systems. *International Journal of Production Economics*, *45*(1-3), 303-310.

Cachon, G. P. (2001). Exact evaluation of batch-ordering inventory policies in two-echelon supply chains with periodic review. *Operations research*, *49*(1), 79-98.

Chen, F., Drezner, Z., Ryan, J. K., & Simchi-Levi, D. (2000). Quantifying the bullwhip effect in a simple supply chain: The impact of forecasting, lead times, and information. *Management science*, *46*(3), 436-443.

Clark, A. (1958). A dynamic, single-item, multi-echelon inventory model.

De Kok, A. G. (2010). Discrete time inventory models, batch mode, *Excel spreadsheet*.

de Kok, T. G., & Fransoo, J. C. (2003). Planning supply chain operations: definition and comparison of planning concepts. *Handbooks in operations research and management science*, *11*, 597-675.

de Kok, T., Grob, C., Laumanns, M., Minner, S., Rambau, J., & Schade, K. (2018). A typology and literature review on stochastic multi-echelon inventory models. *European Journal of Operational Research*, 269(3), 955-983.

Diks, E. B., De Kok, A. G. (1999). Computational results for the control of a divergent N-echelon inventory system. *International Journal of Production Economics, 59(1-3), 327-336.*

Durlinger, P. (1998). *Effectief voorraadbeheer: een stappenplan*. Kluwer.

Heijden, van der, M. C., Diks, E. B., & Kok, de, A. G. (1997). Stock allocation in general multi-echelon distribution systems with (R,S) order-up-to-policies. *International Journal of Production Economics*, 49(2), 157-174. DOI: 10.1016/S0925-5273(97)00005-4

Heijnen, S.G. (2019). Redesign of the Inventory Control Model for the Least Performing SKUs in a Reselling Environment. *Eindhoven: Eindhoven University of Technology*

Kok, de, A. G., & Graves, S. C. (Eds.) (2003). Supply chain management : design, coordination and operation. *Handbooks in operations research and management science*; Vol. 11. Amsterdam: Elsevier.

Montgomery, D. C., & Runger, G. C. (2010). *Applied statistics and probability for engineers*. John Wiley & Sons.

Nahmias, S., & Cheng, Y. (2005). *Production and operations analysis* (Vol. 6). New York: McGraw-hill.

Op 't Veld, B. (2016). Improving inventory performance in France. *TIAS School for Business and Society.*

Tempelmeier, H. (1993). Safety stock allocation in a two-echelon distribution system. *European journal of operational research*, 65(1), 96-117.

Thomopoulos, N. T. (2015). Demand forecasting for inventory control. In Demand Forecasting for Inventory Control (pp. 1-10). *Springer*, Cham.

Van Aken, J. E., & Berends, H. (2007). Problem solving in organizations. *Cambridge University Press.* Chapter 6

Van Strien, P. J. (1997). Towards a methodology of psychological practice: The regulative cycle. *Theory & Psychology*, 7(5), 683-700.

Vargas Suavita, J. (2012). Two-echelon Replishment Policy with Periodic review, Lot sizing and Integral information for the region of UK & Ireland at Office Depot. Eindhoven: *Eindhoven University of Technology*.

Viswanathan, S. (1997). Note. Periodic Review (s, S) Policies for Joint Replenishment Inventory Systems. *Management Science*, 43(10), 1447-1454.

10 Appendices

A. Appendix A: Detailed simulation results of the comparisons

Comparison 1: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with stationary simulated demand and agreed lead time

Table A.1: Detailed stock values and supply chain costs of comparison 1

Warehouse	Stock value		Total supply chain costs	
	Actual lead time	Agreed lead time	Actual lead time	Agreed lead time
E	€ 148.105	€ 145.219	€ 46.898	€ 46.190
F	€ 174.221	€ 173.372	€ 54.354	€ 54.126
L	€ 40.879	€ 40.961	€ 14.603	€ 14.608
R	€ 32.024	€ 31.817	€ 11.701	€ 11.636
M	€ 71.767	€ 70.728	€ 24.767	€ 24.519
1	€ 93.329	€ 92.085	€ 31.793	€ 31.500
009	€ 443.185	€ 442.440	€ 118.770	€ 118.591
CDC	€ 1.268.287	€ 1.241.768	€ 352.586	€ 346.111
Total	**€ 2.271.797**	**€ 2.238.390**	**€ 655.472**	**€ 647.281**

Table A.2: Detailed service levels per warehouse for comparison 1

Warehouse	LDC service level		CDC service level to LDCs		CDC service level to BPs	
	Actual lead time	Agreed lead time	Actual lead time	Agreed lead time	Actual lead time	Agreed lead time
E	98,5%	96,6%				
F	98,9%	97,9%				
L	98,7%	98,6%				
R	98,5%	98,2%				
M	98,7%	98,1%				
1	98,7%	97,5%				
009	98,7%	97,9%				
CDC			96,6%	92,1%	96,0%	91,4%
Total	**98,7%**	**97,7%**	**96,6%**	**92,1%**	**96,0%**	**91,4%**

Table A.3: Supply chain costs breakdown per warehouse for comparison 1

Warehouse	**Inventory holding costs**		**Major order costs**		**Minor order costs**	
	Actual lead time	**Agreed lead time**	**Actual lead time**	**Agreed lead time**	**Actual lead time**	**Agreed lead time**
E	€ 36.286	€ 35.579	€ 1.040	€ 1.040	€ 9.572	€ 9.572
F	€ 42.684	€ 42.476	€ 1.040	€ 1.040	€ 10.630	€ 10.610
L	€ 10.015	€ 10.035	€ 1.040	€ 1.040	€ 3.548	€ 3.532
R	€ 7.846	€ 7.795	€ 1.040	€ 1.040	€ 2.815	€ 2.801
M	€ 17.583	€ 17.328	€ 1.040	€ 1.040	€ 6.144	€ 6.151
1	€ 22.866	€ 22.561	€ 1.040	€ 1.040	€ 7.888	€ 7.899
009	€ 108.580	€ 108.398	€ 1.040	€ 1.040	€ 9.149	€ 9.153
CDC	€ 310.730	€ 304.233	€ 12.004	€ 11.996	€ 29.852	€ 29.882
Total	**€ 556.590**	**€ 548.406**	**€ 19.284**	**€ 19.276**	**€ 79.598**	**€ 79.599**

Comparison 2: Installation stock control with stationary simulated demand and actual lead time vs. installation stock control with actual demand and actual lead time

Table A.4: Detailed stock values and supply chain costs of comparison 2

Warehouse	**Stock value**		**Total supply chain costs**	
	Simulated demand	**Actual demand**	**Simulated demand**	**Actual demand**
E	€ 148.105	€ 136.281	€ 46.898	€ 45.159
F	€ 174.221	€ 160.758	€ 54.354	€ 51.959
L	€ 40.879	€ 40.071	€ 14.603	€ 14.823
R	€ 32.024	€ 29.575	€ 11.701	€ 11.459
M	€ 71.767	€ 66.957	€ 24.767	€ 24.193
1	€ 93.329	€ 85.988	€ 31.793	€ 30.605
009	€ 443.185	€ 414.531	€ 118.770	€ 113.232
CDC	€ 1.268.287	€ 1.354.399	€ 352.586	€ 372.650
Total	**€ 2.271.797**	**€ 2.288.560**	**€ 655.472**	**€ 664.080**

Table A.5: Detailed service levels per warehouse for comparison 2

Warehouse	***LDC service level***		***CDC service level to LDCs***		***CDC service level to BPs***	
	Simulated demand	**Actual demand**	**Simulated demand**	**Actual demand**	**Simulated demand**	**Actual demand**
E	98,5%	90,3%				
F	98,9%	88,6%				
L	98,7%	92,2%				
R	98,5%	92,0%				
M	98,7%	93,9%				
1	98,7%	91,1%				
009	98,7%	86,7%				
CDC			96,6%	83,7%	96,0%	86,5%
Total	**98,7%**	**89,3%**	**96,6%**	**83,7%**	**96,0%**	**86,5%**

Table A.6: Supply chain costs breakdown per warehouse for comparison 2

Warehouse	***Inventory holding costs***		***Major order costs***		***Minor order costs***	
	Simulated demand	**Actual demand**	**Simulated demand**	**Actual demand**	**Simulated demand**	**Actual demand**
E	€ 36.286	€ 33.389	€ 1.040	€ 1.040	€ 9.572	€ 10.731
F	€ 42.684	€ 39.386	€ 1.040	€ 1.040	€ 10.630	€ 11.534
L	€ 10.015	€ 9.817	€ 1.040	€ 1.040	€ 3.548	€ 3.966
R	€ 7.846	€ 7.246	€ 1.040	€ 1.040	€ 2.815	€ 3.174
M	€ 17.583	€ 16.405	€ 1.040	€ 1.040	€ 6.144	€ 6.749
1	€ 22.866	€ 21.067	€ 1.040	€ 1.040	€ 7.888	€ 8.498
009	€ 108.580	€ 101.560	€ 1.040	€ 1.040	€ 9.149	€ 10.632
CDC	€ 310.730	€ 331.828	€ 12.004	€ 11.920	€ 29.852	€ 28.903
Total	**€ 556.590**	**€ 560.697**	**€ 19.284**	**€ 19.200**	**€ 79.598**	**€ 84.183**

Comparison 3: Installation stock control with stationary simulated demand, actual lead time and <u>information sharing</u> vs. installation stock control with stationary simulated demand, actual lead time and <u>without information sharing</u>

Table A.7: Detailed stock values and supply chain costs of comparison 3

Warehouse	***Stock value***		***Total supply chain costs***	
	With info sharing	**Without info sharing**	**With info sharing**	**Without info sharing**
E	€ 148.105	€ 146.536	€ 46.898	€ 46.507
F	€ 174.221	€ 173.985	€ 54.354	€ 54.271
L	€ 40.879	€ 40.855	€ 14.603	€ 14.586
R	€ 32.024	€ 31.786	€ 11.701	€ 11.627
M	€ 71.767	€ 70.671	€ 24.767	€ 24.508
1	€ 93.329	€ 91.759	€ 31.793	€ 31.399
009	€ 443.185	€ 440.066	€ 118.770	€ 118.010
CDC	€ 1.268.287	€ 1.271.765	€ 352.586	€ 353.117
Total	**€ 2.271.797**	**€ 2.267.423**	**€ 655.472**	**€ 654.027**

Table A.8: Detailed service levels per warehouse for comparison 3

Warehouse	***LDC service level***		***CDC service level to LDCs***		***CDC service level to BPs***	
	With info sharing	**Without info sharing**	**With info sharing**	**Without info sharing**	**With info sharing**	**Without info sharing**
E	98,5%	97,4%				
F	98,9%	97,5%				
L	98,7%	98,5%				
R	98,5%	98,3%				
M	98,7%	98,0%				
1	98,7%	97,4%				
009	98,7%	97,9%				
CDC			96,6%	91,9%	96,0%	90,9%
Total	**98,7%**	**97,6%**	**96,6%**	**91,9%**	**96,0%**	**90,9%**

Table A.9: Supply chain costs breakdown per warehouse for comparison 3

Warehouse	***Inventory holding costs***		***Major order costs***		***Minor order costs***	
	With info sharing	**Without info sharing**	**With info sharing**	**Without info sharing**	**With info sharing**	**Without info sharing**
E	€ 36.286	€ 35.901	€ 1.040	€ 1.040	€ 9.572	€ 9.566
F	€ 42.684	€ 42.626	€ 1.040	€ 1.040	€ 10.630	€ 10.605
L	€ 10.015	€ 10.010	€ 1.040	€ 1.040	€ 3.548	€ 3.537
R	€ 7.846	€ 7.788	€ 1.040	€ 1.040	€ 2.815	€ 2.800
M	€ 17.583	€ 17.314	€ 1.040	€ 1.040	€ 6.144	€ 6.154
1	€ 22.866	€ 22.481	€ 1.040	€ 1.040	€ 7.888	€ 7.878
009	€ 108.580	€ 107.816	€ 1.040	€ 1.040	€ 9.149	€ 9.154
CDC	€ 310.730	€ 311.583	€ 12.004	€ 11.980	€ 29.852	€ 29.555
Total	**€ 556.590**	**€ 555.519**	**€ 19.284**	**€ 19.260**	**€ 79.598**	**€ 79.248**

Comparison 4: <u>Installation stock control</u> with stationary simulated demand and actual lead time vs. <u>multi-echelon control</u> with stationary simulated demand and actual lead time

Table A.10: Detailed stock values and supply chain costs of comparison 4

Warehouse	***Stock value***		***Total supply chain costs***	
	Installation stock control	**ME-control (actual lead time)**	**Installation stock control**	**ME-control (actual lead time)**
E	€ 148.105	€ 182.326	€ 46.898	€ 54.984
F	€ 174.221	€ 211.571	€ 54.354	€ 63.255
L	€ 40.879	€ 46.443	€ 14.603	€ 15.923
R	€ 32.024	€ 36.449	€ 11.701	€ 12.753
M	€ 71.767	€ 82.013	€ 24.767	€ 27.217
1	€ 93.329	€ 106.642	€ 31.793	€ 34.851
009	€ 443.185	€ 487.379	€ 118.770	€ 129.320
CDC	€ 1.268.287	€ 718.196	€ 352.586	€ 216.971
Total	**€ 2.271.797**	**€ 1.871.019**	**€ 655.472**	**€ 555.273**

Table A.11: Detailed service levels per warehouse for comparison 4

Warehouse	LDC service level		CDC service level to LDCs		CDC service level to BPs	
	Installation stock control	ME-control (actual lead time)	Installation stock control	ME-control (actual lead time)	Installation stock control	ME-control (actual lead time)
E	98,5%	96,5%				
F	98,9%	93,9%				
L	98,7%	95,3%				
R	98,5%	95,7%				
M	98,7%	96,6%				
1	98,7%	94,5%				
009	98,7%	96,5%				
CDC			96,6%	74,0%	96,0%	75,2%
Total	**98,7%**	**95,3%**	**96,6%**	74,0%	**96,0%**	75,2%

Table A.12: Supply chain costs breakdown per warehouse for comparison 4

Warehouse	Inventory holding costs		Major order costs		Minor order costs	
	Installation stock control	ME-control (actual lead time)	Installation stock control	ME-control (actual lead time)	Installation stock control	ME-control (actual lead time)
E	€ 36.286	€ 44.670	€ 1.040	€ 1.040	€ 9.572	€ 9.274
F	€ 42.684	€ 51.835	€ 1.040	€ 1.040	€ 10.630	€ 10.380
L	€ 10.015	€ 11.379	€ 1.040	€ 1.040	€ 3.548	€ 3.504
R	€ 7.846	€ 8.930	€ 1.040	€ 1.040	€ 2.815	€ 2.783
M	€ 17.583	€ 20.093	€ 1.040	€ 1.040	€ 6.144	€ 6.084
1	€ 22.866	€ 26.127	€ 1.040	€ 1.040	€ 7.888	€ 7.684
009	€ 108.580	€ 119.408	€ 1.040	€ 1.040	€ 9.149	€ 8.872
CDC	€ 310.730	€ 175.958	€ 12.004	€ 11.954	€ 29.852	€ 29.059
Total	**€ 556.590**	**€ 458.400**	**€ 19.284**	**€ 19.234**	**€ 79.598**	**€ 77.640**

Comparison #5: Multi-echelon control with stationary simulated demand and actual lead time vs. multi-echelon control with stationary simulated demand and added lead time

Table A.13: Detailed stock values and supply chain costs of comparison 5

Warehouse	Stock value		Total supply chain costs	
	Actual lead time	Added lead time	Actual lead time	Added lead time
E	€ 182.326	€ 195.406	€ 54.984	€ 58.208
F	€ 211.571	€ 228.389	€ 63.255	€ 67.355
L	€ 46.443	€ 52.463	€ 15.923	€ 17.387
R	€ 36.449	€ 40.886	€ 12.753	€ 13.825
M	€ 82.013	€ 90.086	€ 27.217	€ 29.164
1	€ 106.642	€ 120.308	€ 34.851	€ 38.168
009	€ 487.379	€ 515.385	€ 129.320	€ 136.163
CDC	€ 718.196	€ 967.876	€ 216.971	€ 278.410
Total	**€ 1.871.019**	**€ 2.210.799**	**€ 555.273**	**€ 638.680**

Table A.14: Detailed service levels per warehouse for comparison 5

Warehouse	LDC service level		CDC service level to LDCs		CDC service level to BPs	
	Actual lead time	Added lead time	Actual lead time	Added lead time	Actual lead time	Added lead time
E	96,5%	98,3%				
F	93,9%	98,3%				
L	95,3%	98,9%				
R	95,7%	99,2%				
M	96,6%	98,8%				
1	94,5%	98,3%				
009	96,5%	99,1%				
CDC			74,0%	87,3%	75,2%	88,4%
Total	**95,3%**	**98,6%**	**74,0%**	**87,3%**	**75,2%**	**88,4%**

Table A.15: Supply chain costs breakdown per warehouse for comparison 5

Warehouse	Inventory holding costs		Major order costs		Minor order costs	
	Actual lead time	Added lead time	Actual lead time	Added lead time	Actual lead time	Added lead time
E	€ 44.670	€ 47.874	€ 1.040	€ 1.040	€ 9.274	€ 9.294
F	€ 51.835	€ 55.955	€ 1.040	€ 1.040	€ 10.380	€ 10.360
L	€ 11.379	€ 12.854	€ 1.040	€ 1.040	€ 3.504	€ 3.493
R	€ 8.930	€ 10.017	€ 1.040	€ 1.040	€ 2.783	€ 2.768
M	€ 20.093	€ 22.071	€ 1.040	€ 1.040	€ 6.084	€ 6.053
1	€ 26.127	€ 29.475	€ 1.040	€ 1.040	€ 7.684	€ 7.652
009	€ 119.408	€ 126.269	€ 1.040	€ 1.040	€ 8.872	€ 8.853
CDC	€ 175.958	€ 237.130	€ 11.954	€ 11.996	€ 29.059	€ 29.285
Total	**€ 458.400**	**€ 541.646**	**€ 19.234**	**€ 19.276**	**€ 77.640**	**€ 77.758**

Comparison #6: Multi-echelon inventory control with fixed added lead time vs. multi-echelon inventory control with variable added lead time

Table A.16: Detailed stock values and supply chain costs of comparison 6

Warehouse	Stock value		Total supply chain costs	
	Fixed added lead time	Variable added lead time	Fixed added lead time	Variable added lead time
E	€ 195.406	€ 193.154	€ 58.208	€ 57.648
F	€ 228.389	€ 225.048	€ 67.355	€ 66.599
L	€ 52.463	€ 52.102	€ 17.387	€ 17.300
R	€ 40.886	€ 40.729	€ 13.825	€ 13.769
M	€ 90.086	€ 88.908	€ 29.164	€ 28.875
1	€ 120.308	€ 119.927	€ 38.168	€ 38.094
009	€ 515.385	€ 517.256	€ 136.163	€ 136.592
CDC	€ 967.876	€ 982.216	€ 278.410	€ 281.708
Total	**€ 2.210.799**	**€ 2.219.339**	**€ 638.680**	**€ 640.584**

Table A.17: Detailed service levels per warehouse for comparison 6

Warehouse	LDC service level		CDC service level to LDCs		CDC service level to BPs	
	Fixed added lead time	Variable added lead time	Fixed added lead time	Variable added lead time	Fixed added lead time	Variable added lead time
E	98,3%	98,7%				
F	98,3%	98,9%				
L	98,9%	99,0%				
R	99,2%	99,3%				
M	98,8%	99,0%				
1	98,3%	98,8%				
009	99,1%	99,1%				
CDC			87,3%	89,9%	88,4%	90,1%
Total	**98,6%**	**98,9%**	**87,3%**	**89,9%**	**88,4%**	**90,1%**

Table A.18: Supply chain costs breakdown per warehouse for comparison 6

Warehouse	Inventory holding costs		Major order costs		Minor order costs	
	Fixed added lead time	Variable added lead time	Fixed added lead time	Variable added lead time	Fixed added lead time	Variable added lead time
E	€ 47.874	€ 47.323	€ 1.040	€ 1.040	€ 9.294	€ 9.285
F	€ 55.955	€ 55.137	€ 1.040	€ 1.040	€ 10.360	€ 10.423
L	€ 12.854	€ 12.765	€ 1.040	€ 1.040	€ 3.493	€ 3.495
R	€ 10.017	€ 9.979	€ 1.040	€ 1.040	€ 2.768	€ 2.751
M	€ 22.071	€ 21.782	€ 1.040	€ 1.040	€ 6.053	€ 6.052
1	€ 29.475	€ 29.382	€ 1.040	€ 1.040	€ 7.652	€ 7.672
009	€ 126.269	€ 126.728	€ 1.040	€ 1.040	€ 8.853	€ 8.824
CDC	€ 237.130	€ 240.643	€ 11.996	€ 11.964	€ 29.285	€ 29.101
Total	**€ 541.646**	**€ 543.738**	**€ 19.276**	**€ 19.244**	**€ 77.758**	**€ 77.602**

Comparison #7: <u>Installation stock control policy</u> with stationary simulated demand and <u>actual lead time</u> vs. <u>multi-echelon inventory control</u> with stationary simulated demand and <u>variable added lead time</u>

Table A.19: Detailed stock values and supply chain costs of comparison 7

Warehouse	***Stock value***		***Total supply chain costs***	
	Current control	**ME add variable lead time**	**Current control**	**ME add variable lead time**
E	€ 148.105	€ 193.154	€ 46.898	€ 57.648
F	€ 174.221	€ 225.048	€ 54.354	€ 66.599
L	€ 40.879	€ 52.102	€ 14.603	€ 17.300
R	€ 32.024	€ 40.729	€ 11.701	€ 13.769
M	€ 71.767	€ 88.908	€ 24.767	€ 28.875
1	€ 93.329	€ 119.927	€ 31.793	€ 38.094
009	€ 443.185	€ 517.256	€ 118.770	€ 136.592
CDC	€ 1.268.287	€ 982.216	€ 352.586	€ 281.708
Total	**€ 2.271.797**	**€ 2.219.339**	**€ 655.472**	**€ 640.584**

Table A.20: Detailed service levels per warehouse for comparison 7

Warehouse	***LDC service level***		***CDC service level to LDCs***		***CDC service level to BPs***	
	Current control	**ME add variable lead time**	**Current control**	**ME add variable lead time**	**Current control**	**ME add variable lead time**
E	98,5%	98,7%				
F	98,9%	98,9%				
L	98,7%	99,0%				
R	98,5%	99,3%				
M	98,7%	99,0%				
1	98,7%	98,8%				
009	98,7%	99,1%				
CDC			96,6%	89,9%	96,0%	90,1%
Total	**98,7%**	**98,9%**	**96,6%**	**89,9%**	**96,0%**	**90,1%**

Table A.21: Supply chain costs breakdown per warehouse for comparison 7

Warehouse	***Inventory holding costs***		***Major order costs***		***Minor order costs***	
	Current control	**ME add variable lead time**	**Current control**	**ME add variable lead time**	**Current control**	**ME add variable lead time**
E	€ 36.286	€ 47.323	€ 1.040	€ 1.040	€ 9.572	€ 9.285
F	€ 42.684	€ 55.137	€ 1.040	€ 1.040	€ 10.630	€ 10.423
L	€ 10.015	€ 12.765	€ 1.040	€ 1.040	€ 3.548	€ 3.495
R	€ 7.846	€ 9.979	€ 1.040	€ 1.040	€ 2.815	€ 2.751
M	€ 17.583	€ 21.782	€ 1.040	€ 1.040	€ 6.144	€ 6.052
1	€ 22.866	€ 29.382	€ 1.040	€ 1.040	€ 7.888	€ 7.672
009	€ 108.580	€ 126.728	€ 1.040	€ 1.040	€ 9.149	€ 8.824
CDC	€ 310.730	€ 240.643	€ 12.004	€ 11.964	€ 29.852	€ 29.101
Total	**€ 556.590**	**€ 543.738**	**€ 19.284**	**€ 19.244**	**€ 79.598**	**€ 77.602**

B. Appendix B: Assumed cycle updates in this report

Table B.1: Assumed cycle updates

Cycle number	Week numbers which belong to the cycle
Cycle 1	Week 37 2017 – week 40 2017
Cycle 2	Week 41 2017 – week 44 2017
Cycle 3	Week 45 2017 – week 48 2017
Cycle 4	Week 49 2017 – week 52 2017
Cycle 5	Week 1 2018 – week 4 2018
Cycle 6	Week 5 2018 – week 8 2018
Cycle 7	Week 9 2018 – week 12 2018
Cycle 8	Week 13 2018 – week 16 2018
Cycle 9	Week 17 2018 – week 20 2018
Cycle 10	Week 21 2018 – week 24 2018
Cycle 11	Week 25 2018 – week 28 2018
Cycle 12	Week 29 2018 – week 32 2018
Cycle 13	Week 33 2018 – week 36 2018
Cycle 14	Week 37 2018 – week 40 2018
Cycle 15	Week 41 2018 – week 44 2018
Cycle 16	Week 45 2018 – week 48 2018
Cycle 17	Week 49 2018 – week 52 2018
Cycle 18	Week 1 2019 – week 4 2019
Cycle 19	Week 5 2019 – week 8 2019
Cycle 20	Week 9 2019 – week 12 2019
Cycle 21	Week 13 2019 – week 16 2019

C. Appendix C: Simulation results with negative safety stock values

Comparison 8: Installation stock control policy with stationary simulated demand and actual lead time vs. multi-echelon inventory control with stationary simulated demand, variable added lead time and negative safety stock values

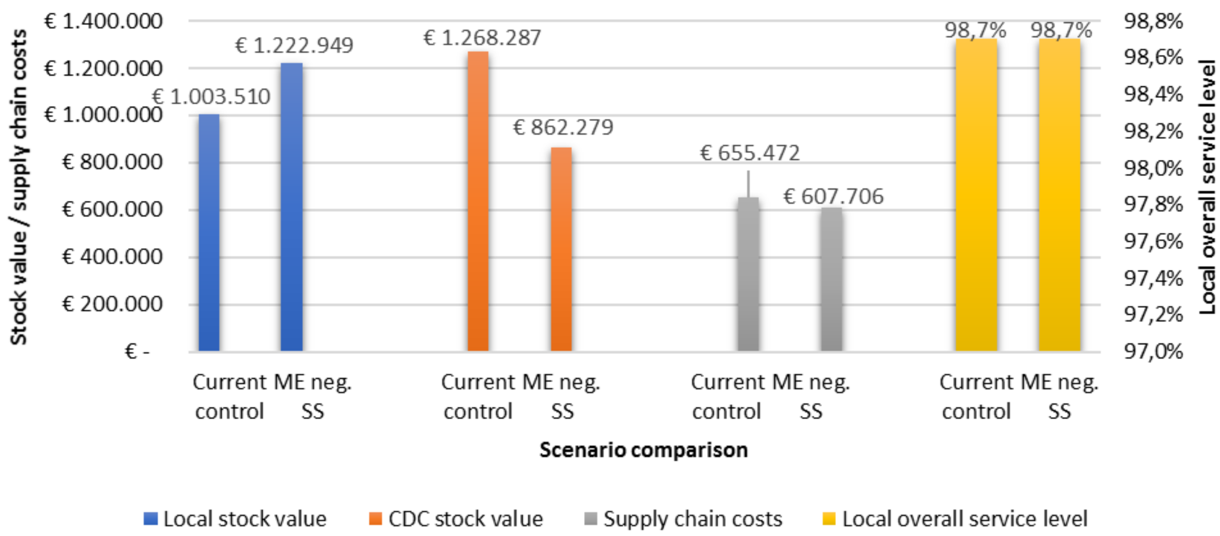

Figure C.1: Installation stock control policy with stationary simulated demand and actual lead time vs. multi-echelon inventory control with stationary simulated demand, variable added lead time and negative safety stock values

Table C.1: Detailed stock values and supply chain costs of comparison 8

Warehouse	Stock value		Total supply chain costs	
	Current	ME neg. SS	Current	ME neg. SS
E	€ 148.105	€ 191.148	€ 46.898	€ 57.109
F	€ 174.221	€ 221.531	€ 54.354	€ 65.747
L	€ 40.879	€ 50.535	€ 14.603	€ 16.923
R	€ 32.024	€ 38.860	€ 11.701	€ 13.346
M	€ 71.767	€ 87.015	€ 24.767	€ 28.406
1	€ 93.329	€ 116.595	€ 31.793	€ 37.275
009	€ 443.185	€ 517.265	€ 118.770	€ 136.612
CDC	€ 1.268.287	€ 862.279	€ 352.586	€ 252.288
Total	**€ 2.271.797**	**€ 2.085.228**	**€ 655.472**	**€ 607.706**

Table C.2: Detailed service levels of comparison 8

Warehouse	LDC service level		CDC service level to LDCs		CDC service level to BPs	
	Current	ME neg. SS	Current	ME neg. SS	Current	ME neg. SS
E	98,5%	98,6%				
F	98,9%	98,5%				
L	98,7%	98,6%				
R	98,5%	98,8%				
M	98,7%	98,5%				
1	98,7%	98,5%				
009	98,7%	99,1%				
CDC			96,6%	85,4%	96,0%	86,5%
Total	**98,7%**	**98,7%**	**96,6%**	**85,4%**	**96,0%**	**86,5%**

Table C.3: Supply chain costs breakdown for comparison 8

Warehouse	Inventory holding costs		Major order costs		Minor order costs	
	Current	ME neg. SS	Current	ME neg. SS	Current	ME neg. SS
E	€ 36.286	€ 46.831	€ 1.040	€ 1.040	€ 9.572	€ 9.238
F	€ 42.684	€ 54.275	€ 1.040	€ 1.040	€ 10.630	€ 10.432
L	€ 10.015	€ 12.381	€ 1.040	€ 1.040	€ 3.548	€ 3.502
R	€ 7.846	€ 9.521	€ 1.040	€ 1.040	€ 2.815	€ 2.785
M	€ 17.583	€ 21.319	€ 1.040	€ 1.040	€ 6.144	€ 6.047
1	€ 22.866	€ 28.566	€ 1.040	€ 1.040	€ 7.888	€ 7.669
009	€ 108.580	€ 126.730	€ 1.040	€ 1.040	€ 9.149	€ 8.842
CDC	€ 310.730	€ 211.258	€ 12.004	€ 11.996	€ 29.852	€ 29.033
Total	**€ 556.590**	**€ 510.881**	**€ 19.284**	**€ 19.276**	**€ 79.598**	**€ 77.549**