MASTER

Inventory level and product availability improvement in a two-echelon divergent supply chain at Ricoh

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Inventory level and product availability improvement in a two-echelon divergent supply chain at Ricoh

by

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I Abstract

This research is about inventory level and product availability improvement within Ricoh's supply chain in Europe. More specifically, a two-echelon divergent supply chain is analyzed, with two different organizations within Ricoh responsible for the different stock locations. Here, the results of the current control policy will be compared to a supply chain with local decision making and at every stock an (R, S)-inventory policy (local control), and to a supply chain with central decision making and an (R, S)-inventory policy on supply chain level (echelon control).

Results of analyzed products indicate that the local control provide better cost results compared to the current control policy at Ricoh. Moreover, the echelon control resulted in even lower supply chain holding costs, indicating the benefits of central decision making. However, a cost allocation rule is required to provide benefits for both parties in the echelon control model. In this two-player allocation game, different concepts all result in splitting the cost savings of echelon control equally over both parties. This is an allocation result within the core of the game.

This report has been made suitable for publication by not-using real product names, and by masking some tables in the Appendix due to confidentiality of the data.

II Management summary

This master thesis is executed at Ricoh Europe Supply Chain Management B.V. (RESCM), located in Bergen op Zoom. Ricoh is a worldwide operating company in the area of image processing devices and RESCM is the central supply chain organization of Ricoh in the regions Europe, Middle-East, and Africa (EMEA). Within Ricoh's supply chain in the EMEA region the focus in this project is on machines having their final assembly at a European factory. These products are procured by the European factories at Asian factories in the form of modules (basic products out of which multiple end products can be created). At the European factories one module can be assembled into different types of finished goods, after which these finished goods are shipped to the European Distribution Centre (EDC) in the Netherlands. Last, customer orders are fulfilled at this EDC. For the project there has been chosen to focus on machines having their final assembly at the Ricoh factory in France, called RIF.

Problem statement

Based on interviews held with relevant employees at Ricoh and information sources within Ricoh the main problem of having sometimes high inventory levels and sometimes low product availability has been identified. Next, four causes have been selected for this main problem to focus on in this project:

1. Inventory target setting is not clear at the different locations in the supply chain;
2. Demand for machines is hard to forecast;
3. Independent replenishment between the replenishment of modules and the replenishment of finished goods;
4. Lack of information sharing between RESCM and RIF.

Currently, the inventory control in this part of the supply chain is based on demand forecasts and target inventory levels. Moreover, ordering decisions are made locally. Research indicated that changing decision making from local to central can reduce the supply chain's inventory levels with 25%, as case studies at Xerox and Hewlett Packard showed (Ganeshan, 1999). Based on this idea, the following research question has been defined:

Which cost savings can Ricoh obtain when their inventory levels in Europe for machines assembled in a European factory are centrally controlled for a given product availability target under the limitations of the chosen model, and how can these cost savings be fairly allocated to the European factory and RESCM?

Supply chain performance

First, the current supply chain performance for machines having their final assembly at the RIF factory has been analyzed. Here, the performance is evaluated based on three Key Performance Indicators (KPIs) which have been identified as most important in this research: inventory level, product availability, and forecast performance.

Historical data analysis for four different modules in the period of August 2011 till February 2012 revealed that for three out of the four module types the achieved inventory levels were high above the targets as set by Ricoh. In contrast, the last module had a low product availability performance.

Moreover, for all four modules the FC (forecast) performance appeared to be much below target, with on average a forecasted demand which was 25% higher than the actual demand. In contrast to what these results indicate, the actual product demand was found to be relatively stable. However, the actual shipments (sales) had much more fluctuation, which can be an explanation of the low FC performance. Moreover, when the FC performance was evaluated based on sales instead of demand data, the performance was slightly better. However, still for almost all months the performance was outside target range.

Supply chain optimization model

Within the optimization model two different stock points will be considered: module stock and FG (finished goods) stock. As mentioned earlier, one module can be assembled into different finished goods. Therefore, the supply chain structure that will be analyzed has the distribution structure, as shown in the figure below. Here, at the end stock points not the physical locations differ, but the type of FG stored at the stock point.

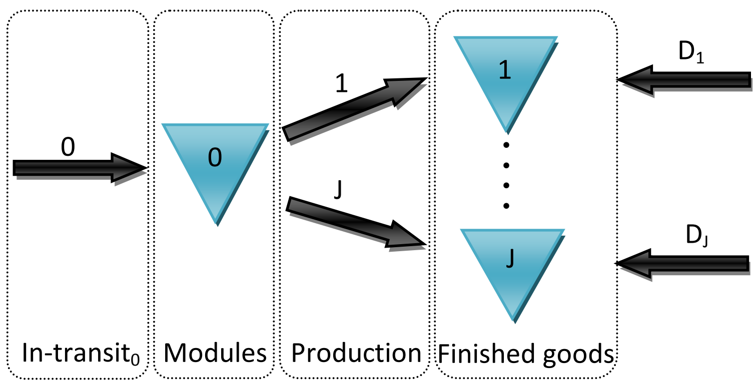

Figure 1: Supply chain distribution structure (Note: D_i = customer demand at end stock point *i*)

This distribution structure will be analyzed with three different control models. First, there is the echelon control model with central decision making by making use of an (R, S)-inventory policy on supply chain level. This echelon control model is based on research of Van der Heijden (2000) and minimizes the inventory holding costs on supply chain level while attaining the customer fill rate as set by the company.

Second, local control will be modeled, having local decision making with every stock point using their own (R, S)-inventory policy. Here at every stock point the required order-up-to level (S) will be determined based on demand, lead time, and fill rate information. This local control model is adapted from Van der Heijden (2000) to a local decision-making setting. Due to the local decision making no cost-based decision about where to locate inventory can be made. Last, a current control model will be analyzed, where replenishment decisions are made locally, based upon inventory targets, and where these inventory targets are based on a general target and average customer demand only. In this model no fill rate constraint is used.

Regarding the information exchange between the different parties in these control models, echelon control requires full information sharing with a (unspecified) central decision making. In the local control model some information has to be shared between module and FG stock points, while in the current control model the information exchange is very limited.

Cost allocation

In the echelon control model decisions are made centrally, resulting in supply chain holding costs. However, in the considered part of the supply chain two different parties are involved: RIF (factory) and RESCM (distribution centre). Therefore, by making use of cooperative game theory a cost allocation proposal will be made. Here, the situation without cooperation between the two parties will refer to the outcomes of the local control model, while the situation in which both players cooperative corresponds to the results of the echelon control model.

In this case there is a two-person allocation problem. Tijs and Driessen (1986) concluded that the allocation solution of three different methods (cost gap allocation, Shapley value, and nucleolus) all resulted in the same allocation proposal. In this allocation proposal both players will receive half of the cost savings when changing from the local to the echelon control model. This will result in an allocation within the core of the two-person cooperative game.

Results

The performance of the three different control models was determined and evaluated for two different modules. When evaluated by supply chain holding costs, a decrease of 49.17% and 57.67% in costs was achieved when moving from current control to local control, and a decrease of 66.35% and 71.65% in holding costs was achieved when changing the current control to the echelon control policy.

When considering the location of the inventory in the supply chain, there were significant changes. First, according to the targets in the current control model 66% of the supply chain inventory was finished goods, and only 24% modules. In the local control model the module inventory percentage increased to 57%, where only 25% of the supply chain inventory was finished goods. In contrast, in the echelon control model only 15% of the supply chain inventory consisted of modules, with 56% finished goods. Furthermore, caused by the high inventory levels in the current control model the achieved fill rate in this model was much higher than the target of 90%. Last, a high dependency of the required inventory level on the coefficient of variation in customer demand has been seen, especially in echelon control.

For both modules the individual cost results for RESCM were higher in echelon control compared to the local control situation. However, as noted before, the supply chain holding costs decreases significantly for the echelon control model compared with local control. Therefore, the cost allocation proposal enabled a cooperation which is beneficial for both parties.

Last, sensitivity analyses and a model extension by including upstream lead time variability provided insights in the effects of changing values of input parameter(s) on the model performance. Here, interesting points were spotted in which lower cost results were achieved for a supply chain in echelon control to having a stockless upstream stock point.

Conclusion and recommendations

Based on the results as presented above the research question can be answered. When Ricoh controls their inventory levels in Europe for machines assembled in a European factory centrally for a given products availability target, results indicate that significant cost savings can be obtained compared to both the local control (decentralized control) and current control (based on inventory targets). Note that analysis of historical data showed even higher inventory levels than the targets values as set by Ricoh, corresponding to the current control model. Moreover, the supply chain cost savings achieved by the echelon control can be allocated to both parties (RIF and RESCM) by splitting the cost savings equally between both parties.

Therefore, the echelon control policy is recommended to Ricoh, including the use of a cost allocation rule to make the policy also beneficial for RESCM. Confidentiality of information in different Ricoh organizations can be a problem within the implementation process. Therefore, another Ricoh organization can become the central decision maker with which all information is shared. Moreover, regarding the currently used targets there is recommended to not-use general targets as used at this moment. For the modules analyzed the targets appeared to be too high, especially for the modules.

However, before the use of the echelon control policy is recommended to Ricoh, they first have to improve their demand forecasting performance, because historical data research showed a bad current forecast performance and a sensitivity analysis indicated to big sensitivity of changes in actual demand based on the demand with which the order-up-to levels were determined. Here, forecasts should be adapted at the end of a replenishment cycle, and thus on a weekly level. Moreover, the use of a central decision maker requires some organizational changes within Ricoh, because this decision maker should have enough power and knowledge, and the parties involved have to accept the decisions made.

Limitations and further research

Limitations in this project include the use of Little's law in the local control model in the calculation of the expected delay of downstream orders at the upstream stock point, the use of a simple variant of the balanced stock rationing rule in the echelon control model together with the use of a different allocation rule in local control compared to echelon control, including only some uncertainties in the control models, the big influence of demand uncertainties, the approximations made within the optimization procedure, and the use of only one cost parameter: holding costs.

Further research could improve the research regarding the limitations summarized above. Moreover, other elements as capacity planning can be included in the model in further research, and the models can be extended to bigger supply chains, possibly with a network structure. This can also make the cost allocation more interesting from a theory perspective.

III Preface

This report is a result of the master thesis project I have executed at Ricoh Europe SCM B.V., located in Bergen op Zoom. This thesis report represents the end of my master in Operations Management & Logistics, and, moreover, the end of a 5-year study period in Industrial Engineering and Management Sciences at Eindhoven University of Technology.

First of all I would like to thank my primary university supervisor Marco Slikker. During the last one and a half year he provided me with input, feedback, and discussion during this master thesis project and the preliminary activities. Moreover, I would like to thank my second supervisor at the TU/e Zumbul Atan for her critical reflection on my report and supporting knowledge in the area of supply chain management.

Also, I would like to thank my two supervisors at Ricoh Europe SCM: Maite Jimenez and Stefan Wischnewski for their support and reflection during the master thesis internship, and the time and energy they spend on guiding me during this project. My thanks also go to Sophie and Mark who gave me the opportunity to conduct my master thesis at Ricoh Europe SCM, and to Soraya and Juliette for explanation of processes within Ricoh and gathering of data for my project. Also, I would like to thank all other colleges at Ricoh Europe SCM for the good working atmosphere and nice time during my 5-months stay in Bergen op Zoom.

Finally, I would like to thank my family and friends for their support during my study and graduation project.

Rob van Pelt

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IV Table of contents

1 Introduction

This document is the result of my master thesis project executed at Ricoh Europe Supply Chain Management (RESCM) in Bergen op Zoom, the Netherlands. RESCM is part of the global Ricoh organization.

First, in section 1.1 an introduction to the company Ricoh will be given, followed by a general introduction of the supply chain of Ricoh in the EMEA region. Then, the product hierarchy used within Ricoh in different parts of the supply chain will be described. In section 1.4 a specific part of the supply chain which is relevant for this project will be described in more detail. Next, the replenishment process for this part of the supply chain is discussed. This first chapter ends with a short discussion about performance measurement used at RESCM. For the whole report, an overview of the abbreviations used can be found in Appendix C, and definitions of the terms used in this report are given in Appendix D.

1.1 Introduction to the company

Ricoh is a company operating worldwide in the area of image processing devices. Ricoh has its global headquarters in Tokyo, Japan, and is, on a high level, divided into five different divisions, all covering their own part of the world. This assignment will be held within Ricoh Europe. Ricoh Europe covers the regions Europe, Middle-East and Africa (EMEA region), and has its headquarters in London, UK. For the EMEA region, Ricoh Europe Supply Chain Management (RESCM) is the central supply chain organization. RESCM has two primary locations, both located in the Netherlands. First, the European Distribution Centre (EDC), located in Bergen op Zoom, focusing on the demand planning and distribution of finished goods and supplies for the EMEA region. Second, there is the European Service Parts Center (ESPC), located at Schiphol-Rijk, dealing with the management of service parts and third party suppliers for the EMEA region.

1.2 Ricoh's supply chain in EMEA region

Ricoh's part of the supply chain for the EMEA region is displayed in Figure 2. For machines, the supply chain starts at the Ricoh suppliers (factories) in Asia. At these Asian factories basic machines are produced, after which they are shipped from these locations to European factories in UK (RPL) or France (RIF), or directly to the European distribution centre in Bergen op Zoom, the Netherlands. At RPL, RIF or EDC these machines have their final assembly.

After assembly, the machines can be configured according to customer requirements at configuration centers located within EDC, RPL or RIF. From these locations the configured machines are shipped to the end customers. This process goes for some countries via satellite locations, and there is always a hub or platform in between at the country of destination. In the rest of this report the term local hub will be used for this hub or platform in country of destination. Also not-configured machines (called finished goods boxed products) are shipped from the EDC or European factories towards the local hubs. Moreover, for supplies and consumables, next to deliveries from the Asian factories also third-party suppliers are used, who deliver most of the products directly to the EDC. Between the EDC and European factories there is also exchange of goods, like the replenishment of supplies.

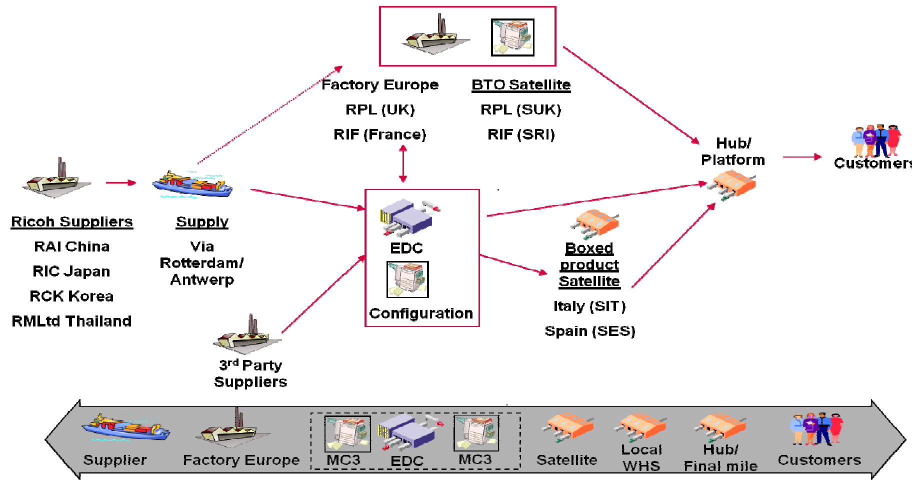


Figure 2: Overview of Ricoh's supply chain for the EMEA region

In the supply chain as displayed in Figure 2, Ricoh Japan (the global headquarters) is responsible for the Ricoh suppliers in Asia and the factories in Europe (RPL and RIF). RESCM is responsible for the EDC, the BTO (Built-To-Order) satellites (configuration centers), boxed product satellites, in-transit goods between these locations, and all goods in-transit from Ricoh or third-party suppliers towards the EDC. Moreover, RESCM is responsible for the products untill they arrive at the local hubs. Other stakeholders within the supply chain are the local sales organizations in the EMEA region. They are responsible for the local hubs and final miles towards the end-customers, and will receive and forecast the orders of the end customers.

1.3 Product hierarchy and specific supply chain

The main products within Ricoh's supply chain are machines. Ricoh uses different terms for machines in different phases of the supply chain, captured in the product hierarchy of the machines. The four relevant levels in this hierarchy are product families, modules, finished goods (FG) boxed products, and (configured) finished goods. In this sequence, in each level the machine is more specified. The product hierarchy used is displayed in Figure 3 and will be explained below, including an example of each level.

The highest level in the hierarchy is the product family. The product family represents a very basic design of a machine, and every machine within this product family has the same product family name. In this example the family name is '1', but in practice family names are used.

A product family consists of one or multiple different modules, which should be seen as a basic version within a product family. Every module can belong to only one product family. In this example there are two different modules, named as '1a' and '1b'. A certain type of module cannot be changed anymore in another type of module, even if it is within the same product family. For example, modules within the same product family can differ in speed (copies per minute) of the machine. This level within the product hierarchy represents the machines before their final assembly. These are the goods shipped from the Asian factories towards the European factories and EDC.

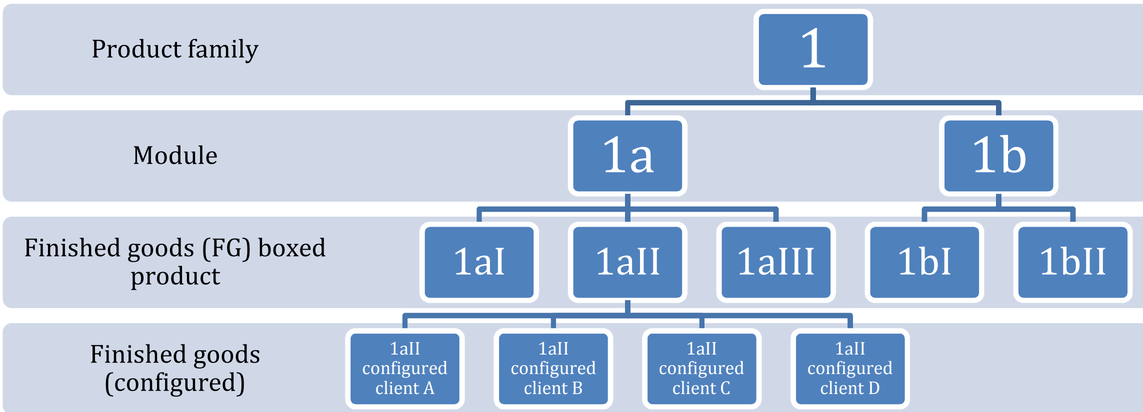


Figure 3: Product hierarchy used at Ricoh. Note that the lowest level is specified in this way for every finished goods boxed product, and het number of specifications in this row is almost unlimited

At the European factories or EDC from a module different types of FG boxed products can be assembled. For every FG boxed product only one module is needed, and from one module only one unit of FG boxed products can be assembled. In the example of Figure 3 out of module '1a' three different FG boxed products can be made, and from module '1b' two different FG boxed products can be assembled. In practice, FG boxed products can differ in whether the machines include a document feeder or a platen cover for scanning. This level within the product hierarchy represents the machines shipped to the configuration centers or shipped directly towards the local hubs in the country of destination as FG boxed products for not-configured machines.

The lowest level within the product hierarchy is the (configured) finished good. This machine is configured based on customer requirements and produced based on a built-to-order principle. In theory, almost an unlimited amount of different finished goods can be created, because of the high number of different options that can be added to the FG boxed products. Examples of options that can be added to a FG boxed product are an extra paper feed unit to increase the paper capacity and a product manual in the required language. Moreover, in a (configured) finished good the required language is set and drivers for the customer are installed. To simplify Figure 3, this (lowest) level is only visualized for one FG boxed product. However, every FG boxed product can be configured. Moreover, the number of possible configurations of one FG boxed products is higher than the four given in this figure.

Within the information systems of Ricoh, each level of the products hierarchy has an identification code or name. First, the product family has its family name as identification. A product family is ordered directly within the replenishment systems of Ricoh, thus no code for this level is required. One level below, the module, is identified by an EDP code. Moreover, also the FG boxed products are identified by an EDP code, but this code is different from the code used at the module-level. Last, (configured) finished goods are identified by the customer order number.

1.4 Supply chain via European factories

A relevant and interesting part of Ricoh's supply chain as described in section 1.2 is the part going via a European factory in the UK (RPL) or in France (RIF). This part will be described in more detail and is given in the figure below. For a better readability of the figure and because of similar processes at both locations, RPL and RIF, and SUK and SRI (the configuration centers located in, respectively, UK and France), are displayed within the same box. Only the type of machines (high-end or midrange machines) and the physical location differ (UK or France). Moreover, in some countries (Spain and Italy) a boxed product satellite location can be in between the EDC and the local hub.

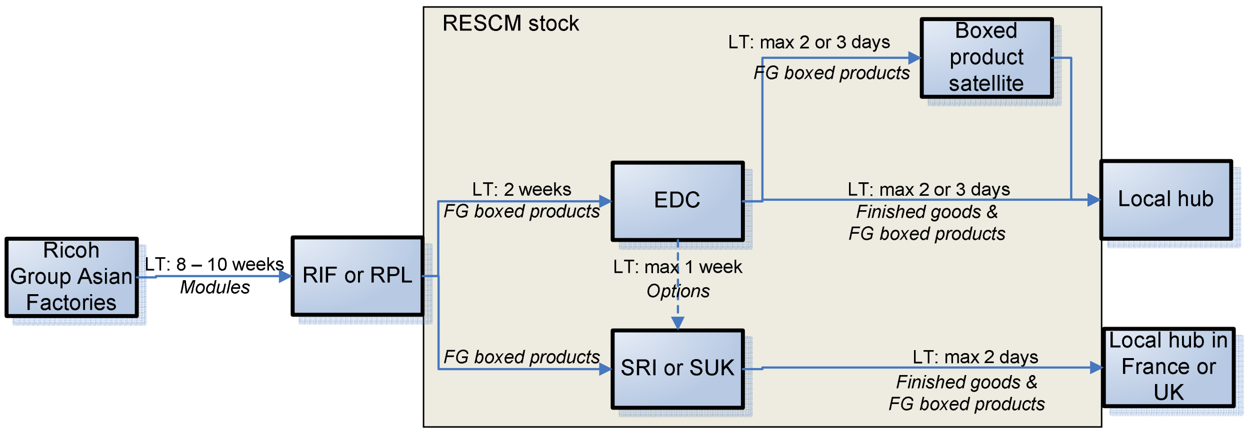


Figure 4: Basic supply chain for machines going via European factories. The text in italic represents the physical products shipped in the direction of the arrow. Note FG = finished goods and LT = lead time.

In short, the process starts with shipment of modules from an Asian factory to a European factory. At a European factory different FG boxed products will be created out of the received modules. At RPL high-end machines have their final assembly, and RIF deals with midrange machines. For the products sold in France or UK, the configuration process will take place at the location of one of the European factories. In France this location is called SRI, and in the UK this location is named as SUK. Both SRI and SUK operate under responsibility of RESCM. Thus, except for machines with customers in the UK or France, the FG boxed products will be shipped from the European factories to the EDC in Bergen op Zoom. These products can then be configured at the EDC location. After configuration, these finished goods are shipped to local hubs in the country of destination. When a FG boxed product is ordered, the shipment to the local hubs goes via one of the configuration locations (SRI, SUK or EDC, depending on the destination), but without a configuration executed at that location.

In Figure 4 also the planned lead times are mentioned. The supply chain of Ricoh has a total planned lead time of 8 to 13 weeks for machines. However, in the whole supply chain also the lead time for the part suppliers to the Asian factories has to be taken into account. This lead time varies between one week and a few months. Thus, in the planned lead time for the whole supply chain can be as high as 5 or 6 months. Last, also RESCM's stock in the supply chain is visualized. In addition, RIF and RPL are responsible for stock after modules leave the Asian factories, till the machines are shipped to a RESCM stock location.

On a high level there can be concluded that the structure of Ricoh's supply chain is a network supply chain, because of the combination of divergent (distribution) and convergent (assembly) elements (Huang et al., 2003). Moreover, a decoupling point in the supply chain can be seen between the push- and pull-oriented part. The supply chain starting at the Asian factories, via a European factory towards a configuration center (EDC, SRI or SUK) is considered as the push part of the supply chain. This part of the process is driven by the demand forecasts made at RESCM. The decoupling point is at the configuration centers, because the configuration process is built-to-order, based on the customer specific requirements for each machine. Thus, the part of the supply chain starting at the configuration centers till the end customer can be considered as pull oriented (Hull, 2002).

1.5 Replenishment

Power (2005) stated that, next to the physical flow of goods within a supply chain, also information (order) and financial flows are important to consider. Therefore, in this section all these three flows will be described in relation with the replenishment processes in Ricoh's supply chain for the EMEA region for items going via a European factory (see Figure 4).

In total, Ricoh uses four different replenishment methods, each with its own replenishment cycle. However, only one replenishment method is used for machines going via European factories: DPSIM weekly. This method operates under weekly replenishment by using a system called DPSIM. DPSIM weekly deals with the two basic replenishment flows related to the considered supply chain for machines (see Figure 4): the replenishment of modules between the Asian factories and European factories (process 1), and the replenishment of FG boxed products between the European factories and RESCM (process 2). Both processes are managed by DPSIM weekly, but there is no connection between replenishment processes 1 and 2 (see Figure 5) within the system, because of no relation between the identification codes of modules and FG boxed products. Moreover, RESCM receives no information about replenishment process 1.

Between the local sales organizations and RESCM there are no replenishment flows, because RESCM just processes the orders directly coming from the local sales organizations. This process is also visualized in Figure 5, where the order flows go directly from the local sales organizations to the RESCM, without interference of DPSIM. Here the built-to-order principle applies, without replenishments.

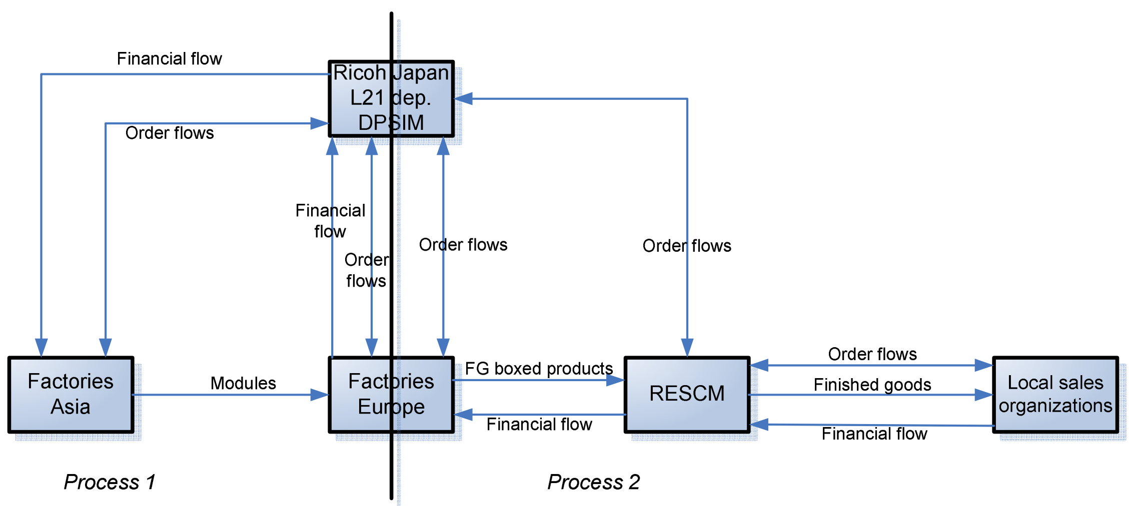


Figure 5: Replenishment flows for machines going via European factories. The straight black line represents the border between the two not-connected replenishment flows (referred to as processes 1 and 2)

Related to the information flows, orders for replenishment processes 1 and 2 all go via the DPSIM system located at the L21 department of Ricoh Japan (see Figure 5). Here, DPSIM regulates the production and shipment quantities for the factories and distribution centers all over the world. Because of the use of the central DPSIM system located in Japan, RESCM cannot calculate stock replenishment quantities by themselves. The only direct influence RESCM has on orders is via product forecasting, but they cannot influence lead times, replenishment policies, and other logistical parameters. Only within the production planning system at the European factories a relation is made between replenishment processes 1 and 2, because in the assembly phase the factory has to make a link between the supply chain of modules and demand for customer goods. However, this production planning system is not assessable for RESCM.

As can be seen in Figure 5, within process 1 the order flows between L21 and the Asian factories, and between the L21 department and European factories go in both directions. First, DPSIM (located at the L21 department) calculates and proposes order quantities to the Asian factories based on the product forecasts made by the European factories and all other information received. The Asian factories will check and confirm the proposed orders and send the possibly adapted and confirmed order quantities back to the DPSIM system. Last, DPSIM will send the confirmed order quantities to the European factories. However, the order quantities cannot be changed anymore after the confirmation. The information flow of sending the confirmed order quantities from DPSIM to the European factory is only informative, such that the European factory knows the order quantities they will receive after a given lead time. The same order flows apply to process 2 between the European factories and RESCM.

The difference between processes 1 and 2 is in the financial flows. For process 1 the financial flow goes via DPSIM, but for process 2 the financial flow goes directly from RESCM to the European factory. Moreover, the physical flows in both processes go directly between Asian and European factories for process 1, and between European factories and RESCM for process 2. All these flows are displayed in Figure 5.

1.6 Performance measures

For supply chain reporting, on high level RESCM uses Key Performance Indicators (KPIs) based on four Strategic Management Objectives (SMOs). These four objectives and related KPIs for RESCM are given in Table 1. Note that more KPIs are used on a lower level at RESCM, but below only the KPIs related to the SMOs are mentioned. These are KPIs where most emphasis is placed on within the organization.

Number	Strategic Management Objective (SMO)	Key Performance Indicator (KPI)
1	Optimize total European inventory levels	Months on hand inventory in relation with the monthly turnover
2	Increase customer satisfaction	Customer satisfaction score (survey results)
3	Ensure cost efficient SCM solutions	Percentage of cost of goods sold of total SCM costs
4	Reduce environmental impact of end-to-end supply chain	Percentage of reduction in annual CO2 footprint

Table 1: SMKOs and KPIs used at high level at RESCM

Improving all KPIs of the table above at the same time can be very hard, because improving one KPI can lead to a reduction in the performance of another KPI. For example, when RESCM wants to reduce their inventory levels, this can have a negative impact on customer service levels with the local sales organizations. In this project the focus is on improving the inventory levels and product availability. This is mostly related to the first SMO. Moreover, improving product availability can indirectly lead to a higher customer satisfaction (the second SMO).

2 Project design

In this chapter the design of the project will be presented. First, in short the main problems are described in section 2.1. Based on this problem definition, the problem statement is given in section 2.2. Then, the research question is given, together with the sub-questions used to answer this research question. In section 2.4 the scope of this project will be defined, after which in the last section of this chapter the research approach is described, including a relation to the outline of the rest of this report.

2.1 Problem definition

The problem definition as presented in this section is based upon interviews held with relevant employees at RESCM and RIF, and performance reports received from RESCM and RIF. Based on these qualitative and quantitative information sources, the main problem for this assignment is identified as:

> ***Ricoh has high inventory levels in relation with low product availability in their supply chain for machines having their final assembly at a European factory***

Measures in relation with high inventory levels and product availability will be given in section 3.1.

Currently, RESCM wants to create a more integrated supply chain in order to improve the supply chain performance. According to Power (2005), an integrated supply chain model consists of three main elements: information systems, inventory management, and supply chain relationships. Therefore, in this problem description, the different causes for the main problem will be classified according to these three elements.

These three elements are covered within the cause-and-effect diagram as presented in Figure 32 (see Appendix E). This diagram is made by using the format designed by Ishikawa (1990). Causes related to information systems deal with the replenishment system DPSIM. Inventory management related causes are inventory level target setting and forecasting of customer demand. Last, causes related to supply chain relationships were defined based on research of Arshinder and Deshmukh (2008) and devided by issues related to the current colloration and behavior of entities within the collaboration.

2.2 Problem statement

Based on the cause-and-effect diagram (see Figure 32) the problem statement can be defined by making a selection of all identified causes. This decision was made together with Ricoh supervisors and a main selection criterion was the possibility of change related to the causes. The following causes for the high inventory levels and low product availability have been selected to analyze in the project in more detail:

- ***Inventory target setting is not clear:*** It is not clear on which parameters and on which product level the target inventory levels are based. For example, an inventory target of 2.7 weeks of demand can be evaluated based on expected demand or realized demand, and this target is sometimes used at product family level but can also be used on item level. Therefore, targets used within the replenishment processes can be based on different parameters and are not clear.

- ***Demand for machines is hard to forecast:*** Due to demand history fluctuations, seasonality effects, short life cycles of machines, and promotions (including related influence of the marketing department on forecasting), it is hard to forecast demand for machines.
- ***Independent replenishment:*** Due to the independent replenishment processes (see Figure 5) information about inventory levels in one part of the supply chain is (almost) not used in the replenishment decisions made in the other part of the supply chain. Therefore, this can lead to higher inventory levels than actually required.
- ***Lack of information sharing:*** Basically, RESCM has information about the RESCM stock (see Figure 4) and there is only weekly, manual retrieved information exchange between the European factories and RESCM. Moreover, there is no information exchange at all between RESCM and the Asian factories.

2.3 Research questions

In the current inventory control system at Ricoh decisions are based upon forecasted demand and target inventory levels. Moreover, this current policy is locally controlled (decentralized decision making) with only limited information sharing. Some of the causes mentioned before, independent replenishments and lack of information sharing, are directly related to the decentralized decision making. Moreover, the cost effectiveness of a local control policy is limited by the lack of information sharing throughout the entire system (Axsäter & Rosling, 1993). A way to solve these causes related to the lack of information sharing can be using an echelon stock policy with centralized decision making. Coordinated decisions have already proven good results at Xerox and Hewlett Packard by reducing inventory levels by 25% (Ganeshan, 1999). Other advantages of a centrally controlled supply chain as mentioned in literature are a reduction of lead time of retailers (end stock points), an improvement in the manufacturer's supplying ability, elimination of the bullwhip effect, and achieving higher performance rates (Yu et al., 2001). Therefore, the research questions will be related to the performance of an inventory system with centralized inventory control.

2.3.1 Research question

The research question for this master thesis project is defined as:

Which cost savings can Ricoh obtain when their inventory levels in Europe for machines assembled in a European factory are centrally controlled for a given product availability target under the limitations of the chosen model, and how can these cost savings be fairly allocated to the European factory and RESCM?

2.3.2 Sub-questions

Related to the research question as given above the following sub-questions can be formulated:

1. *What are the key KPIs for RESCM in relation with inventory level and product availability?*
2. *What is the current performance related to the selected KPIs of inventory control for the selected module(s)?*

3. *Which cost savings can Ricoh achieve with a centralized inventory control model and full information sharing for the selected module(s) given the limitations of the chosen model?*
4. *How can the cost savings of this centralized inventory control model with full information sharing be fairly allocated to the European factory and RESCM?*
5. *Which information is required to be shared between the European factory and RESCM to be able to use this centralized inventory control model?*

2.4 Scope of the project

In this section an overview of the scope of the project will be given, based on the selections made previously in this report. First, there was chosen to focus on Ricoh's supply chain for the EMEA region. Therefore, demand fluctuations in other parts of the world influencing the availability of goods in the EMEA region are considered as out of scope.

Second, previous in this report already a selected part of the supply chain is discussed. This is the supply chain for products assembled in a European factory. RESCM identified more problems in this part of the supply chain, compared with other parts for which they are responsible. Moreover, a reason for selecting the part of the supply chain including a European factory is that in this part different parties are responsible for the stock points involved. As indicated before in Figure 4 (see section 1.4), RESCM's stock only covers a part of the supply chain starting at departure of machines at the European factory until arrival of these machines at the local hub in country of destination. Therefore, an interesting part of the supply chain includes the goods going via a European factory to an RESCM stock location.

Within this selection, there were two possibilities where a focus could have been made on: RPL in the UK and RIF in France. In the RIF factory midrange machines have their final assembly, which can make the results better generalizable than when only the high-end machines of RPL are taken into account. Together with my supervisors at RESCM we therefore decided to focus within this assignment on the machines having their final assembly at the factory in France (RIF). In the rest of this report these machines are called the RIF product range. Currently, the RIF product range consists of five product families, with each product family having one or more module(s).

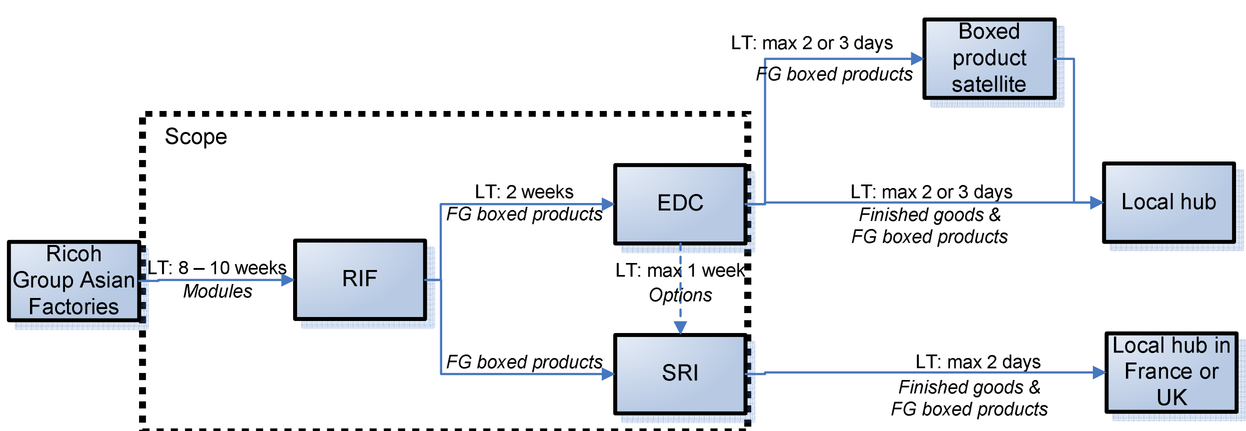


Figure 6: Visualization of scope of this project in the supply chain for RIF product range

Moreover, within the supply chain for machines assembled in RIF the focus will be on the part of the supply chain starting at departure of the modules at an Asian factory and ending at arrival of the products at EDC or SRI. Therefore, the process of customer-specific configuration and transportation to the customer will not be taken into account. The push-part (forecast-based) of the supply chain will be considered in this project.

In short, the scope consists of the processes starting at the Ricoh Group Asian Factories, going via the RIF factory in France to EDC or SRI. Moreover, the focus will be on the supply chain for machines, because they include the main products in Ricoh's supply chain. To summarize, the scope in the supply chain as described above is displayed in Figure 6.

Moreover, also a focus will be made on the processes related to the RIF product range. The focus will be on the inventory control related to the RIF product range, and more specifically on the Purchase, Sales and Inventory (PSI) management. Inventory levels and product availability related to the machines of the RIF product range, for the part of the supply chain between the Asian factories and EDC or SRI, and for PSI processes, will be analyzed in this master thesis project.

2.5 Research approach

The basic setup of a problem-solving project is described by Van Strien (1997) with the regulative cycle, as given in Figure 7. The basic steps include: set of problems, problem definition, analysis and results, plan of action, intervention, and evaluation. In this report the last two steps (intervention and evaluation) will not be executed.

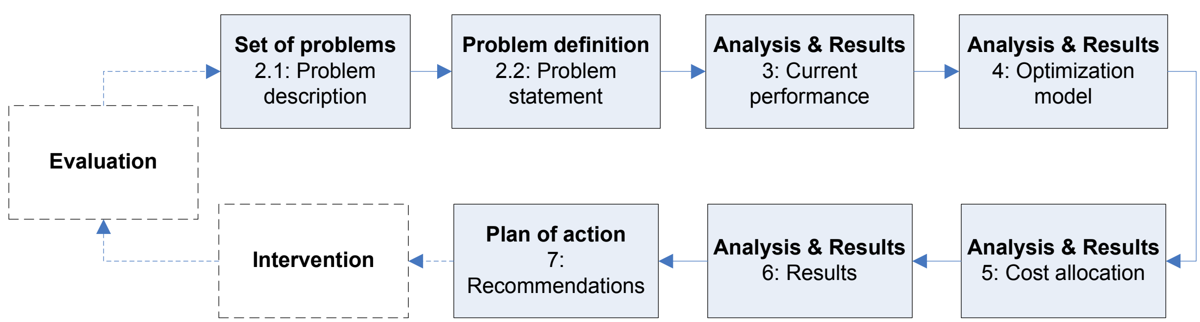


Figure 7: Research approach based on regulative cycle (Van Strien, 1997), including references to chapter numbers where the step is described in this report

In the figure above a relation is made with the outline of the rest of this master thesis by mentioning the section and chapter numbers related to the different steps. Note that the main focus in this project is on the analysis and result-step of the regulative cycle. Therefore, this step is divided into several sub-steps. The steps as presented above are related to the sub-questions as given in 2.3. Sub-questions 1 and 2 will be answered within chapter 3, sub-questions 3 and 4 will be answered within chapters 4 till 6, and sub-questions 5 will be answered within section 7.4.

3 Supply chain performance

In this chapter first the key KPIs (Key Performance Indicators) will be described, after which the current supply chain performance will be evaluated based on these KPIs.

3.1 Key KPIs

In Table 1 (see section 1.6) the four strategic management objectives of RESCM were given, including the corresponding KPIs. However, these four KPIs are on a high level and more specific KPIs are required in the evaluation of the current supply chain performance. As concluded in section 1.6, the first KPI of Table 1 (month on hand inventory in relation with monthly turnover) is most relevant for this project.

Within supply chain performance, quantitative and qualitative measures can be used. Here, the supply chain performance evaluation will be based on historical demand data. Therefore quantitative measures will be used. Within this category, a main distinction can be made between measures based on costs and measures based on customer responsiveness (Beamon, 1998). Costs relevant for this assignment are related to inventory levels, and customer responsiveness will be related to the product availability of finished goods in relation to customer orders. Note from this point on in the report the term finished goods is used for FG boxed products of Figures 3 and 4, because customer configuration is out of scope.

Related to these two types of measures, inventory level and product availability will be used in the performance evaluation, corresponding to the problem definition of section 2.1. Moreover, forecast performance will be added as a measure because of the big influence of forecasting on inventory level and product availability results. This leads to the following three key KPIs:

1. ***Inventory level:*** inventory level expressed in number of weeks of forecasted customer demand.
2. ***Product availability:*** the percentage of PDSO (Past Due Sales Orders; orders with a request date of the customer in the past) that is covered by available FG stock at RESCM. This availability measure is used to exclude delays caused by, for example, the configuration process of machines or transportation.
3. ***Forecast performance:*** the actual customer demand in percentage of the forecasted customer demand made 3-months in advance (to cover the total lead time from Asia to RESCM)

More information related to these three key KPIs and the targets used by RESCM to evaluate these measures is given in Appendix F.

3.2 Performance evaluation

As mentioned in the scope of this project (section 2.4), a focus has been made on the RIF product range. These machines comprise the midrange segment of Ricoh. Out of the five product families of the RIF product range, two families appeared to be newly introduced in the market in the period of analysis (August 2011 till February 2012): Family 4 and Family 5. Due to lack of data for these newly introduced products, a selection has been made on the other three product families of the RIF product range: Family 1, Family 2, and Family 3. When only machines in active status are taken into account (meaning that these machines are purchasable, sellable and shippable for the company), a group of 19 finished goods (11 of Family 1, 4 of Family 2, and 4 of Family 3) remains available for analysis.

Within the three product families Family 1, Family 2, and Family 3, four different models can be identified: Model 1, Model 2, Model 3, and Model 4. Within a model, the modules used in the assembly of the finished goods are similar. An overview of the product hierarchies of these four different models can be found in Appendix G. The finished goods, only mentioned by EDP code in these diagrams, differ between each other in speed, brand, and whether they have an ARDF (Automatic Reversing Document Feeder).

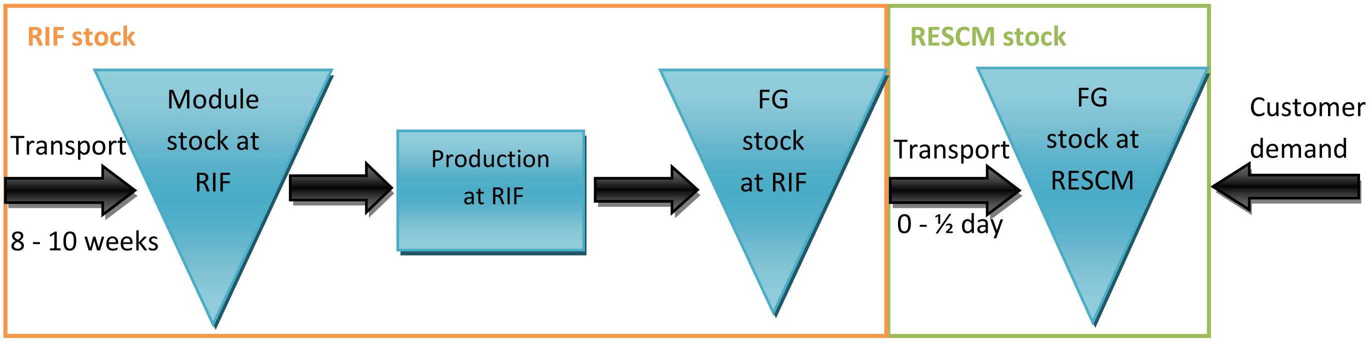


Figure 8: Considered supply chain in more detail. Note that the production of a module can result in different types of FG

In the part of the supply chain as described in the scope three different stock locations can be taken into account: module stock at RIF, FG stock at RIF (after production and before shipment), and FG stock at RESCM, where RESCM refers to the combined stock locations of EDC and SRI (see Figure 8 above). Moreover, to be able to make a relation between module and FG inventory levels, the supply chain performance will be analyzed per model (thus for Model 1, Model 2, Model 3, and Model 4). Thus, the FG performance will be aggregated to a model-level.

3.2.1 Introduction of data

As an introduction to the data, the demand data for Ricoh in the EMEA region are given for each of the four models in the selected part of the RIF product range (see Figure 9).

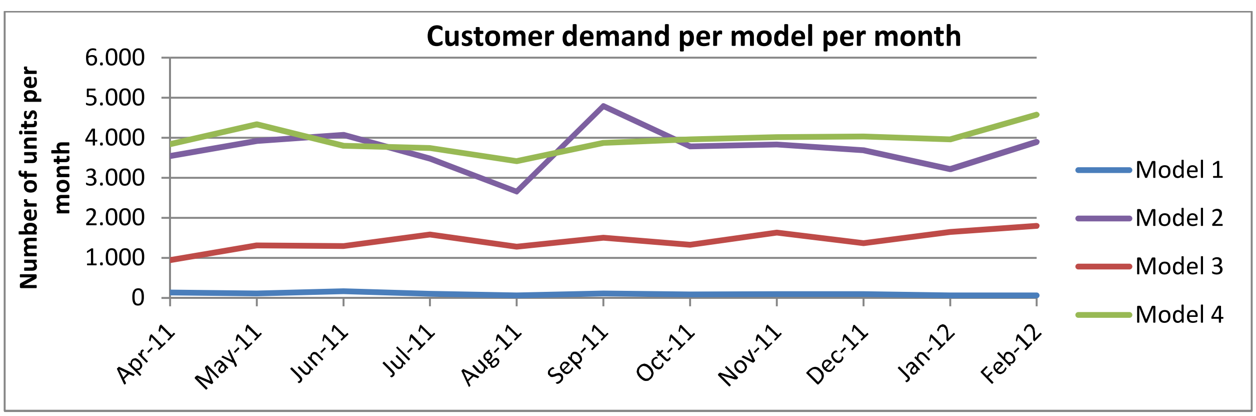


Figure 9: Customer demand data for the selected models of the RIF product range

In the figure above can be seen that there is one model having very low customer demand (Model 1 with mean of 97.9 units per month), one model having moderate customer demand (Model 3 with mean of 1,425.3 units per month), and two models having high customer demand (Model 2 with mean of 3,716.0 units per month and Model 4 with a mean of 3,458.5 units per month).

The demand patterns of most of the models are relatively stable. Only the Model 2 shows some more fluctuation. The decline in demand for Model 2 is caused by the introduction of Model 3, a newer model serving the same customer segment. However, promotion campaigns were started in September 2011 to increase the demand for Model 2, creating an increase in demand for that month, after which the demand was more stable at a similar level as before the drop in customer demand in August 2011. However, in general there can be concluded that the customer demand for the models analyzed is relatively stable.

The demand data as presented above is based on the order request date of the customer. In contrast, sales data are based on the actual date of shipment of orders to the customer. In Figure 10 the sales data of the same time period are given, expressed as a percentage of change from the customer demand data. In long term the total number of units demanded and sold should be approximately equal. However, overall, the sales data were found to be higher than the demand data (a percentage of deviation above 0). No explanation can be given for this remarkable finding. Moreover, there is much more fluctuation in the sales data compared to the demand data.

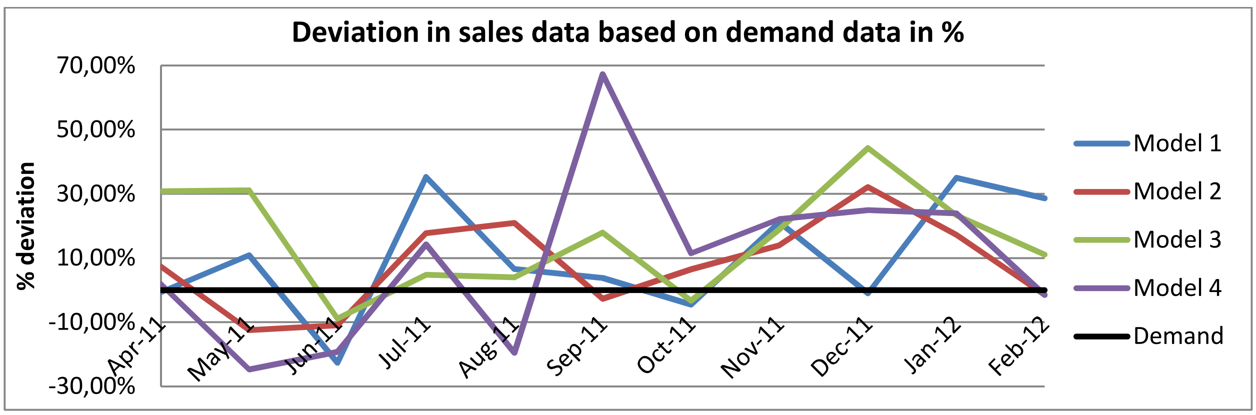


Figure 10: Deviation of sales data based on demand data in percentage of customer demand. Note that percentages higher than zero imply higher sales than demand.

Next, the supply chain performance regarding inventory levels, product availability, and forecast performance will be evaluated for the period August 2011 till February 2012. Note that data about the inventory levels and product availability will be gathered at the last day of each month. For the forecast and demand data, the data of a whole month are taken into account.

3.2.2 Inventory level

In Table 9 (provided in Appendix H) an overview of the supply chain performance in inventory levels is given. In this table the performance is evaluated against the following targets: 1.0 week of module inventory at RIF, 0.4 weeks of FG inventory at RIF, and 2.3 weeks of FG inventory at RESCM (in total 2.7 weeks of finished goods). Here, weeks of inventory are determined based on the 6-months average historical demand data. All red numbers in this table indicated inventory level results above these targets. For Model 1, Model 2, and Model 3 almost all inventory level results are above the targets at all locations. Only for Model 4 the inventory levels are in majority of the cases below the inventory level targets. Therefore, summarizing figures of this table are provided below for Model 2 (high inventory levels; see Figure 11) and Model 4 (low inventory levels; see Figure 12). Graphs similar to Model 2 can be found for Model 1 and Model 3 in Appendix H. Note that here the plotter is considered as the module and that the supply chain inventory target is the sum of the individual targets (3.7 weeks).

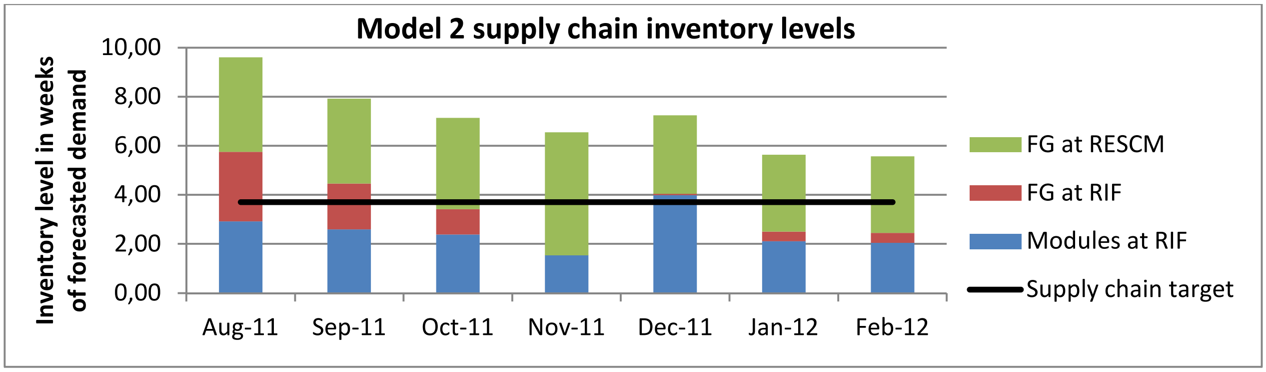


Figure 11: Supply chain inventory levels for Model 2 with plotter considered as module

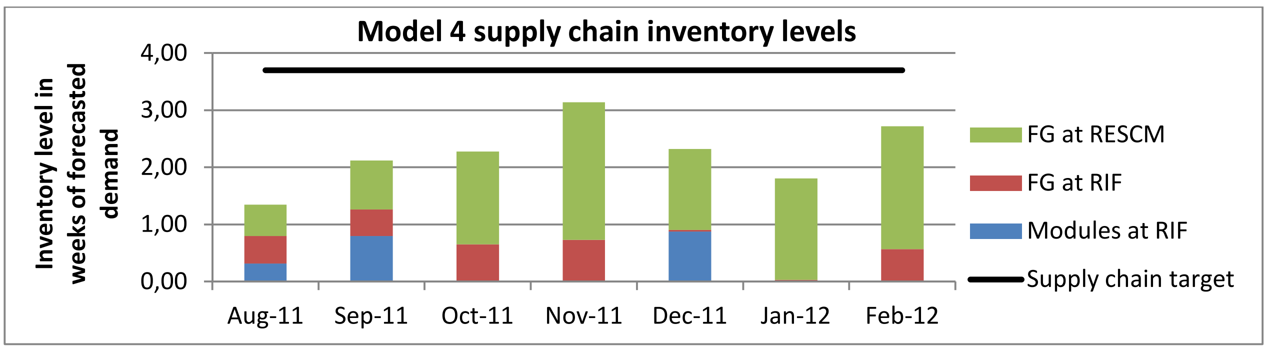


Figure 12: Supply chain inventory levels for Model 4 with plotter considered as module

Taken the two graphs above and the graphs as presented in Appendix H into account there can be concluded that for Models 1, 2, and 3 the inventory levels in the supply chain are on average two times as high as the sum of the target levels, and sometimes even higher. In contrast to what the targets suggest, for Model 1 and Model 3 their supply chain inventory level consisted for the biggest part of modules. For Model 2 the module inventory level was about 40% of the total supply chain's inventory level, while for Model 4 is the module part of the total inventory was only 12%. Sometimes there was even no module inventory at all for Model 4.

3.2.3 Product availability

Next, the performance on product availability will be evaluated. The target level used here is having a percentage of PDSO covered by available FG stock at RESCM equal to or higher than 95%. The results are given in Table 2, where performances below target are indicated by red numbers.

Model	Aug-11	Sep-11	Oct-11	Nov-11	Dec-11	Jan-12	Feb-12
Model 1	55.56%	100.00%	95.00%	50.00%	100.00%	100.00%	95.65%
Model 2	91.41%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Model 3	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Model 4	12.74%	70.50%	100.00%	99.52%	100.00%	100.00%	94.13%

Table 2: Product availability performance per model per month. Red numbers indicate percentages below the target of 95%

From the table above there can be concluded that overall the performance on product availability was very good, with in most of the months equal to 100%. However, for a few months for Model 1 and Model 4 was very much below target, with only 12.74% in August 2011 for Model 4. So, in a few months Model 1 and Model 4 had some availability issues, while the other two models had (almost) no availability issues.

3.2.4 Forecast performance

In this section the forecast (FC) performance is evaluated, because it influences both the inventory levels and product availability significantly. FC performance as used within RESCM is defined as the actual demand as a percentage of the forecasted demand, with a target area of FC performance between 95% and 105%. The FC performance per model is plotted in Figure 13 below.

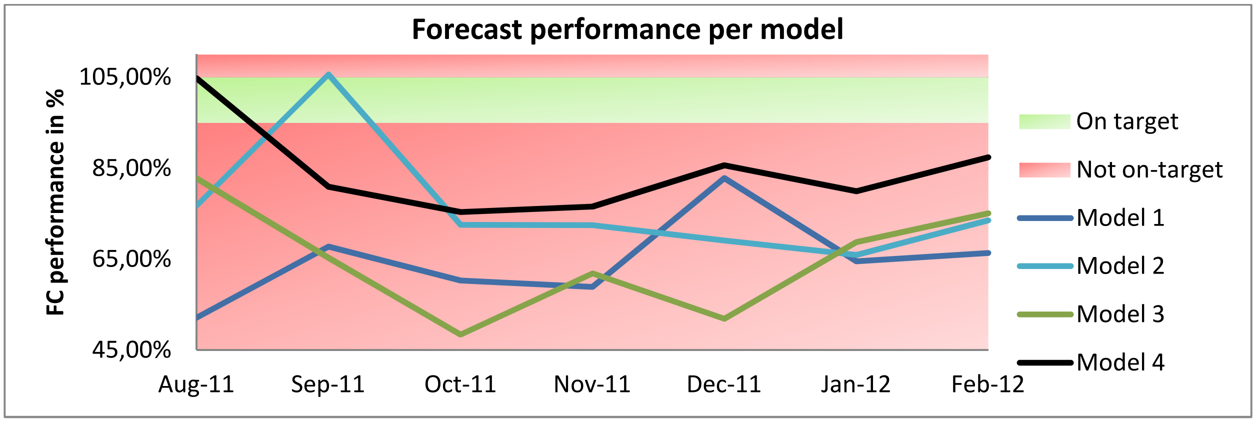


Figure 13: Forecast performance per model per month, based on demand data

In the graph above can be seen that the forecast performance is in almost all cases below the 95%. This suggests having a trend of a higher forecasted demand level than the actual demand per month. On average over all models, the FC performance is below the 75%, which implies that the demand was forecasted too high with more than 25%. Per model there can be concluded that the performance was lowest for Model 3 and Model 1, while Model 4 was forecasted best from the four models.

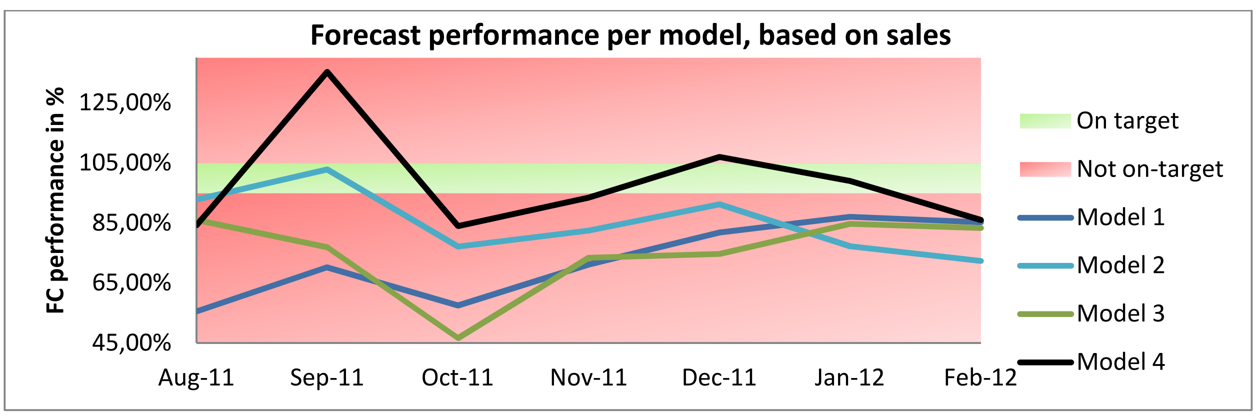


Figure 14: Forecast performance per model per month, based on sales data

As concluded above, the sales data were on-average higher than the customer demand data. Therefore, it is also interesting to see the FC performance when based on sales data. This FC performance is given in Figure 14 above. From this figure there can be concluded that, on-average, the FC performance is based on sales data is better than the FC performance based on demand data as shown in Figure 13. However, the also FC performance based on sales is still in the majority of the months outside the target range of between 95% and 105%, with a value of approximately 80%.

3.2.5 Conclusion

When the results of the three KPIs are combined, the following conclusion can be drawn per model. Model 1 is a low-demand item, with an unstable demand. Therefore this item is hard to forecast, leading to sometimes high inventory levels and sometimes availability issues. Moreover, for this model there are some significant differences in the inventory level of the plotter and scanner.

Model 2 and Model 3 showed similar patterns. Both models had in general very high inventory levels (both in modules and in finished goods), caused by a forecast performance of 70% on average. This implies that much more demand was forecasted compared what the actual demand appeared to be.

In contrast, Model 4 had different results. For this model the supply chain inventory level was never above the target level but sometimes very low, and the forecast performance was best of all models. However, here some availability issues occurred in August and September 2011 investigated. This was due to recovery of a supply chain disruption occurred before the period of analysis.

In general, both forecasted demand (see Figure 13) and sales (see Figure 10) were higher than the actual demand. An explanation for this difference was that in practice sometimes demand was forecasted, but also sales were sometimes forecasted. Thus, at RESCM it is not clear for the employees what should actually be forecasted; demand or sales. However, demand should have been forecasted. Data analysis showed that the FC performance based on sales data was slightly better than the FC performance based on demand data, but still outside the target range for almost all months.

3.2.6 Further analysis

Together with my company supervisors Model 2 and Model 4 have been chosen for further analysis. These include the best-selling products within the selected product range. Moreover, two product types have been chosen which had different supply chain results: Model 2 had high inventory levels and almost no availability issues, whereas Model 4 had availability issues and low inventory levels.

4 Supply chain optimization model

In this chapter the supply chain optimization model will be described. First, an introduction will be given, where three different control models will be introduced. General assumptions and variables are defined in section 4.2, after which for every control model in a separate section the details will be given. Last, in section 4.6 an extension for the control models will be described by adding variability in the upstream lead time.

4.1 Introduction

Within the introduction of the supply chain optimization model, first the supply chain structure used in the model is shortly discussed, followed by a description of the used inventory policy. Last, in section 4.1.3 an introduction to the three different control models is given.

4.1.1 Supply chain structure

The specific part of that scope that will be considered in this optimization model is given by Figure 8 as presented before in section 3.2. Here, three stock locations were distinguished: modules at RIF, FG at RIF, and FG at RESCM. Next, for modeling purposes the stock locations of finished goods at RIF and RESCM will be combined into one stock location for finished goods within the proposed model, because of the small transportation time between both locations and because the same type of products are stored at both locations.

However, when considering the physical products, from each module different types of finished goods can be produced (see also the product structure as presented before in Figure 3). In the part of the supply chain that will be conserved only two levels of this product structure are relevant: module and FG boxed products, which for simplicity will be named as finished goods in the rest of this report. Here the only module that will be considered is the plotter, while in practice also other items as a scanner and an ARDF (Automatic Reversing Document Feeder) are used in the production of a FG.

To capture this product hierarchy in a model, the required structure of the supply chain therefore represents a distribution structure. Moreover, a two-echelon distribution structure will be used, due to combined FG stock locations. Note that the FG stock locations do not differ in physical location, but in the type of FG that is stored at these stock locations. This structure is given in Figure 15 below.

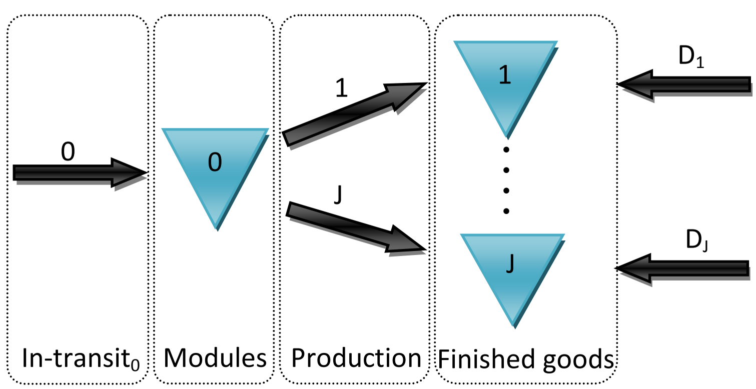


Figure 15: Supply chain distribution structure (Note: D_i = customer demand at end stock point i)

In the figure above the different phases that will be distinguished in the analysis of model performance are given, namely: In-Transit$_0$, Modules, Production, and Finished goods. In the optimization model In-Transit$_0$ will be considered as an external supply process.

4.1.2 Inventory policy

As described before in section 1.5, Ricoh uses DPSIM weekly for both the replenishment of modules and finished goods. Therefore, a periodic inventory policy should be used to represent this replenishment system. Moreover, the DPSIM replenishment system uses order-up-to levels to determine the replenishment quantities. This results into an (R, S)-inventory policy, where R indicates the review period and S the order-up-to level.

Currently at RESCM the order-up-to levels are determined based on demand forecasts. However, as mentioned in the problem statement (see section 2.2), demand is hard to forecast. Figure 13 in section 3.2.4 validated this problem, because when the forecasts of 3-months in advance were evaluated against the actual demand, the forecast performance was on average below 75%. More specifically, when the forecasts made 3-months in advance are compared with the actual demand for the two-highest selling machines of every product family, in 83.3% of the months (summarized over the 6 chosen FG) the actual demand was lower than the forecasted demand. Therefore, there is chosen to not-use the demand forecasts to determine the order-up-to levels, but to use the average customer demand per FG. Here, there is assumed to have stationary stochastic customer demand for every FG, because of the stable demand pattern as identified before in section 3.2.1.

This project is aimed at improving the inventory level and location of inventory in the supply chain. Ballou (1992) estimated that inventories can cost anywhere between 20 and 40% of the product value, which is a significant amount, because the machines used in the analysis have a product value of €1,000 or more. Therefore, inventory costs will be included as a main cost component.

Other relevant costs in a supply chain in relation with inventory decisions are ordering costs and backordering costs. Due to periodic review, high customer demand per week, and the possibility of combining orders for different products, there can be assumed that every review period at least one order is placed which makes ordering costs not relevant. Moreover, most cost optimization models in divergent supply chains use backordering costs to include customer service (Van der Heijden, 2000). However, in practice backordering costs are very hard to determine. Therefore, a model will be chosen having customer service as a fill rate (defined as the fraction of demand satisfied from stock on hand immediately; Van der Heijden, 2000).

Thus, the only cost component included in the model will be inventory holding costs. However, because it is harder to combine both a cost minimization approach and target fill rates in one model, the optimization model as presented in this chapter will be near-optimal.

4.1.3 Introduction to control models

The two-echelon distribution system as given in Figure 15 will be analyzed with centralized (echelon) control (see section 4.3). However, to be able to compare the performance of this echelon control model with the existing situation at Ricoh, a local control policy will also be modeled (see section 4.4), together will the current control policy in this part of Ricoh's supply chain (see section 4.5). First, all three control models will be shortly introduced.

4.1.3.1 Echelon control

The purpose of the echelon control model is to show what the overall supply chain performance is under full information sharing with centralized control. Therefore, a two-echelon distribution system will be analyzed with an (R, S)-policy and weekly replenishment. The order size under echelon (R, S)-policy is chosen such that the echelon stock level is increased to the echelon order-up-to level S, where echelon stock is defined as the physical stock plus all downstream stocks minus all backorders plus the order quantity at the supplier (Van der Heijden, 2000). Note that for the end stock points, echelon stock level and echelon order-up-to level are similar to their local values. The echelon control model should answer the question which echelon order-up-to levels (S) should be used at every FG stock point to obtain the target fill rates for every end stock point at minimal system holding costs.

Within this echelon control model information required for controlling the supply chain centrally will be shared with a central decision maker. The upstream stock points should share their review period, lead time and holding costs, whereas the end stock points additionally have to send information about the customer demand (mean and standard deviation) and the target fill rate to the central decision maker.

4.1.3.2 Local control

For the local control model (decentralized control) again a two-echelon distribution system will be analyzed under an (R, S)-policy with weekly replenishment. However, now at every stock point the order size will be chosen such that the local stock level is raised to the local order-up-to level at every review moment. For the end stock points ($i = 1, \ldots, J$) the order-up-to levels will be determined based on their target fill rate, the mean and standard deviation in lead time from the upstream stock point to their location including the expected waiting time in case of shortage at the upstream stock point 0, the mean and standard deviation of the customer demand for that stock point, and the review period used. However, most of this information is already locally available at the end stock points, apart from information related to the expected waiting time for shortages at the upstream stock point. Thus, only this information is required to be exchanged from the upstream stock point to each end stock point.

Moreover, upstream stock point 0 will determine their order-up-to level S_0 based on their target fill rate, the mean and standard deviation of the total customer demand at all end stock points where they deliver to, the expected lead time from the external supplier, and the review period. Therefore, information required to be shared by the end stock points to the upstream stock point consist of the mean and standard deviation of their customer demand.

The information exchange and calculations in the local control model will have the following sequence. First, the end stock points share the mean and standard deviation of their customer demand with the upstream stock point. There will be assumed that the end stock points share the real customer demand information they have with the upstream stock point. Secondly, the upstream stock point determines, based on the rationing rule that they will use for the orders from the end stock points, the expected waiting time for orders of end stock points, and shares this information with the end stock points. Last, the end stock points determine their required local order-up-to levels to attain the target fill rate.

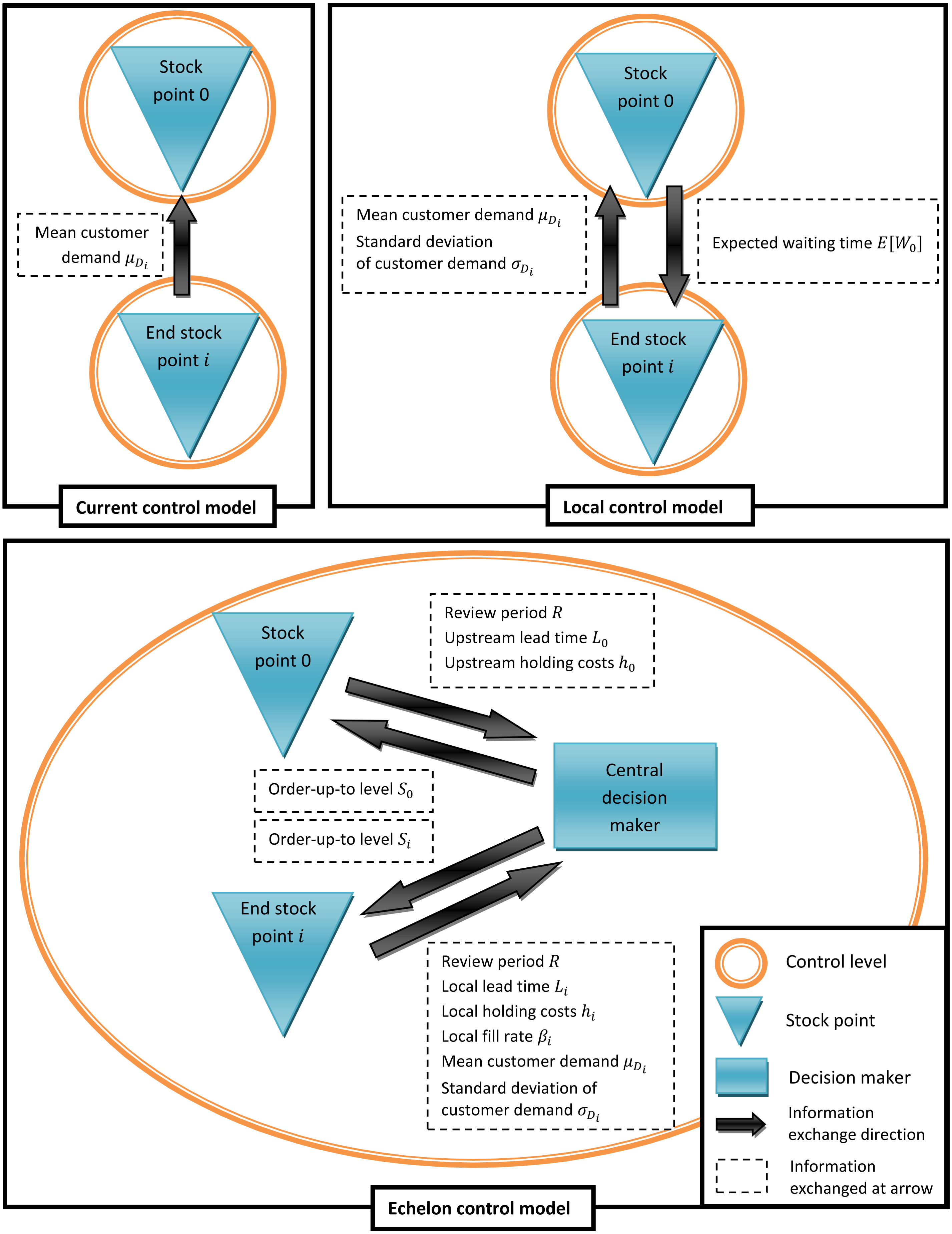


Figure 16: Overview of supply chain control models analyzed and the information exchange within each control model

Thus, compared with the echelon control model, the biggest changes are that for the local control model the upstream stock point 0 only uses local stock levels and local order-up-to levels, and that holding costs, lead times, and fill rate information will not be exchanged anymore due to the decentralized decision making. Here, the order-up-to levels will only be based on the local fill rates for all stock points and will not be influenced by the holding costs because no decision can be made about where to locate inventory. However, in local control no central decision maker is in between both parties.

4.1.3.3 Current control

Last, the current control model should reflect the policy Ricoh currently uses, where the order-up-to levels are determined based on the forecasted demand. In theory, the forecasted quantities should reflect the expected customer demand, because big gaps between forecasted and actual demand can lead to high inventory levels or low product availability. However, as shown in the evaluation of the current supply chain performance (see section 3.2.4), the overall trend was that the forecasted demand was higher than the actual demand (based on the customer's order request date) and that the forecasted quantities where more related to the actual sales data (based on the actual dates of shipment of orders to the customer). Note that due to uncertainty of demand a difference between expected and actual demand is expected, but not that almost always expected demand is higher than the actual demand.

Nevertheless, to be able to analyze the current situation at Ricoh the forecasted demand will be set equal to the average historical demand. Moreover, within the inventory policy currently used the target inventory levels are based upon number of weeks of expected customer demand. Therefore, in the current control model the order-up-to levels will be determined such that the time-average on-hand inventory level is equal to the target inventory levels currently used at Ricoh. The only Information required to be shared in the supply chain is average customer demand, which is shared by the end stock points. The results of this current control model will be used to compare the results of the other two control models.

4.1.3.4 Conclusion

The information exchange within the three control models as described above is summarized in Figure 16. Note that in this figure only one end stock point is displayed for better readability of the figure, but in practice there will be J end stock points. Further, the information exchange as indicated in the figures above should be seen as an additional information exchange next to the regular exchange of order and transportation information in a supply chain.

4.2 Details of general model

For all three control models the following assumptions will be made. In short, assumptions 1 till 4 as mentioned below are based on the situation in practice at Ricoh, where the other ones are mostly made for modeling purposes. Detailed discussion why these assumptions can and will be made is given in Appendix I. Note that these assumptions are partly based on assumptions made in the article of Van der Heijden (2000).

1. Finished goods stock points at RIF and RESCM locations will be considered as one, because of the small transportation time between RIF and RESCM (see Figure 8).
2. Fixed holding costs h_i will be used at all locations i. For the end stock points, the holding costs will be determined as $h_i = 0.148 * h_{i,RIF} + 0.852 * h_{i,RESCM} \;\; for \; i = 1, \dots, J$, due to the two different locations used in practice to store finished goods (see also assumption 1).
3. Only plotters (the main part of the machine) are considered as modules in the most upstream part of the supply chain before production at RIF. When for production of a FG the required module (plotter) is available, all required items for production of that FG will be available for production.
4. The total holding costs for modules (h_0) consists of the holding costs of the module itself and additional holding costs for other basic raw materials used in all types of finished goods which can be produced from that module.
5. Customer demand only occurs for finished goods (at FG stock points $i = 1, \dots, J$)
6. Customer demand is not-known in advance
7. There is stationary stochastic customer demand for every FG, with independent demand across finished goods and across periods in time.
8. There are no lost sales: all unsatisfied demand is backordered.
9. The lead time between the Asian factories and RIF is constant ($\sigma_{L_0} = 0$).
10. There is a constant lead time (including real production time and waiting time) between modules of RIF and finished goods of RIF ($\sigma_{l_i} = 0 \;\; for \; i = 1, \dots, J$).
11. Asian factories have a 100% delivery performance to RIF.
12. There are no fixed order quantities and there are no ordering costs.
13. There are no capacity constraints in transportation.
14. There are no capacity constraints in production.
15. After production of a certain type of FG, it is not possible to remanufacture it into another type of FG.
16. Partial delivery of customer orders is allowed.

All variables used in the optimization model as presented in the next section are listed in Table 10 in Appendix J. Moreover, within the explanation of the formulas the variables used will be explained.

Note that customer demand will be represented in the model by the mean and standard deviation, which makes it independent of the distribution of the customer demand. However, as can be seen later on, a two moment fit with a gamma approximation will be used within the model to cover demand during lead time. This is an approximation commonly made for this type of supply chain models.

4.3 Echelon control model

In this section the most important mathematical formulas for the echelon control model are given. Additional equations and derivations are presented in Appendix K. For this echelon control model, Van der Heijden (2000) is used as reference. More specifically, formulas 1 till 8 are taken from his article.

The objective of the echelon control model is to minimize the total supply chain costs (holding costs) under a fill rate (product availability) constraint at every end stock point. Next, first some extra assumptions will be listed, followed by general formulas and optimization formulas related to the inventory control in the two-echelon supply chain. Then, the optimization procedure will be described stepwise, followed by the results of the model, and, last, the optimization model will be verified.

4.3.1 Specific assumptions

Next to the general assumptions as described in section 4.2, the following specific assumptions will apply for the echelon control model. These assumptions are mostly made for modeling purposes. Again, in Appendix I detailed explanation for every assumption is provided.

17. An (R, S)-policy is used with $R = 1$ week under echelon control with a central decision maker.
18. All required demand, ordering, shipment and inventory information is shared among all supply chain members in the echelon control model.
19. The following rationing rule is used to deal with shortages at the upstream stock point: a simple variant of the balanced stock rationing in the sequel (Van der Heijden, 2000). See formula (1) below.
20. The lead time and demand of a stock point are independent random variables.

4.3.2 Rationing rule

An important concept within divergent supply chains is the rationing rule which is used in case that the upstream stock point has insufficient inventory to satisfy all replenishment orders from its successors. A rationing rule ensures that all order quantities are adjusted according to this rule. Different types of rationing rules are proposed in literature, as consistent appropriate share rationing, balanced stock rationing, an adapted consistent appropriate share rationing, and a simple variant of the balanced stock rationing rule (Van der Heijden et al., 1997). This simple variant of the balanced stock rationing rule simplifies the calculations of the rationing fractions considerably, but is still based on the idea of balanced rationing to minimize imbalance. Imbalance is defined as the phenomenon causing the rationing rule to allocate negative order quantities (Van der Heijden, 2000), and this has to be minimized as much as possible. Imbalance in the analyzed echelon control model for Ricoh will be discussed in section 6.3.1.3.

Van der Heijden et al. (1997) tested the performance of the rationing rules mentioned above and concluded that the original balanced stock rationing rule performs best in a two-echelon supply chain with a fill rate target. However, also the simple variant of this rule performs better than both variants of consistent appropriate share rationing. The simple variant of the balanced stock rationing rule will lead to straightforward rationing fractions, making it possible to determine near cost-optimal inventory policies. Moreover, these rationing fractions are particularly suitable for supply chains with non-identical successors (Van der Heijden, 2000). The supply chain that will be analyzed consits of non-identical successors, and will therefore be used in the model that will be described next.

The simple variant of the balanced stock rationing rule is as follows (Van der Heijden, 2000). Here, p_i refers to the rationing fraction of stock point i. Then, when the shortage at a supplying stock point k equals x, the echelon stocks of its successors $i = 1, \dots, J$ are not raised to S_i but to $S_i - p_i x$ where p_i are rationing fractions such that $\sum_{i=1}^{J} p_i = 1$, calculated as:

$$p_i = \frac{1}{2J} + \frac{\sigma^2(D_i)}{2\sum_{j=1}^{J}\sigma^2(D_j)} \quad for\ i = 1, \dots, J \tag{1}$$

where $\sigma^2(D_i)$ denotes the variance of the echelon demand per period at successor i. Note here the drawback of this rationing rule that this rule does not give best solution when differences in standard deviation of demand between stock points are big. Then the high-variance demand stock points will perform worse.

4.3.3 Echelon control (R, S)-model

As described before in the introduction of the control models (section 4.1.3), in the echelon control model there will be a central decision maker who determines the best order-up-to levels according to the input parameters as given in Figure 16 under minimal system holding costs. The parameter which will be optimized in order to get the minimal holding costs is Δ_0. This parameter represents the maximum physical stock level at stock location 0 and can be determined with the following formula:

$$\Delta_0 = S_0 - \sum_{i=1}^{J} S_i \tag{2}$$

This implies that Δ_0 is the difference between the echelon order-up-to level S_0 and the sum of the local order-up-to levels (echelon is similar to local for end stock points) at the end stock points S_i (for $i = 1, \dots, J$). The value of Δ_0 will be determined by a system cost minimization. Based on the value of Δ_0 and the fill rate restriction, the value of the order-up-to levels at the end stock points S_i can be determined. Last, the value for the near-optimal echelon order-up-to level S_0 can be determined.

The objective of the echelon control model is to find near cost-optimal order-up-to levels in a two-echelon system under the given assumptions and the approximations made. Therefore, the time-average total (system) costs ($\bar{Z}(\Delta_0)$) have to be minimized. These time-average costs are based upon the time-average on-hand inventory at stock point i ($\overline{\Psi}_i$), the time-average inventory level in pipeline to stock point i ($\widetilde{\Psi}_i$), and the unit holding costs at stock point i (h_i). In the formula below the pipeline stock is only taken into account for $i = 1, \dots, J$. The in-transit stock from the external supplier to RIF is not taken into account, because this is an external supply process.

$$\bar{Z}(\Delta_0) = \sum_{i=0}^{J} h_i \left\{ \overline{\Psi}_i(\Delta_0) + \sum_{j=1}^{J} \widetilde{\Psi}_j \right\} \tag{3}$$

Here, the time-average on-hand inventory level for all stock points is dependent on the value of Δ_0. However, the time-average in-transit inventory level to stock point i is not dependent on the value of Δ_0, because it just covers the expected demand during the lead time of the pipeline ($E\left[D_{i,L_i}\right]$) and can simply be determined by using the following formula:

$$\widetilde{\Psi}_i = E\left[D_{i,L_i}\right] \quad for\ i = 0, \dots, J \tag{4}$$

For stock point 0 the calculation of time-average on-hand inventory level is straightforward by subtracting the expected demand during lead time of stock point 0 from the maximum physical stock level at stock point 0 ($E[X_0]$) and adding the expected shortage at the same stock point ($E[Y_0]$):

$$\overline{\Psi}_0 = E[(\Delta_0 - X_0)^+] = \Delta_0 - E[X_0] + E[Y_0] \tag{5}$$

Formulas to determine $E[X_0]$ and $E[Y_0]$ are given in equations (16) and (17) in Appendix K. In the further derivations, X_0 will be approximated with a two-moment fit by using a gamma distribution with parameters α and λ (see equations (18) till (24) in Appendix K).

The time-average on-hand inventory level is indirectly dependent on the value of Δ_0, and given by the following formula:

$$\overline{\Psi}_i \approx \frac{1}{6} * E[(S_i - X_i)^+] + \frac{4}{6} * E\left[\left(S_i - D_{i,\frac{R}{2}} - X_i\right)^+\right] + \frac{1}{6} * E\left[\left(S_i - D_{i,R} - X_i\right)^+\right] \quad for\ i = 1, \dots, J \tag{6}$$

Formula (6) is dependent on the order-up-to level at the end stock point S_i, the expected demand during lead time for an end stock point plus the fraction of expected shortage at stock point 0 allocated to the end stock point (in total: X_i), and the demand during a review period ($D_{i,R}$). Equations needed to calculate formula (6) are given in Appendix K (see equations (22) and (25)).

4.3.4 Optimization formulas

In the optimization phase the approximated optimal value for the time-average cost function of formula (3) has to be determined. However, in the optimization procedure Van der Heijden (2000) introduces the cost function $Z(\Delta_0)$, which represents the system inventory costs, just before the arrival of a replenishment order. This cost function is given by the following formula (where μ_i represents the average weekly customer demand and β_i the target fill rate, both at stock point i):

$$Z(\Delta_0) = h_0\{\Delta_0 - E[X_0] + E[Y_0(\Delta_0)]\} + \sum_{i=1}^{J} h_i\{S_i(\Delta_0) - E[X_i(\Delta_0)] - R\mu_i\beta_i\} \tag{7}$$

Van der Heijden (2000) stated that optimizing formula (7) is in general easier than optimizing formula (3). Therefore, he investigated the minimim cost outcomes of both formulas by plotting both cost functions for a number of instances. For comparing both cost functions, first a new variable has to be introduced: a_0, defined as $a_0 = \Delta_0 / E[X_0]$. This new variable can be seen as the ratio between the maximum physical on-hand inventory level at stock point 0 and the expected demand during the lead time of stock point 0. When $a_0 = 0$, there will be no stock at the upstream stock point.

To show the effect of this varaible a_0, an example will be given with similar values as the example given in Van der Heijden (2000). Specifically, the following values for the input parameters in this example are used: $R = 1, J = 2, \mu_{l_i} = 1\ \&\ \sigma_{l_i} = 0\ (i = 0, .., 2), \mu_{D_i} = 100\ \&\ \sigma_{D_i} = 40\ (i = 1, 2), \beta_i = 0.95\ (i = 1, 2), h_i = 1\ (i = 1, 2),$ and $h_0 = 0.25$. Based on these values for the input patameters the graphs as given in Figures 17 and 18 can be made. In these graphs the cost outcomes ($Z(\Delta_0)$, and $\bar{Z}(\Delta_0)$) are plotted against the values for a_0, with $a_0 = \Delta_0 / E[X_0]$.

In these two graphs there can clearly be seen that both cost functions have the same shape, and will result in approximately the same values of a_0 (and thus Δ_0) for the local optima. The figures below are only displayed for one set of input values. However, according to Van der Heijden (2000) it is a common phenomenon that the location of the minima of both cost funcitons is about the same. In the model validation in section 6.4 this is also checked for the values used in this analysis Thus, there can be concluded that both formulas will result in approximaltely the same outcomes for Δ_0. In consequence, he continued with optimizing function (7), and detemined after the optimization the cost results with formula (3). Note that in Figures 17 and 18 there is a difference in the cost values on the y-axis, because Figure 17 is about the inventory level just before the arrival of a replenishment order (lowest level), while the cost values in Figure 18 are based on the time-average inventory levels.

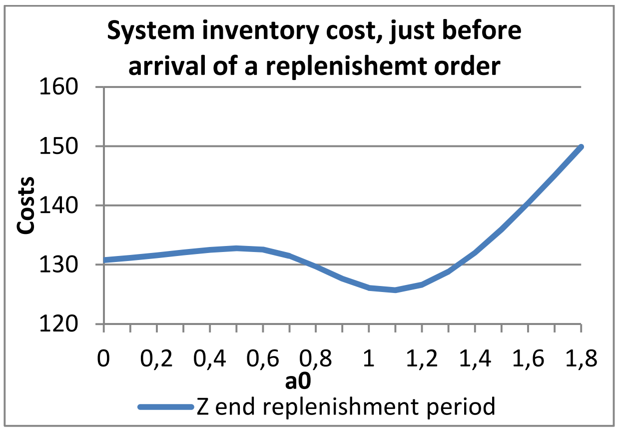


Figure 17: Graph $Z(\Delta_0)$ for example values

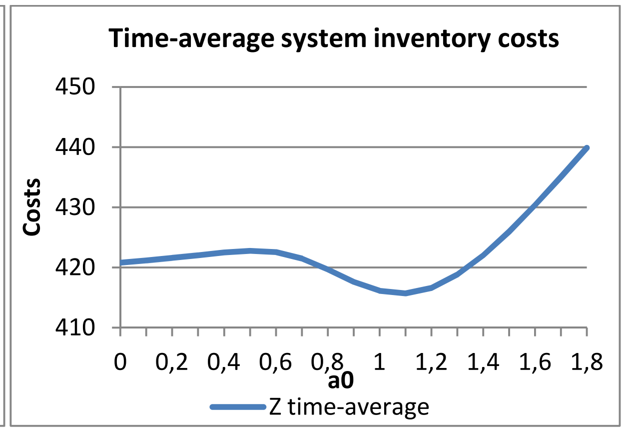


Figure 18: Graph $\overline{Z}(\Delta_0)$ for example values

To minimize the cost function (7), the derivative of this function will be set equal to zero to get the optima of this function ($Z'(\Delta_0) = 0$). However, before the optimization can start, first there has to be checked whether $Z'(\Delta_0) = 0$ results in a minimum or maximum. The shape of formula (7) is given in Figure 17 for the example as described before. In this graph multiple local optima can clearly be seen which have to be taken into account while optimization the cost function. One of these optima will be a local minimum, but the other point will be a local maximum.

Moreover, also the boundary value of $a_0 = 0$ has to be checked (negative stock levels are not allowed). This point may not be a local optimum, but the cost result at $a_0 = 0$ might be lower than for the local minimum found. Therefore, also the boundary value of $a_0 = 0$ has to be considered in determining the cost-minimal value of a_0.

Last, the approximate optimal value for Δ_0 will be determined by comparing the cost results for the two local optima (found by solving $Z'(\Delta_0) = 0$) and the cost result related to the situation of no central stock ($a_0 = 0$). Then, the value of Δ_0 with the lowest cost result will be the global minimum. This procedure is stepwise described in section 4.3.5. Based on numerical experiments with a computationally very intense grid search as benchmark, Van der Heijden (2000) concluded that the global minimum was found in all cases for the two- and three echelon model he tested with this procedure. Thus, there can be concluded that in almost all cases the local minima are around $a_0 \approx 1$ and at $a_0 = 0$, and the global minimum costs will be found using this optimization procedure.

In relation to the cost function of formula (7), the following equation has to be solved to be able to determine the near-optimal value (lowest cost value): $Z'(\Delta_0) = 0$, with:

$$Z'(\Delta_0) = h_0 F_0(\Delta_0) + \sum_{i=1}^{J} h_i \{S_i'(\Delta_0) - p_i[1 - F_0(\Delta_0)]\} \tag{8}$$

Here, $F_0(.)$ denotes the probability distribution function of X_0. Formulas needed to calculate $S_i'(\Delta_0)$ are given in Appendix K in equations (27) till (33).

4.3.5 Optimization procedure

The previous section results in the following optimization procedure:

1. Solve $Z'(\Delta_0) = 0$ by using equation (8). In all cases checked this resulted in two local optima: a local minimum and a local maximum (see also Figure 17).
2. Determine for both local optima the corresponding cost results (value for $Z(\Delta_0)$) by filling in the value of Δ_0 related to the local optima.
3. Determine Δ_0 for $a_0 = 0$ and the related cost results $Z(\Delta_0)$.
4. Choose from the outcomes of steps 2 and 3 the value of Δ_0 with the lowest cost result $Z(\Delta_0)$.

4.3.6 Results

After determining the near-optimal value for Δ_0, the required order-up-to levels can be determined by using equations (34) and (35) as provided in Appendix K. Note here that two-moment fit with gamma approximation is required in the calculation. Further, the average inventory levels for each stock point and in-transit to each stock point can be determined using formulas (4), (5), and (6), and the time-average system costs can be determined using formula (3), as given before.

Last, the system costs can be split into the costs made by RIF and the costs made by RESCM. Here, in accordance to assumption 2, the on-hand holding costs at the end stock points will be split into 14.8% for RIF and 85.2% for RESCM (see also equations (36) and (37) in Appendix K).

4.3.7 Model verification

For analyzing the echelon control model, the formulas as given in the previous sections of these chapters were implemented in Excel. First, the model as inserted in Excel has been checked by testing many different input values. For all cases checked this analysis resulted into outcomes as expected by the model, thereby verifying the model as implemented in Excel. However, extreme cases checking resulted in some computational errors in the Gamma function of Excel, due to very low or high values. This occurred for coefficients of variation in customer demand (defined as standard deviation of customer demand divided by the average customer demand) of lower than 0.0001, or when the differences in coefficient of variation in customer demand between the different stock point distinguished a factor bigger than 1,000 (for example: 10 and 0.001).

In contrast, extreme values for the other input parameters lead times (1,000 weeks), holding costs (difference in stock points with a factor of 1,000), and fill rate (0.99999) did not result in computational errors and resulted in outcomes as expected. For example, longer lead times resulted in higher inventory levels due to increased variability of demand during lead time, very high upstream holding costs led to no upstream stock, and very high fill rates resulted in very high downstream inventory levels.

Moreover, to test the optimization model, an example was used with similar values for input parameters as used by Van der Heijden (2000). This example was already introduced in section 4.3.4 and resulted in the graphs as given in Figures 17 and 18. These graphs are similar to the figures presented as outcome in his article. Therefore, there can be concluded that the echelon control model in Excel is verified in relation with the model as presented in Van der Heijden (2000). Validation specifically in relation to the model that will be optimized is given in section 6.4.

4.4 Local control model

In short, the local control model implies that decisions are made locally and only limited information is shared. The information shared contains the customer demand information at the end stock points, and the expected waiting time at the upstream stock point (see also Figure 16).

4.4.1 Specific assumptions

Next to the general assumptions as described in section 4.2, the following specific assumptions will apply for the local control model. These assumptions are mostly made for modeling purposes. Again, detailed explanation for every assumption is provided in Appendix I.

21. An (R, S)-policy is used with $R = 1$ week under local control for every stock point.
22. The only information shared by the end stock point with upstream stock point 0 is the mean and standard deviation of customer demand, while the upstream stock point returns only the expected waiting time to all the end stock points (see Figure 16 for the local control model).
23. In case of shortages at the upstream stock points, orders at this stock point will be rationed to the end stock point proportional to the number of units ordered by that end stock point.
24. The on-hand inventory level at upstream stock point 0 will always be non-negative at the start of a new review period, just after arrival of the replenishment order made L_i weeks ago.
25. The customer demand information shared by the end stock points with the upstream stock point is equal to the actual demand information they have.
26. Every customer demands one unit of a product
27. Every customer has a demand of one unit.

4.4.2 Formulas

Within the local control model each stock point optimizes its own inventory levels by using only local information. In this situation no decision has to be made about where to locate inventory, because each local stock point can only decide about its own ordering decisions. Therefore, in this model the best order-up-to level has to be determined for <u>every</u> stock point, and has to satisfy the fill rate constraint. This requires solving the following equation for every stock point (Van der Heijden, 2000):

$$\frac{E\left[\left(X_i + D_{i,R} - S_i\right)^+\right] - E[(X_i - S_i)^+]}{R\mu_{D_i}} = 1 - \beta_i \;\; for\; i = 0, \ldots, J \tag{9}$$

Again, the required order-up-to levels will be determined using the approximate inversion of the gamma distribution after approximation of the quasi-probability function $\beta_i(S_i)$ by a gamma distribution (see formula (33) in Appendix K; Van der Heijden, 2000) and a two-moment fit.

For determining the first two moments in the situation of local control, new expressions for $E[X_i]$ and $E[X_i^2]$ have to be found reflecting the changed control policy. Now $X_i = D_{i,L_i+R}$ for every stock point, because there is no dependency anymore in the downstream inventory level on the upstream stock point inventory level, and because the review period has to be seen as extra lead time in the local (R, S) inventory control policy.

This time, for the end stock points no extra term to deal with shortages at the upstream stock is inserted in the mean and variance formulas (see equations (38) and (39) in Appendix L). However, in another way there is dealt with shortages at the upstream stock point, namely by adding waiting time to the lead time of the end stock points (see equations (40) and (41) in Appendix L). This waiting time serves as the expected waiting time that an order from an end stock point has to wait due to shortages at the upstream stock point.

Here, the assumption has been made that orders are rationed proportional of the total number of units ordered at the upstream stock point in case of shortages at this stock point (assumption 23), together with the assumption that the on-hand inventory level at the upstream stock point is always non-negative at the start of a new review period, just after arrival of the replenishment orders (assumption 24). This implies that the maximum length of a shortage period for a specific order will be the length of one review period R. Therefore, the expected waiting time can be calculated by dividing the expected units of shortage during a replenishment cycle ($ESPRC_0$) with the expected demand during a replenishment cycle (D_{0,L_0+R}; see formula (42) in Appendix L). This relation can be made because of the application of Little's law. This implies that the waiting time is analogous to the throughput in the system, the shortage level is analogous to the work-in-progress, and the demand rate is analogous to the throughput. This is under the assumption that lead times are treated as equal to their means (Hopp & Spearman, 2008).

Van der Heijden and De Kok (1992) mentioned that Little's law can only be applied in case of a fixed demand per customer. In this case the total demand within a certain period is concerned, with no distinction in the customer arrival rate and the demand per customer. Moreover, due to the high product value of a single machine and that demand rates are high and origin from a lot of different customers from many different countries. Therefore, in this way there will be assumed that every customer has a fixed demand of one unit (see assumption 26), which makes the use of Little's law possible.

Further, they mentioned that there can be some error in the approximation of the expected waiting time due to the periodic review system, instead of the continuous review system for which the expected waiting time equation (see formula (42) in Appendix L) was developed. However, approximations for the expected waiting time in a (R, S) divergent supply chain will make the calculations much more complicated and very difficult to solve. Moreover, formulas for these specific situations that can be found in literature are only based upon Poisson customer inter-arrival times, which is a different approach than the two-moment Gamma approximations for demand during lead time used in the echelon control model. Further, there is assumed (see assumption 24) that the on-hand inventory level at the start of a new review period, just after arrival of the replenishment orders, is non-negative. Therefore, there will be assumed that the expected waiting time formula for continuous review systems can be properly used in this periodic review system.

Note that the rationing rule used in the local control model is different than the one used in the echelon control model. In the echelon control model the rationing fractions are based on the standard deviations in customer demand. In contrast, in the proportional rationing rule the fractions are based on the average customer demand. Thus there is some difference in both rationing rules. However, stock points with a much higher demand have in most cases also a higher real standard deviation in customer demand than a stock point with a small average and standard deviation in customer demand. Moreover, the fill rates used by Ricoh are high, requiring enough inventory to be able to attain the fill rate and reducing the number of cases of shortage at the upstream stock point. Therefore, the impact of the different rationing rules will be relatively small.

Now, $ESPRC_0$ has to be determined (Silver et al., 1998) by calculating the number of units of demand during lead time higher than the order-up-to level used at the same stock point 0 with formula (43) as given in Appendix L. With these formulas the expected delay due to the backorders at the upstream stock point can be calculated for the end stock points, resulting in a total expected lead time between the upstream and end stock points.

4.4.3 Results

In this local control supply chain no cost minimization function is required, because, with the fill rate constraint the model calculates the inventory level necessary to satisfy this constraint, and due to the local control no decision can be made about in which type of product (module or FG) the inventory has to be stored. The required order-up-to level immediately follows from the fill rate constraint (see equation (34) in Appendix K), and will not change by increased holding costs.

The output of this local control model is given by the same formulas as for the echelon model, in relation with the inventory levels. However, this time for the upstream stock point the same formulas will be used as for the end stock points. This implies that equation (6) will change in the way that it is applicable for $i = 0, \dots, J$ now. The time-average inventory levels in pipeline can again be determined with equation (4), after which the system costs can be calculated by using formula (3), and the costs specifically for RIF and RESCM are given by formulas (36) and (37), respectively. However, this time there is no dependency on Δ_0 anymore in these formulas (see equation 6' in Appendix L).

4.4.4 Model verification

Similar as done for the echelon control model, also the local control model will be verified based on outcomes as expected and extreme values. In this model changing input parameters will mainly affect the stock points directly related to these parameters. For example, a change in the fill rate at the end stock points only influences the required inventory levels at the end stock points. Furthermore, a change in holding costs does not affect the inventory levels, which should also be the case in the local control model.

In contrast, changing the upstream fill rate should also affect the inventory levels downstream. This happens in the local control model, but for low upstream fill rates (for example 60%), the effect on the downstream inventory levels is lower than what might be expected. This is due to the use of Little's law in the calculation of the expected waiting time for downstream orders at the upstream stock point, in combination with the small lead time tested between upstream and downstream stock point. Therefore, the model performance might not be completely representative with a low upstream fill rate in combination with a low downstream lead time. Moreover, extreme cases checking in a similar way as performed for the echelon control model resulted not into computational problems within Excel.

4.5 Current control model

In the current control model the on-hand inventory levels are simply determined by using the target inventory level expressed in weeks of expected demand and the expected weekly customer demand. This control model should reflect the current situation at Ricoh in the supply chain of RIF products. However, as could be seen in the current performance analysis (see section 3.2) this is often not the case. Next, two additional specific assumptions are listed, after which the model itself will be shortly described.

4.5.1 Specific assumptions

Next to the general assumptions as described in section 4.2, the following specific assumptions will apply to the current control model. These assumptions are made to let the model fit with reality. Again, detailed explanation for every assumption is provided in Appendix I.

28. The only information shared in whole the supply chain is the mean customer demand as shared by the end stock points with the upstream stock point (see also Figure 16 for the current control model)
29. The target inventory level represents the time-average on-hand inventory level

4.5.2 Explanation

The performance of the current control model regarding the time-average inventory levels and costs will be purely based upon the average customer demand and the target inventory levels as defined by Ricoh. The targets levels (given by variable A_i), represented by the time-average inventory level expressed in weeks of average customer demand with the corresponding values, are given in Table 3.

On-hand time-average inventory target in terms of average weekly demand	
Modules at RIF ($= A_0$)	1.00
Finished goods at RIF	0.40
Finished goods at RESCM	2.30
Finished goods total ($= A_i \ for \ i = 1, \ldots, J$)	2.70

Table 3: Target time-average on-hand inventory levels in terms of average weekly demand

Using these targets and the expected weekly demand (input parameter of the model), the time-average inventory levels can be determined for this current control model (see formulas (46) and (47) in Appendix M), and the corresponding time-average inventory costs results can be calculated with the formulas given for the echelon control model (see equations (3), (36) and (37)). However, there is no dependency on Δ_0 in these formulas. Then, based on an equivalent (R, S) inventory system, the corresponding order-up-to levels and fill rates can be determined (see Appendix M).

4.6 Extension of model

Van der Heijden et al. (1999) concluded based on a sensitivity analysis within an extensive numerical experimentation that especially upstream lead time has a significant impact on the order-up-to levels required to fulfill the fill rate constraint in a divergent (R, S) echelon controlled inventory model. Results indicate that the effect of upstream lead time variation even dominates the effect of demand variation on the order-up-to levels required to attain the fill rates.

Due to the very small production time, it is not relevant to consider stochastic production times. Moreover, Van der Heijden et al. (1999) concluded based on their experiments that the lead time variation between a central depot and multiple retailers has a limited impact on the supply chain performance compared to the effect of variation in upstream lead time. Furthermore, the delivery performance at the Asian factories is in general very good, which makes it not necessary to include stochastic delivery performance from their side. Therefore, the following extension will be made to the model: stochastic lead time of modules from Asia (elimination of assumption 9).

Having stochastic lead times will only influence the echelon and local control models. In the echelon control model the same formulas for $E[X_0]$ can still be used (see formula (16) in Appendix K), but the formula for $\sigma^2(X_0)$ (20; Appendix K) cannot be shortened anymore in formula (21; Appendix K) due to the added variability in L_0.

For the local control model some variability in the lead time will be added to the transportation time between Asia and stock point 0 in the same way as done for the lead time between stock point 0 and the end stock points. So, formulas (38) and (39) can still be used for stock point 0, but this time some extra variability in L_0 is added in the calculations. Last, within the current control model still the same order-up-to levels will be used because they are only based upon average customer demand and expected lead time.

5 Cost allocation

After determining the cost results for the local and echelon control model, the costs made in the echelon control model have to be divided among the two relevant parties: RIF and RESCM. This division will be based on the time-average expected cost functions. First, some game theoretical cost allocation concepts will be discussed, after which the cost allocation concepts specific for two-player games will be described in more detail. Last, the specific cost allocation model in this project will be given.

5.1 Introduction to allocation concepts

The type of cost allocation game applicable to this project is a cooperative game in characteristic function form. This implies that this game has multiple players who can communicate and (perhaps) improve (reduce) their costs by cooperation. For games having a characteristic function form, these are the three most important solution concepts: the core, the Shapley value, and the nucleolus (Leng & Parlar, 2005).

Leng and Parlar (2009) suggested that first the stability criterion of a coalition has to be checked for this type of allocation games. However, as noted in game theoretical literature, actually there has to be checked whether the core is nonempty, instead of only checking whether a project will decrease the total costs for the participating players to determine the profitability of cooperation (Slikker, 2011).

The core of a cooperative cost allocation game is a set that consists of cost vectors $x \in \mathbb{R}^N$ satisfying the conditions of efficiency ($\sum_{i \in N} x_i = c(N)$) and stability ($\sum_{i \in S} x_i \leq v(S)\ for\ all\ S \subseteq N$). Here, $c(S)$ indicates the cost results related to coalition S, and N indicates the set of players in the game. When the core of a cooperative game is nonempty there can be concluded that no coalition of players has an incentive to leave the grand coalition and form a coalition on their own (Tijs & Driessen, 1986; Slikker, 2011).

The Shapley value can be used to determine a unique (fair) allocation scheme and represents cost results distributed fairly by an outside arbitrator (Leng & Parlar, 2005). The Shapley value is based on the marginal costs for a player when entering a coalition. However, the Shapley value does not always need to be in the core of the game, also if the core is non-empty. Therefore, there can be concluded that the Shapley value fails to be stable and can thus result in situations where players have an incentive to leave the coalition (Tijs & Driessen, 1986).

A solution concept without these drawbacks is the nucleolus. This concept minimizes the unhappiness of the most unhappy coalition. This concept has found to be efficient for only a few players, but can result in very large linear programming problems for games with more players (Leng & Parlar, 2005). Nevertheless, the supply chain considered consists only of two players (RIF and RESCM), which makes the nucleolus concept well applicable.

Last, Tijs and Driessen (1986) introduced another allocation method, called the Cost Gap Allocation (CGA) method, which is based on the concept of the τ-value. This method is found to be efficient in all games, and stable for two- and three-player games. The CGA method works as follows. Let (N, c) be a cost game, where N denotes the player set and c the cost vector. Then, define

$m^c = (m_1^c, m_2^c, \dots, m_n^c) \in \mathbb{R}^n$ as the marginal cost vector for (N, c), with $m_i^c = c(N) - c(N\backslash\{i\})$ for all $i \in N$. Then, for each coalition S the cost gap of this coalition S in the game (N, c) as:

$$g^c(S) := c(S) - \sum_{i \in S} m_i^c \quad \text{if } S \neq \emptyset \ \text{ and } g^c(\emptyset) := 0 \tag{10}$$

In general, it is assumed that the cost gap function is nonnegative. Note that $g^c(N)$ is equal to the non-separable cost in the cost game. Next, the maximal contribution of player i to the non-separable cost $g^c(N)$, given by the w_i^c is defined as follows:

$$w_i^c := \min_{S; i \in S} g^c(S) \quad \text{for all } i \in N \tag{11}$$

where $w^c = (w_1^c, w_2^c, \dots, w_n^c) \in \mathbb{R}^n$ is the corresponding weight vector. After assuming that the total of these maximal contributions covers the non-separable cost, $\sum_{i \in N} w_i^c \geq g^c(N)$, the cost gap allocation method assigns the following cost allocation (Tijs & Driessen, 1986):

$$CGA(c) = \begin{cases} m^c, & \text{if } g^c(N) = 0 \\ m^c + g^c(N) * \left(\dfrac{1}{\sum_{i \in N} w_i^c}\right) * w^c, & \text{if } g^c(N) > 0 \end{cases} \tag{12}$$

5.2 Allocation in two-player games

Specifically for two-player games, Leng and Parlar (2009) suggested the use of the egalitarian proposal if a two-player coalition is stable. This egalitarian proposal simply divides the joint costs equally to the players. However, Tijs and Driessen (1986) mentioned that the egalitarian proposal does not possess strategic aspects: this allocation rule is not individually rational (individual rationality is defined as: $m^c \leq c(\{i\}) \ \text{for all } i \in N$).

Nevertheless, Tijs and Driessen (1986) also analyzed two-person allocation problems. They concluded that the solution of the cost gap allocation for a two-player allocation game is similar to the solutions of the Shapley value and the nucleolus. Moreover, because the cost gap allocation is efficient and found to be stable, the cost allocation proposal will belong to the core.

Specifically, they stated that for any two-person cost allocation game (N, c) the Cost Gap Allocation (CGA) solution (which is thus similar to the solutions of the Shapley value and the nucleolus) is given by the following formula (Tijs & Driessen, 1986):

$$CGA(v) = \frac{1}{2} * \big(c(\{1\}) - c(\{2\}) + c(\{1,2\}), -c(\{1\}) + c(\{2\}) + c(\{1,2\})\big) \tag{13}$$

Here the cost savings of the grand coalition will be equally divided to both players. In the next section this allocation proposal will be discussed is relation to the supply chain analyzed in this research.

5.3 Cost allocation model

The analyses of the echelon and local control model resulted in time-average inventory holding costs for RIF and RESCM for all the models by using formulas (36) and (37), and in the total time-average holding costs as determined with formula (3). Note that the sum of the outcomes of formulas (36) and (37) will give the same outcome as formula (3) gives.

Within the cooperative game model two types of situations will be distinguished, where cooperation is considered as willing to participate in joint decision making regarding the inventory control. Note that when only one player wants to cooperative (situation 1), no joint decision making can occur and thus the local control model has to be used.

1. **One player wants to cooperate:** refers to the local control model (see section 4.4), with $\bar{Z}_{RIF,Local}$ and $\bar{Z}_{RESCM,Local}$ as cost results.
2. **Both players want to cooperate:** refers to the echelon control model (see section 4.3), with $\bar{Z}_{Total,Echelon}$ as cost result.

These two situations will result in the time-average costs. This results in the following two-player cost allocation game with the player set $N = \{RIF, RESCM\}$:

$$c(S)\begin{cases} 0 & if\ S = \emptyset \\ \bar{Z}_{RIF,Local} & if\ S = \{RIF\} \\ \bar{Z}_{RESCM,Local} & if\ S = \{RESCM\} \\ \bar{Z}_{Total,Echelon} & if\ S = N \end{cases} \tag{14}$$

Then, the solution of the cost allocation problem, as indicated by formula (10), is given by the following equation:

$$CGA(v) = \frac{1}{2} * \left(c(\{RIF\}) - c(\{RESCM\}) + c(N), -c(\{RIF\}) + c(\{RESCM\}) + c(N)\right) \tag{15}$$

The solution derived from this formula will be within the core (with efficiency and stability property; Tijs & Driessen, 1986). Moreover, in the solution no player (RIF and/or RESCM) will have an incentive to leave the grand coalition and form a coalition on their own. Note that the outcome of the current control model will not be used within the proposed cost allocation concept.

6 Analysis and results

In this analysis two different models will be considered (Model 2 and Model 4; in the rest of this chapter referred to as Model 2 and Model 4), both consisting of four different types of finished goods (see also Figures 34 and 36 in Appendix G). Therefore, in both cases a two-echelon divergent supply chain will be considered with one upstream stock point and four end stock points. Product characteristics about the finished goods that are part of the models are provided in Table 11, Appendix N.

6.1 Input parameters

The values for input parameters used in this analysis are given in Table 12, provided in Appendix N. Next, explanation about the calculation of the input parameters used in the optimization model will be given.

6.1.1 Lead time

Lead times are equal to the average values which are currently applicable to Ricoh. A constant lead time of two working days (0.4 week) between the upstream and end stock point should be seen as the production time, including some waiting time for production due to limited production capacity (see assumption 10 of optimization model). The upstream lead time is constant and equal to 10 weeks due to the transportation over sea from Asia to Europe. Here, variance in lead time will be added in the extension of the model (see section 6.6).

6.1.2 Holding costs

Different types of costs are associated with having products on stock. In general, three different types can be distinguished: (1) inventory storage costs, (2) cost of capital, and (3) costs related to risk (Bertrand et al., 1998). Inventory storage costs are related to the storage location (building, handling, and insurances), the cost of capital is related to the money invested in inventory on hand, and the cost related to the risk of capital covers damage, obsolescence, and theft (Silver et al., 1998).

For Ricoh, the inventory storage costs and the cost of capital are the two most important cost factors related to having inventory. Therefore, these two cost components will be included in the holding cost calculations. The risk of having obsolete inventory will be negligible, because the chance of having obsolete machines is considered as minimal for the machines, due to high number of units sold each week.

The inventory storage costs will be determined based on the yearly costs of the storage location. Together with the total space in the storage location, the space required for storing one pallet of the associated product (including required safety and handling space), and the number of products that fit on one pallet, the inventory storage cost per unit can be determined. Note, that here is assumed that all inventory storage costs are variable, and will be fully dependent upon the number of units having on stock. In practice there will also be fixed costs, but because a lot of different items will be stored on one location such that reducing inventory of one item will create more storage space for other items, and in case of high inventory levels external storage space has to be rented, variable holding costs will be assumed.

The cost of capital will be based upon the product value as used within the financial department of Ricoh, and the interest rate related to the cost of capital. This interest rate will be the interest rate Ricoh uses in general for the cost of capital related to inventory. Due to confidentiality issues at the RIF factory, RIF does not want to share their product value information with RESCM. Therefore, there will be assumed that the total product value of the raw materials at RIF (scanners, plotters, and ARDF) will be 75% of the product value of the FG as used at RESCM. Because of different pricing of the different types of finished goods assembled from the same modules, the value will be determined proportional to the average customer demand derived from historical data. The calculations made to derive the holding values are given in Appendix O. Note that in section 6.5.3 a sensitivity analysis on this holding cost factor will be given to show the impact of some error in this approximation.

6.1.3 Fill rate

The fill rate is set equal to 90% for the end stock points and 95% for the upstream stock point in the local control model, according to the current targets used at Ricoh.

6.1.4 Customer demand

The customer demand (mean and standard deviation) for both types of machines is determined based on one year history of demand, aggregated to a weekly level. Specifically, it includes the period April 1st, 2011 till March 31st, 2012. This reflects one financial year used within Ricoh. However, for Model 4 the last month (March 2012) is not taken into account in the calculations of the mean and standard deviation, because starting by March 2012 the versions of the machines investigated will be replaced by newer versions. Therefore, during March 2012 the customer demand will not be representative anymore, and will not be used in the calculations. For new models (with no historical data) demand forecast should be used, in combination of historical demand information of similar models.

6.2 Output parameters

In section 3.1 three key KPIs were identified as most important for this project, namely: inventory level, product availability, and forecast performance. In this model product availability is used as a customer service target. Forecasting is not directly used in the model, but only in the way of using the mean and standard deviation of customer demand. However, customer demand is only used as input parameter in the model. Therefore, inventory levels will be evaluated as the most important output parameter.

Related to the inventory levels, the time-average on-hand and in-transit inventory levels expressed in average weekly customer demand, the holding costs at the different locations in relation with the inventory levels, and the location of the inventory within the supply chain will be discussed. Moreover, the order-up-to levels will be given as output of the model, on which the inventory levels are based. Last, for the current control model an approximation of the attainted fill rate with the target inventory levels will be given, related to the product availability KPI.

6.3 Results

Next, the result of the analysis by using the three different control models will be given. First, the results of Model 2 will be given, followed by the results for the Model 4. Last, in 6.3.3 a conclusion will be drawn based on the results of both models.

6.3.1 Model 2

Based on the demand input parameters (mean and standard deviation), the following coefficient of variations (cv) can be calculated, with $cv_{D_i} = \sigma_{D_i}/\mu_{D_i}$ (well known; see e.g. Hopp & Spearman, 2008). This results in these coefficient of variations: $cv_{D_1} = 0.988$, $cv_{D_2} = 0.261$, $cv_{D_3} = 1.155$, and $cv_{D_4} = 0.268$ (see also Table 17 in Appendix P).

These data show that the finished goods with high demand (2 and 4) have a relatively low coefficient of variation, where the products with a low average demand have a coefficient of variation around the value of 1. Next, Table 18 in Appendix P gives the values for the different output parameters after running the models with the values for the input parameters as described before in section 6.1. Note that the order-up-to levels for the echelon control model as presented in Table 18 represent the echelon order-up-to levels. The corresponding local order-up-to levels are for the end stock points similar to the echelon order-up-to levels, but for the upstream stock point the corresponding local order-up-to level is given by Δ_0. The outcomes of the local control model refer to the situation where no cost minimization approach is used in the supply chain, but for every stock point individually the required order-up-to levels are determined based on demand, lead time, and fill rate input values.

Further note that the upstream order-up-to levels S_0 include both the on-hand stock at stock point 0 and the in-transit stock towards stock point 0. However, due to the large upstream lead time the inventory level in-transit from the external supplier to the upstream stock point is very high. For example, when evaluated in units, the percentage of units in the total supply chain which is in-transit varies between 92.4% and 80.3% for the three control models in case of Model 2. For all three control models the time-average number of units in-transit towards the upstream stock point equals 8,607.20 units, resulting in yearly holding costs when evaluated with the h_0 value in a cost factor of €1,376,556.20. Moreover, these costs do not change, because the on time-average level the number of units in-transit from Asia to RIF is equal to the average lead time multiplied by the average customer demand. These parameters are similar in all three models. Therefore, in contrast to the scope as identified in Figure 6 in section 2.4, the in-transit inventory level and holding costs for the pipeline towards the upstream stock point will not be included in the analysis.

Next, diagrams summarizing the results of Model 2 will be given, based on the output values as presented in Table 18, Appendix P.

6.3.1.1 Cost results

First, the best way of comparing the performance of the three control models is by comparing the supply chain holding costs. This cost comparison is given in Figure 19. From this figure there can be derived that, compared with the current control policy, the total holding costs decrease with 49.17% when the local control policy is used at both locations (RIF and RESCM), and decrease with 66.35% when the echelon control policy is used. Note that when the holding costs for in-transit towards the upstream stock point are included, the percentages in change will drop to 16.18% when the local policy is used instead of the current policy, and to 21.82% when echelon control is used instead of the current control.

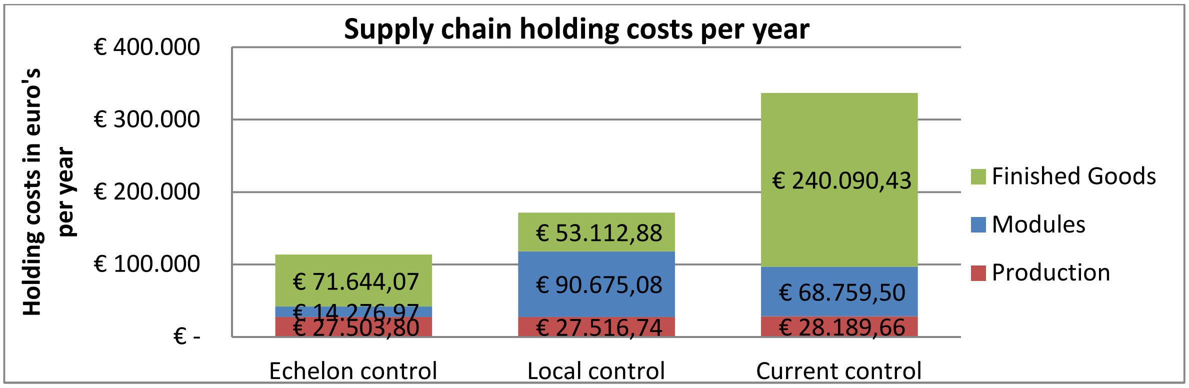


Figure 19: Holding cost performance of the three control models for Model 2

The cost results on the different models are also evaluated on location in the supply chain; see also Figure 15 in section 4.1.1. In contrast to the supply chain cost results, the module holding cost increase when adopting the local control policy. This cost increase is caused by a higher fill rate constraint used in the local control model (95.00%; actual performance is 94.66%) than it was in the current control for these parameter settings (89.62%). Nevertheless, the module holding costs drop with 97.69% when adopting in the echelon control model compared with the local control model. In contrast, the FG holding costs decrease with 77.88% when moving from the current control policy to the echelon control, but increases with 65.67% when moving from the local control to the echelon control policy.

Further, a small change in the production holding cost can be seen in Figure 19. This is caused by the expected waiting time due to shortages at the upstream stock point in the local and current control model which is included in the production holding costs.

6.3.1.2 Location of inventory in supply chain

Next, the location of the inventory in the supply chain will be discussed, based on the inventory levels in units. The results are given in the diagrams below (see Figure 20).

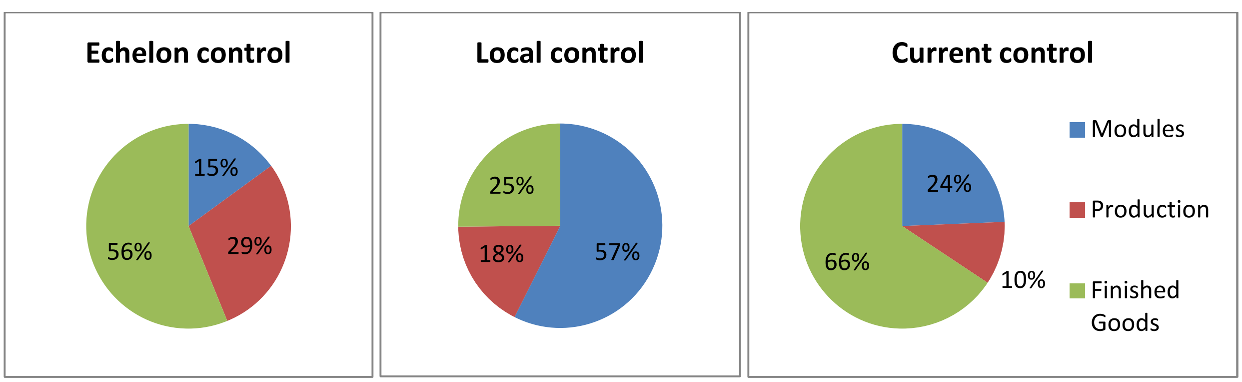


Figure 20: Location of inventory in supply chain, based on inventory levels in units for Model 2

In the diagrams displayed above clearly the change in where inventory is placed in the supply chain can be seen between the three types of control models. The FG inventory decreases when changing the current control policy into the local control policy, but increases again when exchanging the local control with the echelon control policy. Note that the real number of units of FG inventory is decreased from

2,323.94 units in the current control to the 822.84 units in the echelon control model. The module inventory level has the opposite pattern.

The decrease in FG inventory in local control is caused by the high inventory levels of modules required to deal with the variability in customer demand during the long upstream lead time, while attaining an upstream fill rate of approximately 95% (higher than the customer fill rate). The short production lead time and high upstream fill rate caused the low FG inventory in the local control. The decrease in module inventory, while having a lower holding cost for modules, is caused by the policy behind the echelon control to only have a customer fill rate at the end stock points. Customer demand occurs at the end stock points, so the only reasons the keep module inventory is because of the lower holding costs and to keep flexibility in production of different types of finished goods. Therefore keeping some module inventory is suggested by the echelon control model with the current parameters. However, the echelon control model suggests having almost all inventory at the end stock points (as finished goods).

6.3.1.3 Inventory levels

Next the time-average on-hand inventory levels based on average weekly customer demand are given in Table 4 below for every stock point. As a reference, for FG stock points a time-average on-hand inventory level of 0.5 weeks would imply that, on average, zero stock at the end of a review period, just before arrival of a new replenishment order. For module stock the inventory level does not change constantly during a review period, due to the periodic replenishment of the end stock points and periodic ordering policy used for modules, with a constant lead time. Therefore, the given inventory level for modules is constant during a review period.

There can be concluded from the table below that the inventory levels of finished goods for the echelon and local control model are heavily dependent on the coefficient of variation in the customer demand. FG 1 and FG 3 both have low customer demands (less than 5 units per week), but the coefficient of variation is around 1. Therefore, their inventory levels expressed in terms of expected weekly customer demand are higher than the inventory levels for FG 2 and 4. These two high-selling products have namely coefficient of variations of approximately 0.26. Thus, there can be concluded that the coefficient of variation of customer demand influences the inventory levels outcomes significantly, especially in the echelon control model.

	Module	FG 1	FG 2	FG 3	FG 4
Echelon control	0.21	14.43	0.63	85.19	0.68
Local control	1.32	2.08	0.57	2.53	0.58
Current control	1.00	2.70	2.70	2.70	2.70

Table 4: On-hand inventory levels in weeks of average customer demand per stock point for Model 2

However, there has to be noted that the extremely high inventory levels in terms of weekly customer demand in the echelon control model are caused by the rationing rule used in this model and are not realistic. Nevertheless, higher on-hand inventory levels (expressed in weeks of average customer demand) are required for these stock points to be able to deal with the high variation in customer demand. As noted before, a simplified version of the balanced stock rationing rule is used, where half of the allocated fraction in case of shortage at the upstream stock point is independent of the customer demand (the $\frac{1}{2J}$ part of the equation). Therefore, each stock point has at least an allocation fraction of $\frac{1}{2*4}$. The purpose of this allocation rule is to minimize imbalance (negative order quantities). This analysis showed that on time-average there were no negative allocations fractions. However, in day-to-day business negative allocation fractions can occur due the big difference in customer demand per stock point. Moreover, on time-average level no negative inventory levels will occur, because of the high customer fill rate that has to be attainted for every stock point. Only when the actual customer demand deviates significantly from the predicted customer demand, negative allocation fractions can occur.

6.3.1.4 Fill rate

In Figure 21 below approximations for the attained fill rate per FG are provided for all three control models. For the echelon and local control model the fill rate was used as a constraint in the model. However, due to approximations in the calculations of the required there is some deviation from the target customer fill rate of 90.00%, especially for the finished goods with a low demand and higher variability in demand (FG 1 and 3).

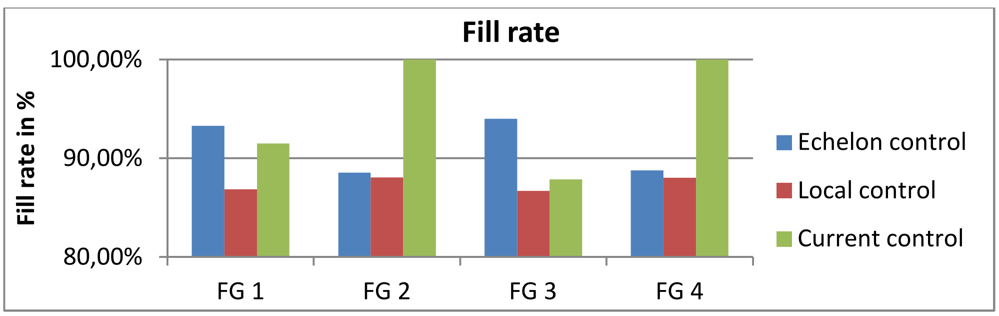


Figure 21: Fill rate results for Model 2

In the current control model the inventory level based on the average customer demand is kept stable. Here, the effect of the coefficient of variation can be seen clearly, because for FG 2 and 4 (low cv) the fill rate is almost 100%, while for FG 1 and 3 (high cv) the achieved fill rate is around or below the target of 90%.

6.3.1.5 Cost allocation

Next, the cost allocation rule can be applied for the echelon control model. However, first the cost results for RIF and RESCM for the different control models without cost allocation are given (see Table 5).

Holding costs per year	*Echelon control*	*Local control*	*Current control*
RIF	€ 52,394.71	€ 126,060.40	€ 132,518.12
RESCM	€ 61,030.14	€ 45,244.31	€ 204,521.48
Total	€ 113,424.85	€ 171,304.71	€ 337,039.59

Table 5: Holding costs results per organization per year for Model 2

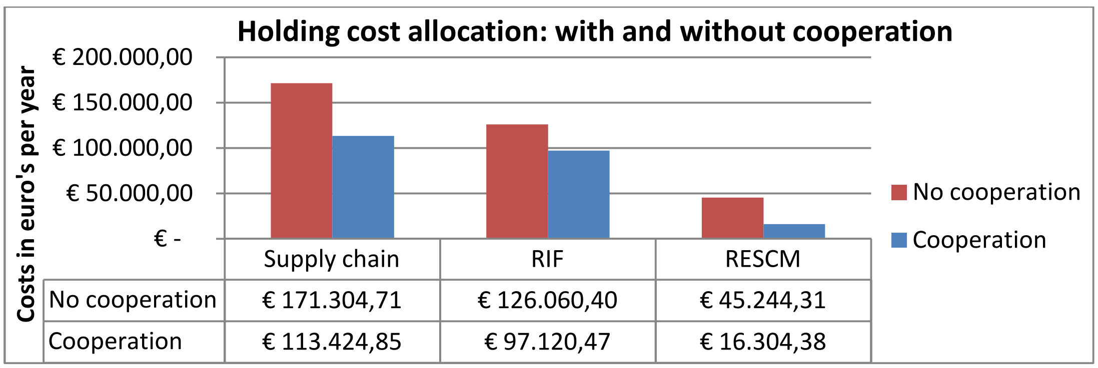
From this table there can be concluded that the RESCM holding costs increase with €15,785.83 (34.89%) when moving from the local control model to the echelon control model. Thus, there is no incentive for RESCM to cooperate in the echelon control model. However, the supply chain costs decrease with €57,879.86 (33.79%). Therefore a cost allocation rule will be used to ensure that both parties in the cooperation (RIF and RESCM) have an incentive for cooperation. Specifically, the following rule will be used, as introduced before in section 5.3:

$$CGA(v) = \frac{1}{2} * \big(c(\{RIF\}) - c(\{RESCM\}) + c(N), -c(\{RIF\}) + c(\{RESCM\}) + c(N)\big)$$

With ($N = \{RIF, RESCM\}$):

$$c(S)\begin{cases} € \; 0 & if \; S = \emptyset \\ € \; 126{,}060.40 & if \; S = \{RIF\} \\ € \; 45{,}244.31 & if \; S = \{RESCM\} \\ € \; 113{,}424.85 & if \; S = N \end{cases}$$

After using this allocation rule, RIF and RESCM will have the cost results in the echelon control model as given by the cooperation columns in Figure 22. Note that “no cooperation” refers to the situation of local control. In this cost allocation none of the players has an incentive to leave the grand coalition and form a coalition on their own. Therefore, the core of the game is nonempty and the allocation of the costs is within the core.



	Supply chain	RIF	RESCM
No cooperation	€ 171.304,71	€ 126.060,40	€ 45.244,31
Cooperation	€ 113.424,85	€ 97.120,47	€ 16.304,38

Figure 22: Cost allocation: costs results without cooperation (local control model) versus allocated costs in echelon control model (cooperation) for Model 2

6.3.2 Model 4

Now, in short the results for Model 4 will be presented. First, the demand characteristics of the four FG types of Model 4 are given in Table 19, in Appendix Q. The corresponding coefficients of variations are: $cv_{D_1} = 0.988$, $cv_{D_2} = 0.261$, $cv_{D_3} = 1.155$, and $cv_{D_4} = 0.268$. When comparing the demand characteristics of Model 4 and Model 2 (see section 6.3.1), there can be concluded that both product types have two high-selling finished goods, which both have a relatively low coefficient of variation. Moreover, also for Model 4 the two low-selling finished goods have a relatively high coefficient of variation in their customer demand. Therefore, for Model 4 only the figure with the supply chain cost results will be given. Other figures are provided in Appendix Q.

In Figure 23 below the supply chain holding cost results are plotted per control model per part of the supply chain. From this figure can be derived that the total holding costs decrease with 57.67% when the local control policy is used at both locations (RIF and RESCM) compared with the current control policy, and decrease with 71.65% when the echelon control policy is used. However, again there has to be noted that, when the holding costs for in-transit towards the upstream stock point is included (with a cost value of €904,382.68), the percentages in change will go to a decrease of 19.24% when the local policy is used instead of the current policy, and a decrease of 23.90% when echelon control is used instead of the current control.

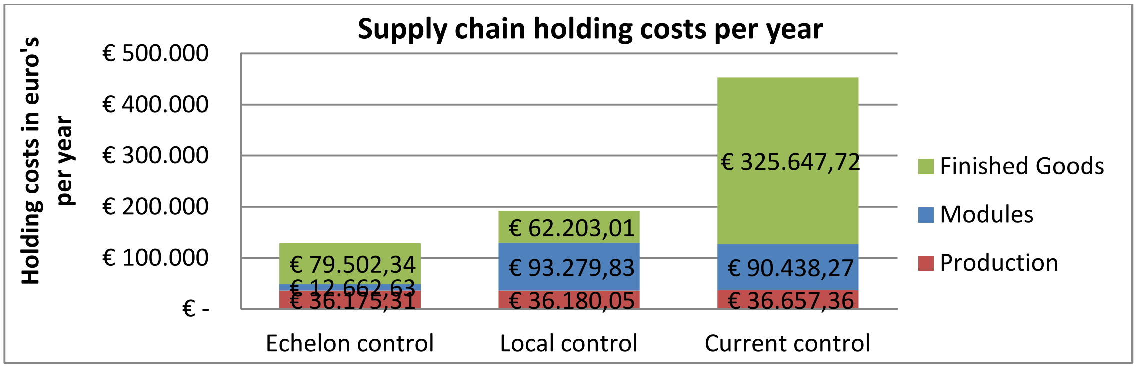


Figure 23: Holding cost performance of the three control models for Model 4

From Figure 23, in comparison with the similar figure for Model 2 (see Figure 19), there can be concluded that there are relatively less module inventory costs in the local control model for Model 4 compared with Model 2. Moreover, the holding costs for finished goods and production are slightly higher for Model 4 in the local control model. This is caused by the slightly higher total customer demand for Model 4, but with a lower coefficient of variation in customer demand for the highest-selling FG of Model 4. This observation can also be seen in the other graphs of Model 4 as presented in Appendix Q.

6.3.3 Conclusion

Overall, there can be concluded that for Model 2 and Model 4 the total holding costs compared to the current control model decreased with respectively 49.17% and 57.67% in the local control model, and with respectively 66.35% and 71.65% in the echelon control model. Note again that these percentage changes are much lower when the holding cost for in-transit towards the upstream stock point is taken into account.

In the analysis three different stages in the supply chain were distinguished: module stock (on-hand inventory at stock point 0), production (in-transit inventory between stock point 0 and stock point i for $i = 1, \dots, 4$), and finished goods stock (on-hand inventory levels at end stock point i for $i = 1, \dots, 4$). Regarding the location of the inventory in the supply chain there can be concluded that the local control model has most of its inventory located at the module stock point, while the echelon control model has most of its inventory located at the FG stock points. When the inventory levels are specified per FG type, there can be concluded that relatively more inventory is needed for products with a higher coefficient of variation in customer demand. This is a straightforward outcome. However, in the echelon control model the inventory levels for the product with low demand and high variance of demand are relatively very high (up-to 85.19 weeks of average customer demand). This is caused by the use of the simplified rationing rule which made it possible to derive optimization formulas for the echelon control model.

The inventory holding costs made by RESCM increases when moving from local to echelon control. Therefore a cost allocation rule is required to make RESCM and RIF cooperate as in the echelon control model. This is the allocation rule which allocated the cost savings between local and echelon control model half to RIF and half to RESCM. Thus, both parties will have the holding cost value in the echelon control model after allocation of the local control model minus half of the supply chain savings in holding costs achieved in echelon control.

Last, as mentioned before, there is a limited difference between the cost outcomes of Model 2 and Model 4 because of the similar product characteristics. Therefore, in the sensitivity analysis and extension of the model only Model 2 will be considered.

6.4 Model validation

In this section two tests for model validation will be performed. First the accuracy of the fill rate approximations will be tested for both the echelon and local control model. When comparing with the target fill rate of 90.00% which was used as input for the model, in Figure 21 (see section 6.3.1.4) some deviations from the target fill rate can be seen. In the echelon control the actual performance is higher than the target for the low demand items with a high coefficient of variation, while for the other two finished goods (high demand and low variation) the achieved level is 1.5% lower than the target. For the local control model the deviations are slightly higher. Thus, the inventory levels should be a little bit higher for all FG in local control and FG 2 and 4 in echelon control to really achieve the target fill rates. For FG 1 and 3 in echelon control their inventory level can be lowered. An important reason for this difference in approximated and actual value is the high on-hand inventory levels for the low-demand items and relatively low on-hand inventory levels for the high-demand products.

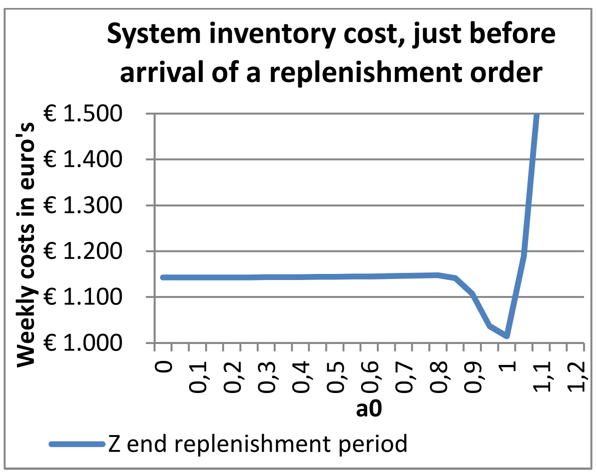


Figure 24: Graph $Z(\Delta_0)$ in optimization model

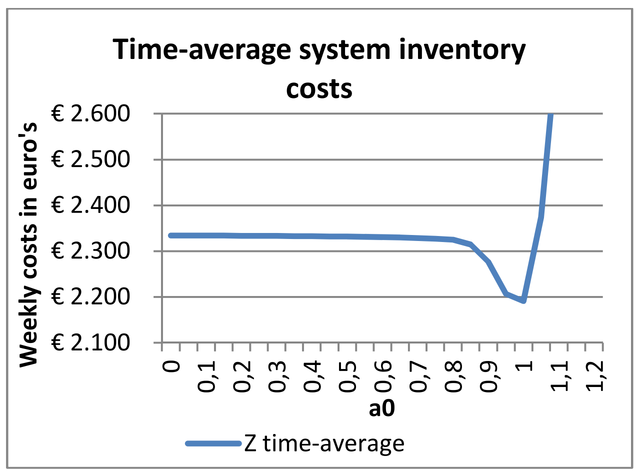


Figure 25: Graph $\bar{Z}(\Delta_0)$ in optimization model

Second, the used optimization procedure will be validated. In this procedure the inventory cost function related to the inventory level just before arrival of a replenishment order is used instead of the time-average inventory cost function. In section 4.3.4 this optimization procedure was described including two graphs made based on an example of Van der Heijden (2000). For Model 2 similar graphs can be derived, as given in the figures below. Here can be seen that both cost functions have a similar shape, and further checking resulted that both functions have their minimum cost value around the value of $a_0 = 0.98$. Thus, the optimization procedure with making use of the different cost function is also validated.

6.5 Sensitivity analyses

In this chapter sensitivity analyses will be made for different input parameters, in which a cost comparison is made between the echelon and local control model. The current control model is not included in the sensitivity analysis because in this model the inventory levels can only change linearly when customer demand is varied. Moreover, some more detailed results will be presented for the echelon control model to see the influence of the different input parameters on the location of the inventory in the supply chain.

In the next sections the sensitivity analyses will be discussed. Some analyses will be presented analytically, others will be explained with figures. Note for every sensitivity analysis only the value of the mentioned parameter(s) varied in the given range, the others are kept equal to their start values. The black column in all graphs below refers to the original value of the input parameter. Note that the height of this column gives no indication of the outcome with the original values, but the original outcomes can be found at the intersection point of the black column with the lines in the graphs.

6.5.1 Fill rate at upstream stock point

First, the sensitivity of the fill rate at the upstream stock point will be described analytically. This fill rate is only used within the local control model, so it will only influence these results. The direct impact of a decrease in fill rate at the upstream stock point is that the order-up-to level and correspondingly the on-hand inventory level at this stock point will decrease, due to the direct influence in formula (9; section 4.4.2) of β_i on S_i. However, the expected shortages during a replenishment cycle ($ESPRC_0$) will increase due to the decrease in S_0, causing an increase in $E[W_0]$, and therefore an increase in the order-up-to levels and on-hand inventory levels at the end stock points will be seen (see also formulas (42) and (43) in Appendix L).

6.5.2 Customer fill rate

In contrast to the sensitivity of the upstream fill rate, the customer fill rate also influences the outcomes of the echelon control model. Analytically, in the echelon control model the supply chain inventory level should raise when the customer fill rate increases, because of the high customer service which has to be attained. Therefore, also the supply chain costs will increase. Interesting here is the decision about where to place the extra inventory in the supply chain. The upstream holding costs are lower than the downstream holding costs. Therefore, part of the extra supply chain inventory needed for an increase in the customer fill rate will be placed at the upstream stock point. However, as can be seen in Figure 43 (see Appendix R) the increase in the inventory levels at the end stock points is greater than the increase in the upstream stock point inventory level. This is because a higher inventory level is needed close to the customer to attain the increased customer fill rate.

In contrast, in the local control model only the end stock points will be influenced, because the required order-up-to level at the upstream stock point is determined based on customer demand, upstream stock point fill rate, and the upstream lead time, which will all not change. Therefore, there will be no influence on the upstream stock point. However, all effect of a change in the customer fill rate is on the end stock points. A higher customer fill rate will result in an increase in the order-up-to level and correspondingly in an increase in the on-hand inventory level at the end stock points. All increase in supply chain inventory will be at the end stock points. Therefore, there will be a bigger increase in on-hand inventory level compared to the echelon control model.

6.5.3 Holding cost factor

Within the echelon control model there is a cost minimization approach. Therefore, the effect of the ratio factor between upstream and downstream holding costs on the inventory results of this echelon control model will be interesting to see. In this sensitivity analysis the cost increase in echelon control is much lower for a cost increase in module holding costs than for the local control model (see also Figure 44 in Appendix R). The reason for still having an increasing slope in the line for high upstream holding cost values is that the production lead time is also valued based on the upstream holding costs h_0, and the number of units in this part of the supply chain does not change due to the change in holding costs for the echelon control model. This can be seen in Figure 26.

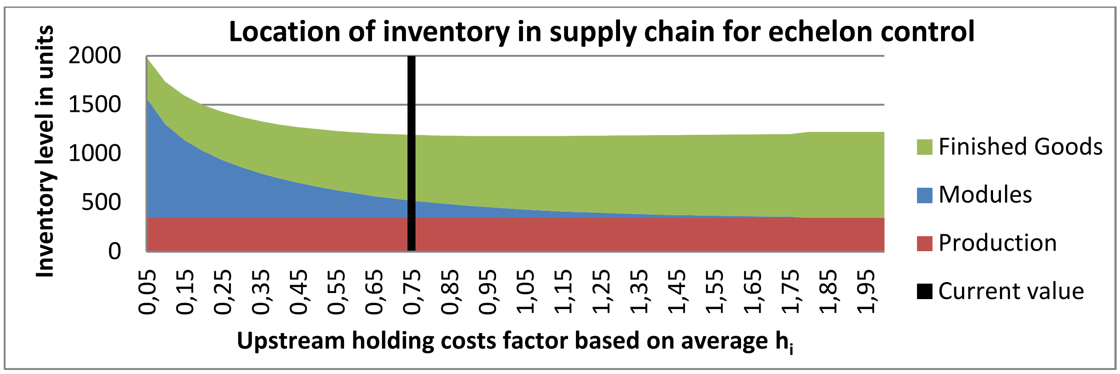


Figure 26: Sensitivity of location of inventory in supply chain on upstream holding costs for echelon control for Model 2

In this graph can be seen that by increasing the upstream holding costs (compared to the downstream holding costs) the inventory level at the module side of the supply chain decreases very rapidly. Moreover, when the upstream holding costs are 1.80 times the average downstream holding costs or higher (remember that the holding costs at the end stock points varies between €92.38 and €123.59), there are lower cost results for the situation of zero on-hand stock at the upstream stock point 0. The change from having upstream inventory to having no upstream inventory has to deal with the optimization procedure as described in section 4.3.5, where the lowest cost result is chosen between the boundary point of $a_0 = 0$ and the local optima around $a_0 = 1$. This is visualized in Figure 27 below.

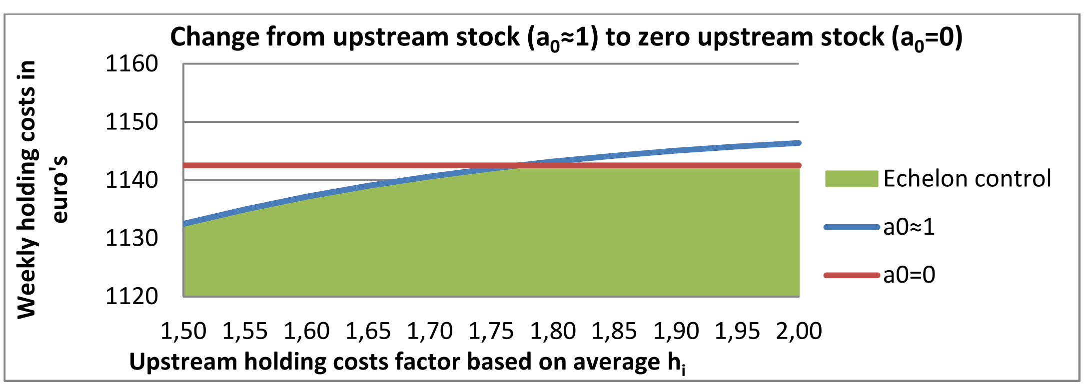


Figure 27: Change in having upstream inventory ($a_0 \approx 1$) to having no upstream inventory ($a_0 = 0$) for echelon control based on the optimization procedure as described in section 4.3.4

In contrast to Figure 26 where the inventory levels in units are presented, in Figure 27 the supply chain holding costs are plotted. Therefore the supply chain holding costs are constantly increasing, while the supply chain inventory level is almost constant. Note that only the value of the upstream holding costs changed, in relation to the holding costs at the end stock points. Therefore, the cost outcome for $a_0 = 0$ does not change based on the change in upstream holding costs.

6.5.4 Upstream lead time

Next, the sensitivity of the upstream lead time is tested. Note that the in-transit inventory during this upstream lead time will change linearly with a change in the upstream lead time, but is not included in the supply chain inventory level. Therefore, the supply chain inventory level is only affected by the change in variability of demand during the upstream lead time. Thus, in both the echelon and local control model an increase in upstream lead time will lead to an increase in supply chain inventory. Due to the service level constraint at the upstream stock point in the local control model, in this model all extra inventory will be placed at the upstream stock point. In contrast, in the echelon control model both the inventory at the upstream stock point and at the end stock points will raise. However, the increase in supply chain inventory level for both control models is almost similar. Nevertheless, due to the decision about where to place inventory the echelon control model performs better (see Figures 45 till 47 in Appendix R).

6.5.5 Production lead time

The effect of production lead time on the control model results is straightforward. An increase in this lead time will lead to a raise in the in-production inventory, which is linear to the increase in lead time. Moreover, the inventory levels at the upstream stock points will increase slightly, due to an increasing variability in demand during lead time. These results are similar for the echelon and local control model.

6.5.6 Customer demand

Next, there is the sensitivity analysis for the variability in customer demand. This variability is expressed by the coefficient of variation in customer demand. The current values for this coefficient of variation are: 0.988, 0.261, 1.155, and 0.268 for FG 1 till 4, respectively. In this sensitivity analysis these current values are multiplied by a factor, which is varied, and can be found on the x-axis of Figure 28 below. Note that the average customer demand is kept constant, such that the standard deviation changed.

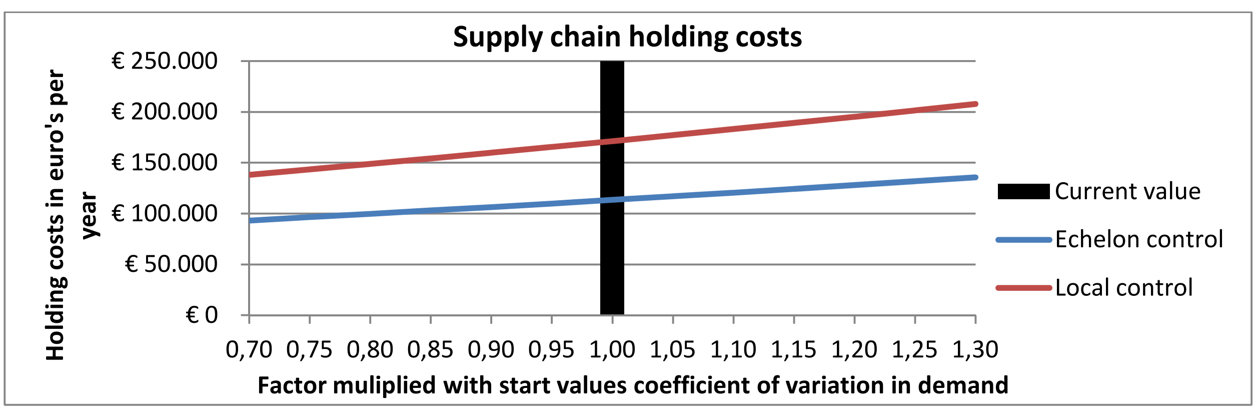


Figure 28: Sensitivity of supply chain holding costs on coefficient of variation in customer demand for Model 2

In this sensitivity analysis there can be seen that the effect of customer demand variability is bigger for the local control model than for the echelon control model. Interestingly, most of the extra inventory in the local control model needed to cope with a higher coefficient of variation is placed at the upstream stock point (see Figure 49 in Appendix R). This is because the upstream stock point has already to attain a fill rate, and due to the increase of demand variability and the long upstream lead time, most of the extra inventory will be placed at the upstream stock point. In contrast, in the echelon control model the module inventory level changes, but the changes in FG inventory level is bigger (see Figure 48 in Appendix R). This looks surprisingly because of the lower upstream holding costs, but the increase in supply chain inventory in the local control is much higher than the increase in supply chain inventory in the echelon control model, when the customer demand variability increases.

Next to the sensitivity in demand variability, it is important to check what the effect is of a change in the average customer demand. In order to test this, first the order-up-to levels were determined for echelon and local control model based on the start input values as provided in Appendix N ('forecasted demand'). Then, the performance of both control models was evaluated when the there is a long-term increase or decrease in the mean customer demand of 5% for all finished goods ('actual demand'). Analysis showed that a relatively small increase in customer demand has a big effect on the achieved fill rate in the echelon control model (between 70% and 75% only) due to very low inventory levels, while a decrease in customer demand of 5% lead to a cost raise of approximately 40%, but with fill rates of more than 95%. In contrast, the effects on the performance of the local control model were less, but still significant with for example a cost increase of 24% when customer demand decreased with 5%. Here the effect of a changing standard deviation was only marginal. Thus, long-term changes in actual customer demand have a big influence on the supply chain performance, especially in the echelon control model. Note that short-term changes are reflected in the standard deviation of demand.

6.5.7 Sensitivity analyses of varying two input parameters simultaneously

Last, twice a sensitivity analysis is performed in which the value of two input parameters is varied simultaneously. This is done for the holding cost factor and the customer fill rate (see Figure 29), and for the holding cost factor and coefficient of variation in customer demand (see Figure 30).

In both graphs there can be seen that the cost lines are rising when the holding cost factor increases, but with a decreasing slope. Additionally, the larger the holding cost factor, the larger the differences between the customer service-lines and coefficient of variation-lines. Moreover, from Figure 30 can be concluded that relatively the effect of an increase in the coefficient of variation on the supply chain holding costs is higher than the effect of the module holding cost increase. In contrast, the effect of the customer service level when varied between 85% and 95% is more equal to the effect of the increase in holding cost factor. Note that these results are heavily dependent on the ranges considered in the sensitivity analysis, so these graphs only provide an indication of the sensitivity effects.

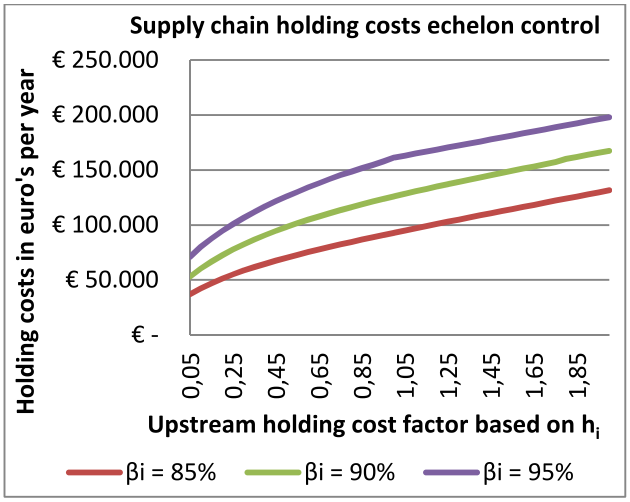


Figure 29: Sensitivity of supply chain holding costs on holding cost factor with different customer fill rate values in echelon control for Model 2

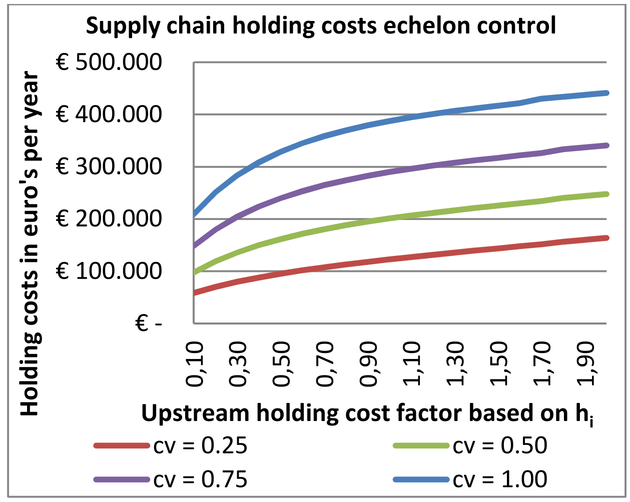


Figure 30: Sensitivity of supply chain holding costs on holding cost factor with different coefficients of variations in customer demand in echelon control for Model 2

6.5.8 Conclusion

An interesting point in the sensitivity analysis of the holding cost factor is that when the module holding cost are much higher than the FG holding costs (a factor of 1.80 or higher) the point of having no upstream stock is reached. This shows well the decision made in the optimization procedure of comparing the cost outcomes when having upstream stock with the case of having no upstream stock (see also Figure 27). However, in practice this point is not reached (the factor is approximately 0.75), and, moreover, it does not happen often in reality that upstream holding costs are higher than downstream.

Another conclusion that can be drawn is that the supply chain inventory level changes, in general, less in the echelon control compared to the local control model. Here, the advantage of the echelon control model is shown by making decisions based on both the holding cost difference between upstream and downstream with the customer fill rate that has to be attained. In the local control model in most of the cases only one of the locations (modules or FG stock points) has to absorb the change in the input parameters, having a bigger effect of the total supply chain inventory level and cost result.

Regarding the supply chain inventory levels, there can be concluded that the holding cost values have almost no influence, because still the same customer demand with the same variability has to be satisfied under the same customer fill rate. Only for really low upstream holding costs the supply chain inventory level raises, because due to the big holding cost difference less inventory will be held downstream, but upstream more units are needed to cover the extra demand variability during lead time between downstream and upstream stock points.

Moreover, changing customer fill rate leads to an almost exponential change in the supply chain inventory level, where changing the upstream lead time has smaller changes to the supply chain inventory level. Note that the inventory in-transit from the external supplier to the upstream stock point changes linearly with the changes in average upstream lead time, but this in-transit inventory level is not included in the supply chain inventory level due to its large quantity. This linear increase in in-transit inventory is similar to what can be seen in the graph related to the sensitivity analysis of the average production lead time (see Figure 46). Last, changing the variability in customer demand has, relatively, the biggest effect on the supply chain inventory level, because still the same fill rate has to be fulfilled. This result can also be derived from the sensitivity analyses of two input parameters, as provided in 6.5.7.

6.6 Extension: variability in upstream lead time

Next, the extension of having variability in the upstream lead time will be investigated. In practice, the variation in upstream lead time is not very high. Therefore, there is chosen to vary the standard deviation of the upstream lead time between 0 and 5 weeks. Note that the mean of the upstream lead time is 10 weeks. Results of this analysis are given in Figure 31.

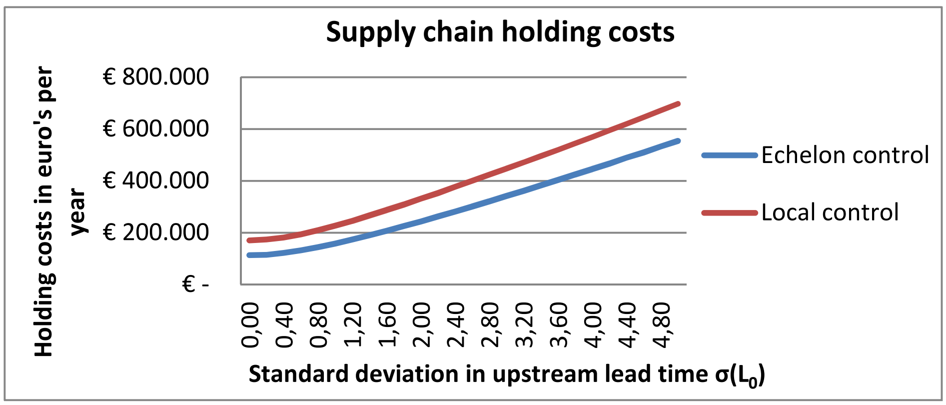


Figure 31: Sensitivity of supply chain holding costs on standard deviation in upstream lead time for Model 2

From this graph there can be concluded that there is a significant effect of upstream lead time variability on the required inventory levels and on the corresponding supply chain holding costs. Moreover, an increase in the variability in lead time has a slightly bigger impact on the local control cost results than on the echelon control cost results. This is again caused by the cost minimization approach in the echelon control model with the decision about where to locate the inventory.

7 Conclusions and recommendations

This last chapter starts with a conclusion and discussion of the whole project, followed by limitations and further research, and some findings for science. Last, recommendations for Ricoh will be given.

7.1 Conclusion and discussion

The main research question to be answered in this project was: Which cost savings can Ricoh obtain when their inventory levels in Europe for the RIF product range are centrally controlled for a given product availability target under the limitations of the chosen model, and how can these cost savings be fairly allocated to RIF and RESCM? To answer this question, five sub-questions were defined (see section 2.3.2).

The first sub-question was related to the identification of the key KPIs related to inventory levels and product availability. Chapter 3 resulted in three key KPIs: (1) inventory level expressed in number of weeks of forecasted customer demand; (2) product availability expressed as the percentage of PDSO that is covered by FG stock at RESCM; and (3) forecast performance expressed as the forecasted demand in percentage as the actual demand. Within the optimization model product availability was captured as the fill rate towards the customers.

Based on these identified KPIs the current supply chain performance over the period August 2011 till February 2012 was analyzed. Here, data analysis showed that for most of the analyzed models the inventory level was way above target. Only Model 4 showed inventory levels below target, where the low inventory levels caused product availability issues. Moreover, the forecast performance was very low, with in general much more forecasted demand than what the actual demand appeared to be. A possible cause is that sometimes the number of sales (based on the actual shipment date to the customer) was forecasted instead of the customer demand (based on the order request date of the customer). Thus, as an answer to the second sub-question, often inventory level and forecast performance targets were not reached (the target were according to the current values of RESCM).

Next, within the optimization model three different control models were introduced: current control, local control, and echelon control. The current control model is based upon the targets currently held by RESCM. However, as mentioned above, in the current supply chain performance these targets were not met, mostly by having higher inventory levels than the targets suggest. Therefore, savings in holding costs are possible when the supply chain performance is in accordance to their inventory targets set.

The second control model introduced was the local control model. This model has a decentralized decision making approach, with a periodic review order-up-to policy at each stock point. The main advantage of the local control model over the current control model is that the order-up-to levels and the resulting time-average inventory levels are for the local control model fully based on the demand characteristics (mean and standard deviation), while in the current control model the inventory levels and order-up-to levels are only based on the mean customer demand. Sensitivity analyses showed that inventory levels are really dependent upon the coefficient of variation of customer demand, indicating that the local control model, in general, provides better results than the current control model due to the inclusion of customer demand variability in the calculations.

Last, in the echelon control a centralized decision making approach was introduced. In the echelon control model the two independent replenishment processes as described in section 1.5 and Figure 5 will be connected. From the results there can be concluded that the echelon control model has lower cost results compared to the the local control model for the cases analyzed. This is achieved by having a central decision maker with access to all required information, creating full visibility in the supply chain, and removing the delay in information in the supply chain in local control caused by the periodic review. Moreover, the cost minimization approach in the echelon control model provides the opportunity to decide upon the location of inventory in the supply chain, based on both the holding costs at the different stages and the customer fill rate which has to be attained. Especially when variability (demand and/or lead time) in the supply chain raises the echelon control model performs better than the local control model in terms of supply chain holding costs.

When comparing the inventory level results of the local and echelon control model with the current control model, there can be concluded that the upstream inventory level in the local control model is higher than the inventory level target as used in the current control model, while the inventory level for finished goods is much lower than the target of 2.7 weeks as currently used. In contrast, the echelon control model suggests a larger part of the inventory at the end stock points, due to the small difference in upstream and downstream holding costs. This is similar to results of Van der Heijden (2000), who concluded that most of the stock should be kept local even when there is some difference between upstream and downstream costs. Only in case of large difference between upstream and downstream holding costs more stock will be placed at the upstream location. The small amount of stock kept upstream is mostly to cover variability in customer demand during the long upstream lead time, and to keep flexibility in production of different types of finished goods.

As shown in the sensitivity analysis of the holding cost factor, when the upstream holding costs are much higher than the downstream holding costs, there is no reason anymore to keep upstream inventory, even when the upstream lead time is long. This is similar to results in literature (see Van der Heijden, 2000), and shows nicely the cost-based choice in the optimization procedure between having and not-having upstream inventory. Thus, when moving from the local control to the echelon control model for both parties, the largest part of the supply chain where inventory is located changes from upstream to downstream. Therefore, the costs RIF makes in the echelon control are much smaller than the costs in the local control model, while the holding costs increases for RESCM. This is where cost allocation comes into play.

In the game theory literature different allocation rules are proposed. However, because there are only two players in this game (RIF and RESCM), the Shapley value, nucleolus, and cost gap allocation all result in the same allocation proposal: splitting the supply chain cost savings for both parties. In case of moving from the local control to the echelon control model, this allocation rule ensures that both players do not have the inventive to leave the grand coalition of cooperation, making the allocation proposal part of the core of the game. In the proposed echelon control model the problem of lack of information sharing will be solved. A possible problem of the echelon control model is, as also identified by Larsen et al. (2003), sharing of valuable information with other parties. Already during this research this problem occurred, requiring the assumption made in relation to the product value of modules. For the local and current control model the information sharing is limited, which should not give a problem regarding the confidentiality of the shared information. Note that the last sub-question about the information shared in the echelon control model will be answered in the recommendations section.

To answer the main research question as introduced in the beginning of this section, in the echelon control model significant cost savings can be obtained compared to both the local and current control model. This is similar to results of Axsäter and Rosling (1993), who concluded that echelon control is more cost-effective than installation stock policy (local control policy). Moreover, the echelon control model solves some causes for the identified low supply chain performance by solving the problem of unclear inventory target setting in the way of not-using the targets anymore, the problem of independent replenishments by combining both replenishment processes, and the problem of lack of information sharing by exchanging all required information with a central decision maker. The problem of hard machine forecasting is partly captured in the customer demand sensitivity analysis, where was shown that the effect of long-term changes in customer demand significantly influences the model performance. Allocation of these cost savings is proposed as splitting the supply chain cost savings between both parties.

7.2 Limitations and further research

In the local control model a major difficulty was the determination of the customer demand characteristics at upstream stages and the determination of the delay time characteristics, especially for periodic review policies (Diks et al., 1996). For simplicity Little's law was used to calculate the expected delay of downstream order due to shortages at the upstream stock point, but this resulted in some approximation error. Therefore, a first limitation is the use of Little's law for dealing with delay time characteristics. Moreover, the use of Little's law together with the small lead time between upstream and downstream stock locations made the upstream inventory levels not dependent enough from the delivering capability of the upstream stock point as might be expected. Therefore, further research in this area should include better approximations for the delay in the local control model.

In the echelon control model difficulties in relation to imbalance come into play (Diks et al., 1996). The use of a simple variant of the balanced stock rationing rule is a limitation in this analysis, because it works not properly in case of big difference in variance and average customer demand between different end stock points (Van der Heijden, 2000). Therefore this analysis resulted in relatively high inventory levels for the items with low average demand, but with a high coefficient of variation of customer demand. This can be improved in further research by making use of, for example, the 'complete' balanced stock rationing rule instead of the simplified version of the rule (see Van der Heijden et al., 1997). Moreover, a different allocation rule was used in echelon and local control. This is another limitation in relation to the rationing rule. In further research this can be improved by using the same allocation rule for both control models.

Also uncertainties are important in the results of the different inventory control models. In general different kinds of sources of uncertainty along the supply chain have to be taken into account: demand (volume and mix), process (yield, machine downtimes, and transportation reliabilities) and supply (part quality, delivery reliability). Enough inventory has to be used to protect the chain from these uncertainties (Lee & Billington, 1993). However, only some of these uncertainties are taken into account in this research. For example, machine downtimes and part quality are not taken into account, with can be included in the models for further research. Moreover, for customer demand the same demand was used to evaluate the supply chain performance as was used to determine the order-up-to levels. Sensitivity analyses showed the big influence of small a long-term change in average customer demand on the model performance. Therefore, a limitation is the sensitivity of the model performance to demand fluctuations.

Another limitation has to deal with the optimization procedure in which the value of Δ_0 was determined by minimizing the cost at the end of a replenishment cycle instead of time-average during replenishment cycle. However, as mentioned in the model validation (section 6.4), deviations will be small, but for further research the optimization can be improved by determining the value of Δ_0 with the time-average cost function.

In this research, the only cost parameters considered in the cost minimization was holding costs. However, in practice, another important cost factor at the European factories is elated to production flexibility. Upgrading or downgrading of production is very costly, because of hiring and firing of employees, and the learning curve of new employees. Therefore, the factory tries to keep the production as stable as possible. This may require some higher inventory levels of modules at the factory. Therefore, in further research in should be investigated whether production schedules can be combined with the echelon inventory control model.

A last limitation is related to the several approximations used in the formulas of the control models. The formulas as adapted from Van der Heijden (2000) are due to the approximations near-optimal. Therefore, some approximation errors may have occurred in this analysis. In further research possibly more exact equations can be created.

In further research the two-echelon supply chain could be extended into a three-echelon or bigger supply chain. For Ricoh a three-echelon supply chain is required for analyzing an echelon control model including the Asian factory. Here, the inventory levels before and after production at the Asian factories can also be taken into account, while in the two-echelon model the Asian factory is only considered as an external supplier. However, Asian factories have more customers than Ricoh Europe, thus this will complicate the supply chain model.

Another possible extension in further research is to include all raw materials required at the assembly at RIF instead of only including the plotter and assuming that the there is sufficient stock for the other raw materials when there is sufficient stock for the plotter. This will create a network structure of the supply chain and will add more uncertainty into the supply chain model. Therefore, most likely, higher raw material inventory levels are required. Moreover, a delivery performance of the Asian factories which is not equal to 100% can be added to the model, which will also create more uncertainty in the supply chain, requiring higher inventory levels.

7.3 Findings for science

This research showed a comparison between local and echelon controlled two-echelon divergent supply chain, which has also been done by other researchers (see e.g. Axsäter & Rosling, 1993). However, here a periodic review order-up-to policy under service level constraints is investigated for both echelon and local control. In addition to the echelon control model as proposed by Van der Heijden (2000), variability in upstream lead time is added to the model. This factor had a big influence on the required order-up-to levels.

Last, due to the combination of a local and echelon controlled model, a cost allocation proposal could be made about how to divide the costs made jointly in the echelon control model. In this way for both parties an incentive will be given for participate in the echelon controlled supply chain.

7.4 Recommendations for Ricoh

Based on the results as presented in chapter 6 the use of the echelon control model is recommended to Ricoh. This requires Ricoh to move to a less-functional and more process-oriented organization throughout the supply chain (Larsen et al., 2003). To deal with the joint cost results of the echelon control model a cost allocation rule is required, because otherwise the cooperation will not be beneficial for RESCM.

Moreover, information sharing is required in the echelon control model. More specifically, in the echelon control model RIF should share information related to the review period, lead time, and holding costs with the central decision maker, where RESCM should share this information complemented with information about the customer fill rate and customer demand (both mean and standard deviation). The use of a central decision maker requires a change in the organizational structure of Ricoh, where this decision maker will have an important role. Here, this decision maker needs to have sufficient knowledge regarding inventory control in a supply chain environment, together with specific information concerning processes within RIF and RESCM and in the pipeline. Moreover, RIF and RESCM have to agree in, for example, a contract that they will accept and execute the outcomes of the calculations made by the central decision maker. In the local and current control model less information has to be shared (see Figure 16 in section 4.1).

In practice problems can occur in sharing all of this information in the echelon control model, due to the unwillingness to share all information, mostly in relation with confidentiality of this information. A solution can be that both parties agree on the holding cost components and calculation method, and only share the end result of the holding costs (where the product value cannot be directly derived from). Moreover, Ricoh can use another party (next to RIF and RESCM) as a central decision maker in the process, for example the L21 department located at Ricoh Japan. This central decision maker would then determine the order-up-to levels in the echelon control model based on all values for the input parameters. Then RIF and RESCM should agree in contracts to share the true information to this decision maker. A way to incorporate the echelon control policy in the current business at Ricoh is to implement this control mechanism in DPSIM, and make directly the relation between the replenishment process of modules and the replenishment process of finished goods. In the current situation there is no relation between these two replenishment processes within DPSIM (see Figure 5 in section 1.5).

A recommendation to both RESCM and RIF in general is that the current inventory targets (5 working days of modules and 2.7 weeks of finished goods) should not be set as general as they are set now. For products with low coefficient of variations the targets are too high, while for products having a coefficient of variation of approximately one, 2.7 weeks of finished goods' inventory is only a little bit too high. So Ricoh should not base the target inventory levels only on expected or average customer demand, but should include variability in their inventory control. However, Ricoh has to be careful in using the low inventory levels as suggested by the echelon control model, due to the big sensitivity of the performance on long-term changes in customer demand, as mentioned before in the limitations (see section 7.2). Here, forecasting remains very important in the supply chain performance. Historical data analysis showed a bad forecast performance (see section 3.2). Therefore, before implementing the echelon control model as proposed in this research, Ricoh has to improve their demand forecasting to be able to use the inventory levels as suggested by the echelon control model and still perform according to their targets. Moreover, forecasts should be updated at the end of every replenishment cycle (thus on a weekly level).

Regarding to product life cycle (Kotler & Keller, 2006), for machines in the mature phase, the mean and standard deviation can be determined based on historical demand data. However, in the introduction phase of the product life cycle the average customer demand should be based on marketing predictions and production introductions of related machines in the past. For the growth and decline phase of the life cycle a factor should be applied on the historical demand data to cover to growth or decline. Additionally, the demand forecast should be updated very frequently to respond quickly to demand changes. So, for products not in a mature phase Ricoh has to be more careful in their inventory control.

The echelon control model is also applicable to other types of machines of RIF, to the machines assembled in RPL in the UK, and for other items ordered via the European factory, when the European factory orders this item at a Ricoh supplier. However, no correlation in demand is considered in the model, which may be an important effect in practice for options used in the configuration (customization) process of machines. Adding correlation of demand will influence the impact of demand variability on the required order-up-to levels. For items ordered by the European factory at suppliers outside the Ricoh Company it may be difficult to adopt the echelon control model, because a lot of valuable information would have to be shared with a central decision maker.

Last, this echelon control model can also be applied for machines ordered directly by RESCM at Asian factories. In that case the assembly process will take place at RESCM location instead of a European factory. Due to the assumption that the FG stock points at RIF and RESCM are combined (and thus the transportation time between RIF and RESCM is neglected), a similar supply chain model can be used. However, here implementing this strategy will be less difficult because the same party takes case of the whole part of the considered supply chain. Therefore, a cost allocation proposal is not required.

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Appendix A List of figures

Appendix B List of tables

Appendix C List of abbreviations

Abbreviation	Explanation
ARDF	Automatic Reversing Document Feeder
BTO	Built-To-Order
DPSIM	Daily Purchase Sales Inventory Monitoring
EDC	European Distribution Centre
EDP	Product identification code
EMEA	Europe, Middle-East and Africa
ESPC	European Service Parts Centre
FC	Forecast
FG	Finished Goods
KPI	Key Performance Indicator
LT	Lead Time
OpCo	Operating Company, otherwise called local sales organization
PDSO	Past Due Sales Order: orders with a request date of the customer in the past
PSI	Purchase Sales Inventory
RESCM	Ricoh Europe Supply Chain Management
RIF	Ricoh Industrie France S.A.: European factory of Ricoh in Colmar, France
RINKS21	Information system used for production planning at the European factories
RPL	Ricoh UK Products Ltd: European factory of Ricoh in Telford, UK
SCM	Supply Chain Management
SMO	Strategic Management Objective
SRI	BTO satellite at RIF factory in France
SUK	BTO satellite at RPL factory in UK

Table 6: Abbreviations used in report

Appendix D List of definitions

Term	Definition
Active item	An item which is purchasable, sellable and shippable for RESCM
Available stock	Part of the total stock having not an 'on hold'-status, which means that it can be sold
Configuration	Process where machines are customized
FC performance	Actual customer demand as a percentage of the forecasted customer demand for a certain month
Final assembly	Process where finished goods boxed products are assembled from modules
Final mile	Last part of the supply chain covering transportation from local hub towards end-customers in the country of destination (OpCo's responsibility)
Finished goods (FG)	Machines configured according to customers' requirements, which are shipped towards the end customers
Finished goods (FG) boxed product	Finished goods without configuration. These goods are shipped to configuration centers or directly towards the end customers
L21 department	Department within Ricoh Japan responsible for the logistical operations in the global supply chain
Local hub	Location in the supply chain from which the products are delivered towards the end customers.
Model	Group of machines originating from the same module
Modules	Basic products (machines) before their final assembly at the factories. Every module belongs to one product family.
Options	Products added to machines during the configuration process
Platform	Location in the supply chain from which the products are delivered towards the end customers. In this report called local hub.
Product availability	The percentage of PDSO that is covered by available FG stock at RESCM
Product family	Group of products consisting of different related modules, and having the same family name
Ricoh Japan	Global headquarters of Ricoh, located in Tokyo, Japan
RIF product range	Range of products having their final assembly at the factory RIF
Satellite	Stock location of RESCM used next to the main stock location EDC
Sales data	Sales data refer to the shipment data of goods to the customers

Table 7: List of definitions

Appendix E Cause-and-effect diagram as used in problem definition

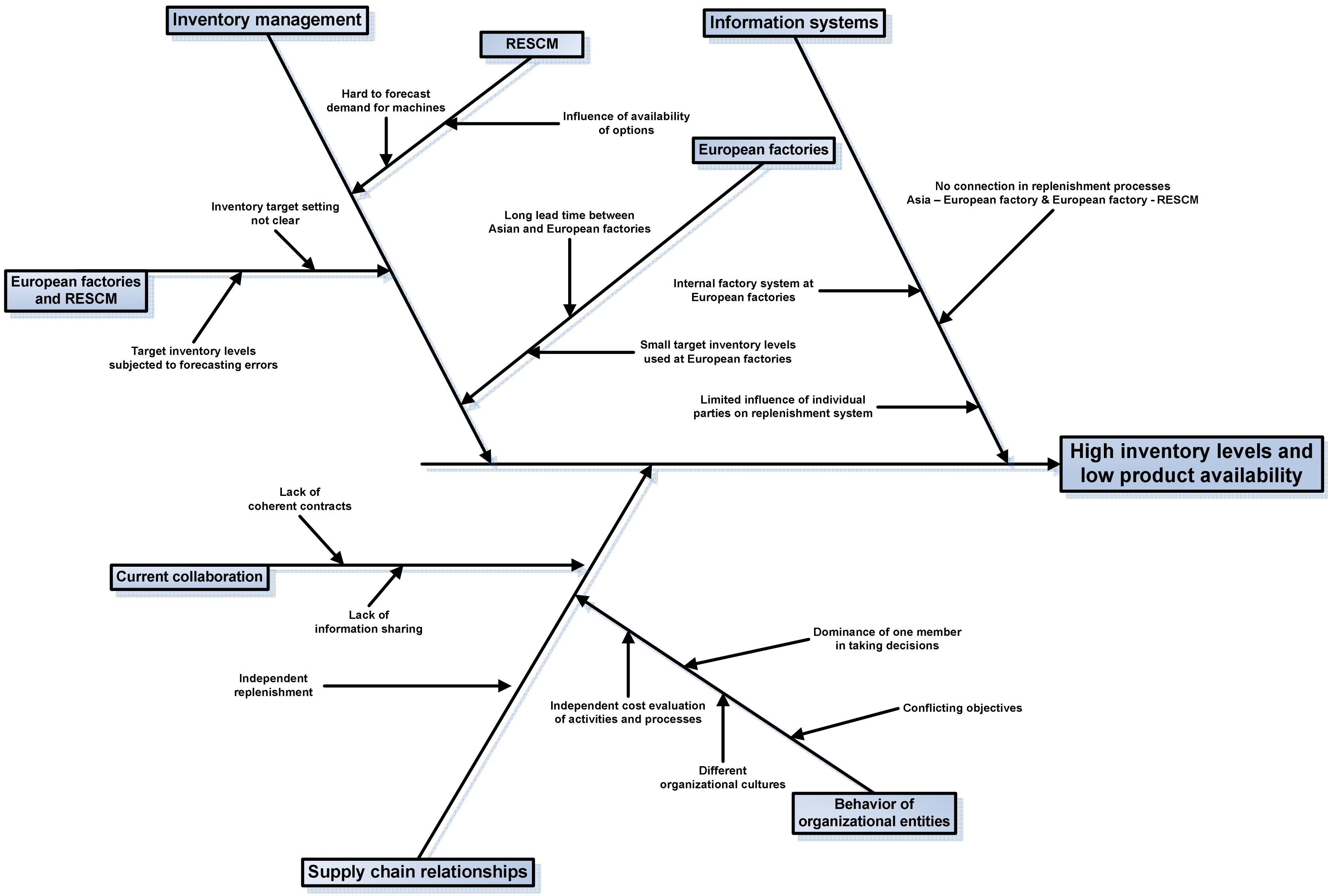


Figure 32: Cause-and-effect diagram for research problem, based on the format created by Ishikawa (1990)

Appendix F Key performance indicators

KPI	Dimension	Target	Explanation
Inventory level	Number of weeks of forecasted customer demand by RESCM	• *FG at RESCM:* 2.3 weeks • *FG at RIF:* 0.4 weeks • *Modules at RIF:* 1 week	The order quantities at RIF are based upon the forecasted demand by RESCM 3 months in advance, to cover the long lead time for the modules arriving at RIF. Inventory levels are the result of this forecasted demand 3 months in advance. Therefore this inventory level measure should be based upon forecasted demand made 3 months earlier.
Product availability	Percentage of PDSO covered by available FG stock at RESCM	95%	Percentage of the PDSO (Past Due Sales Orders; orders with a request date of the customer in the past) that is covered by available stock at RESCM. This measure is used to only include customer performance related to product availability, and to not include other causes that can influence the delivery performance at the customer, more downstream in the supply chain (think about problems in customization and transportation to the customer)
Forecast (FC) performance	Actual customer demand in percentage of the forecasted customer demand	≥ 95% and ≤ 105%	Compares the actual demand of FG boxed products for a month with the forecasted demand for that month, for fixed months. For the forecasted demand, the forecasted demand made 3 months in advance are taken into account to cover the total lead time from the Asian factories to RESCM.

Table 8: Identified key KPIs

These three KPIs will be determined with the following formulas:

$$Iventory\ level = \frac{Inventory\ level}{Forecasted\ customer\ demand\ for\ 1\ week}$$

$$Product\ availability\ \% = \frac{Available\ stock}{PDSO}$$

With PDSO = sum of all orders with a request date in the past, at a point in time (in units)

$$FC\ performance\ month\ N\ (\%) = \frac{Total\ customer\ demand\ in\ month\ N}{Total\ forecasted\ demand\ for\ month\ N}$$

Appendix G Product hierarchies

For confidentiality, in the figures below the finished goods (bottom of the product hierarchy diagram) are numbered.

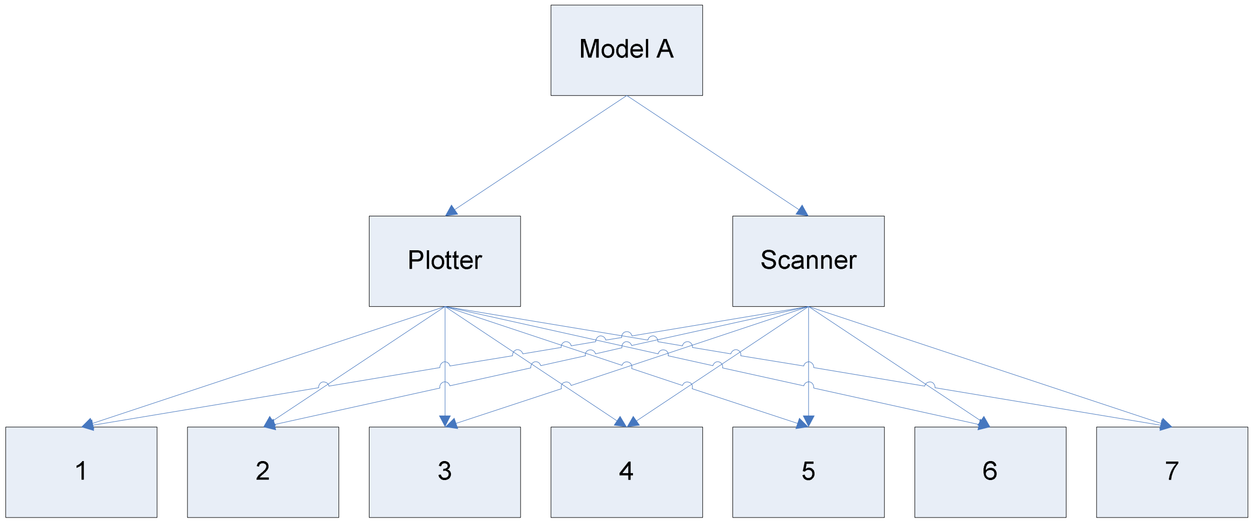


Figure 33: Product hierarchy Model 1

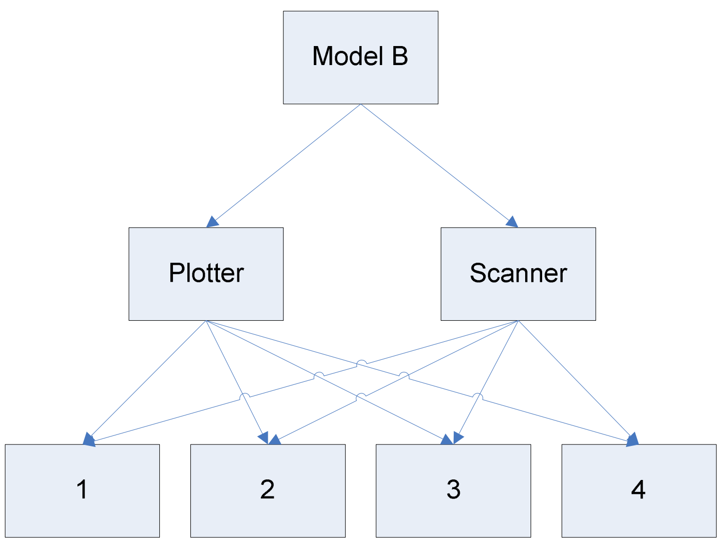


Figure 34: Product hierarchy Model B

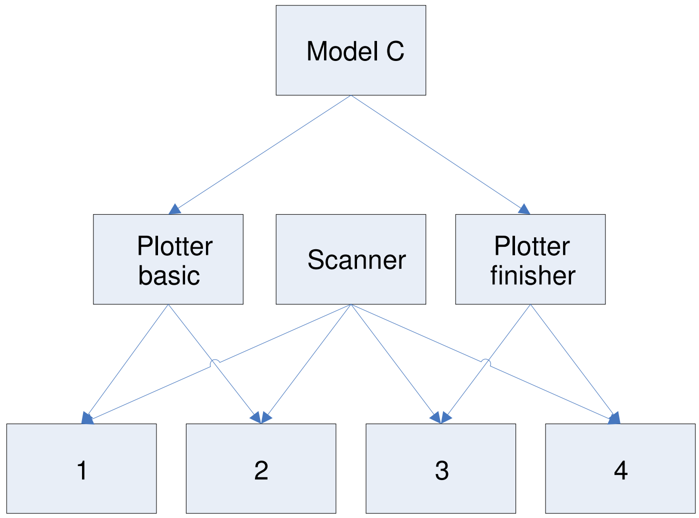


Figure 35: Product hierarchy Model 3

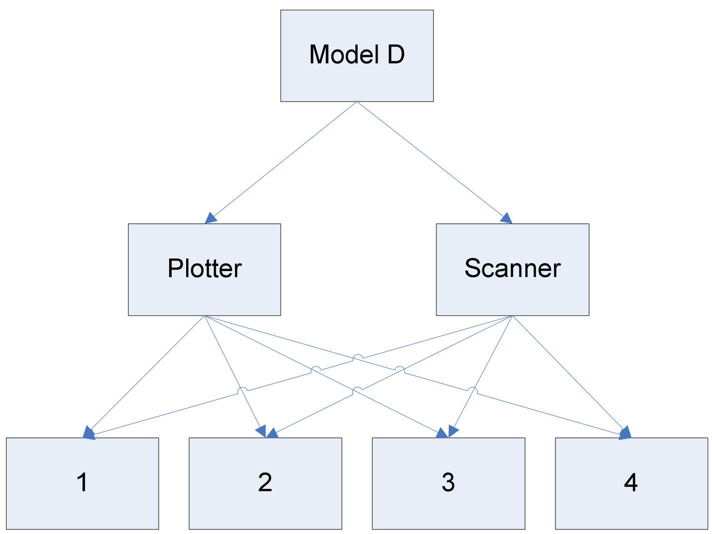


Figure 36: Product hierarchy Model D

Appendix H Supply chain performance

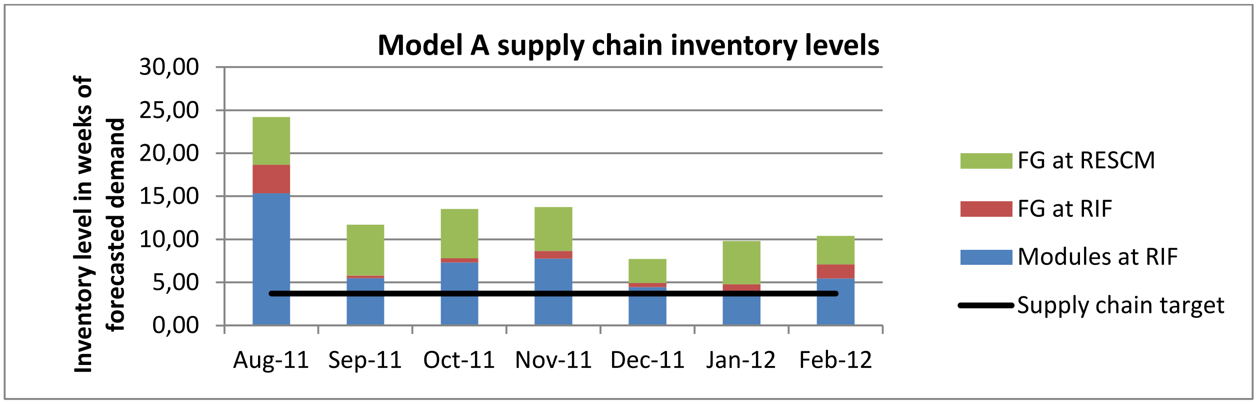


Figure 37: Supply chain inventory levels for Model A with plotter considered as module

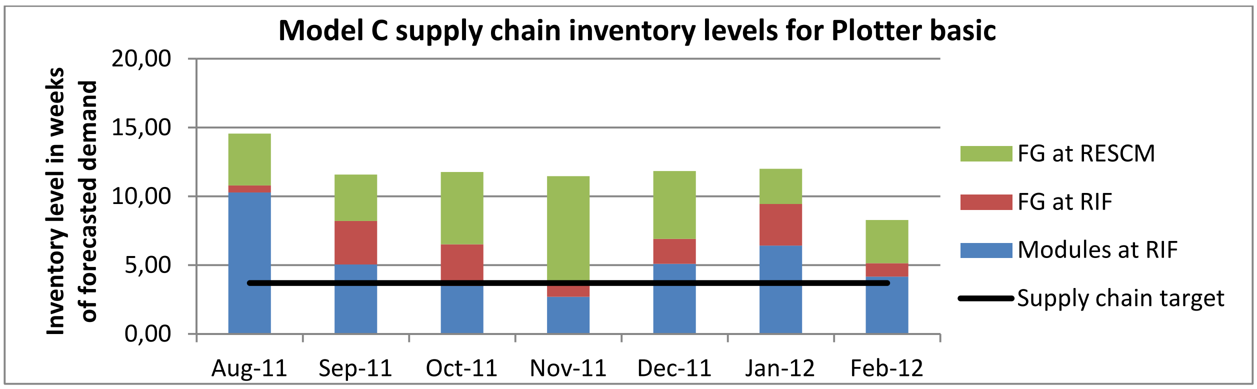


Figure 38: Supply chain inventory levels for Model C with Plotter basic considered as module

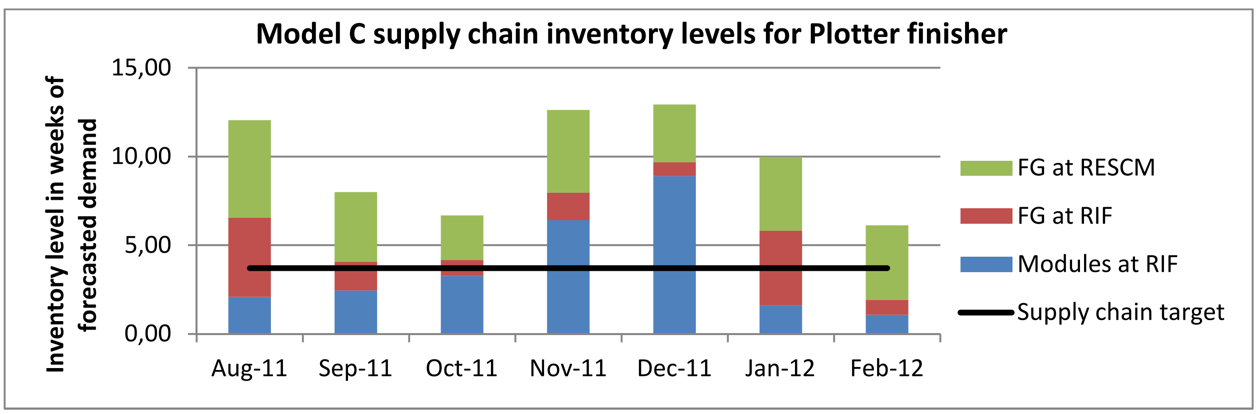


Figure 39: Supply chain inventory levels for Model C with Plotter finisher considered as module

Table 9: Inventory level performance. Red numbers indicate values above the targets of 1 week of modules, 0.4 weeks of FG at RIF, and 2.3 weeks of FG at RESCM - Confidential

Appendix I Reasonableness of assumptions in optimization model

In this Appendix for every assumption made in the optimization model in chapter 4 (below repeated in *italic*) the reasonableness of the assumption is discussed.

General assumptions (see section 4.2)

1. *Finished goods stock points at RIF and RESCM locations will be considered as one, because of the small transportation time between RIF and RESCM (see Figure 8).*
   The focus within the model is not on the physical location of the items but on the type of machines, because of the very small transportation time between both FG stock locations and because the intention of Ricoh is to have (almost) no FG stock at RIF location.
2. *Fixed holding costs h_i will be used at all locations i. For the end stock points, the holding costs will be determined as $h_i = 0.148 * h_{i,RIF} + 0.852 * h_{i,RESCM}$ $for\ i = 1, \dots, J$, due to the two different locations used in practice to store finished goods (see also assumption 1).*
   For every type of product fixed FG holding costs will be used. Moreover, to deal with the combined FG stock locations of RIF and RESCM, weighted average holding costs will be determined for the finished goods based on the target that Ricoh wants to have: 14.8% (0.4 weeks) of its FG inventory at RIF and 85.2% (2.3 weeks) of its FG inventory at RESCM stock locations ($h_i = 0.148 * h_{i,RIF} + 0.852 * h_{i,RESCM}$ for $i = 1, \dots, J$).
3. *Only plotters (the main part of the machine) are considered as modules in the most upstream part of the supply chain before production at RIF. When for production of a FG the required module (plotter) is available, all required items for production of that FG will be available for production.*
   The used supply chain model will be of a distribution (divergent) type. Therefore, only one module can be concerned per FG. Moreover, for every plotter only one scanner (the other basic module) is needed, and the demand for the scanner is similar to the demand of the plotter. Therefore, there is assumed that for every ordered plotter the required type of scanner is ordered simultaneously. The same assumption applies for other, smaller, raw materials used in the assembly process.
4. *The total holding costs for modules (h_0) consists of the holding costs of the module itself and additional holding costs for other basic raw materials used in all types of finished goods which can be produced from that module.*
   To deal with the holding costs related to the assumption above, the additional costs are incurred to make the model fitting better with reality.
5. *Customer demand only occurs for finished goods (at FG stock points $i = 1, \dots, J$)*
   In practice there is no customer demand for modules and also for modeling purposes this assumption is often made.
6. *Customer demand is not-known in advance*
   This assumption requires the use of stochastic customer demand and will deal with the uncertainty Ricoh experiences in practice in relation to the customer demand.
7. *There is stationary stochastic customer demand for every FG, with independent demand across finished goods and across periods in time.*

Within the model this assumption is made for easier modeling of customer demand. In practice, data analysis showed that the customer demand is relatively stable, with no clear trends, which makes the assumption of stationary stochastic demand appropriate to make. Independent customer demand for finished goods can be assumed because buying one type of FG does not, logically, result in buying another type of FG within the same product family.

8. *There are no lost sales: all unsatisfied demand is backordered.*
   RESCM works with orders, which sometimes will pass their due date (unsatisfied demand) and then will be delivered at a later point in time. Normally, orders are not cancelled in case of passing the due date of the order, which makes the assumption of no lost sales fitting with reality.
9. *The lead time between the Asian factories and RIF is constant ($\sigma_{L_0} = 0$).*
   The lead time between the Asian factories and RIF is quite long due to transportation by ship from Asia to France. Moreover, a lot of different effects can influence the exact transportation time. However, first the assumption of constant lead time will be made in accordance to the assumption made by Van der Heijden (2000), but in the extension of the model variations in the upstream lead time will be included (see section 4.6).
10. *There is a constant lead time (including real production time and waiting time) between modules of RIF and finished goods of RIF ($\sigma_{l_i} = 0 \;\; for \; i = 1, \dots, J$).*
    In practice, the real production time at the RIF factory is very small. However, because only one type of FG per module can be produced at once and because the factory has also to deal with some capacity constraints, some waiting time will be added to the real production time, which will result in the total production lead time. This total production lead time is assumed to be constant, because in practice deviations will only be very small and the focus in this research is not on production planning.
11. *Asian factories have a 100% delivery performance to RIF.*
    Also the Asian factories have to order their raw materials at their suppliers and have to ensure that they have enough goods to satisfy the demands of RIF. Moreover, the Asian factories will receive orders from other factories in the world. However, when there are no big changes in the ordering quantities of RIF it should not be a problem for the Asian factories to deliver the required number of goods.
12. *There are no fixed order quantities and there are no ordering costs.*
    The size of one machine and the ordering quantities are relatively big. Therefore, the effect of fixed order quantities will be not significant. Moreover, due to the weekly replenishment and big customer demands there will (almost) always be enough order quantity, and otherwise orders of different items can be combined, which makes it not necessary to consider fixed order sizes and include ordering costs in the model.
13. *There are no capacity constraints in transportation.*
    In practice Ricoh has to deal with capacity constraints in transportation. However, due to the use of big third-party logistics providers in transportation, there is still some flexibility in transportation capacity. Therefore, there is assumed that there are no capacity constraints regarding transportation.

14. *There are no capacity constraints in production.*
    In practice Ricoh has to deal with production capacity constraints, especially regarding the production capacity flexibility, which is quite small due to workforce laws in France. However, this research is not scoped towards production planning, but towards inventory level optimization in a supply chain. Therefore, there is assumed that there are no production capacity constraints, and as mentioned in assumption 11, there will be dealt with the capacity constraints in having some extra lead time for production (to cover the waiting time due to production capacity constraints).
15. *After production of a certain type of FG, it is not possible to remanufacture it into another type of FG.*
    This assumption is model-based but also used in practice. Only in extreme cases remanufacturing can happen, but these operations are out of scope for this project.
16. *Partial delivery of customer orders is allowed.*
    This assumption is allowed to make, because the distribution of finished goods towards the local sales organization and further towards the end customers is out of scope for this project. Therefore, when a FG is available, there is assumed that it will be delivered and does not negatively influence the fill rate.

Assumptions for echelon control model (see section 4.3)

17. *An (R, S)-policy is used with $R = 1$ week under echelon control with a central decision maker.*
    This policy reflects the policy Ricoh would like to achieve and is identical to the policy used in the model in the article of Van der Heijden (2000). Note that the same review period is used within the whole supply chain.
18. *All required demand, ordering, shipment and inventory information is shared among all supply chain members in the echelon control model.*
    This information exchange is required for echelon-based decision making and is the idea behind this model. Note that this assumption will not be made for the local control model. Specific information about what will be shared in the model is given in Figure 16 (see section 4.1).
19. *The following rationing rule is used to deal with shortages at the upstream stock point: a simple variant of the balanced stock rationing in the sequel (Van der Heijden, 2000). See formula (1) below.*
    An assumption about the rationing rule is required to be made in case of shortages in periodic review distribution models. According to Van der Heijden (2000) this balanced stock rationing rule is best applicable for the type of model that will be used.
20. *The lead time and demand of a stock point are independent random variables.*
    This assumption is required to be made in the calculations of demand during lead time.

Assumptions for local control model (see section 4.4)

21. *An (R, S)-policy is used with $R = 1$ week under local control for every stock point.*
    This policy reflects the current inventory control policy of Ricoh in a way it should operate under the same general modeling assumptions as used for the echelon control model. Note that the same review period is used within the whole supply chain.

22. *The only information shared by the end stock point with upstream stock point 0 is the mean and standard deviation of customer demand, while the upstream stock point returns only the expected waiting time to all the end stock points (see Figure 16 for the local control model).*
    This information exchange is required for local decision making and is the idea behind the local control model.
23. *In case of shortages at the upstream stock points, orders at this stock point will be rationed to the end stock point proportional to the number of units ordered by that end stock point.*
    In the calculation of the expected waiting time an assumption has to be made about how the upstream stock point ration units to the end stock points in case of shortage at the upstream stock point. Due to the periodic review inventory policy at every end stock point where every end stock point has the same review period and places orders at the same moment, no rationing decision of orders can be made based on the order arrival date. Therefore, the following simple rationing rule will be used. The upstream stock point sums up all the orders received from the end stock points and determines the shortage quantity. Then, the total shortage quantity will be proportionally rationed to the end stock points based on the ordered quantity. This implies that an end stock point which ordered more units will have more units in shortages, but the percentage of units in shortage in similar for every end stock point.
24. *The on-hand inventory level at upstream stock point 0 will always be non-negative at the start of a new review period, just after arrival of the replenishment order made L_i weeks ago.*
    This assumption can be made because of the assumption of stationary stochastic demand (assumption 7), and because the fill rates used at Ricoh are high, to be able to gain a high customer service level. Therefore, the expectation of having a higher shortage level than the number of units of the weekly replenishment order (this order quantity is by expectation equal to the weekly demand for all finished goods that can be produced from this module) is assumed to be negligible. This assumption is required to make for the calculation of the expected waiting time and is related to the assumption above about the proportional allocation rule at the upstream stock point. More explanation will be given in the discussion of the expected waiting time formula.
25. *The customer demand information shared by the end stock points with the upstream stock point is equal to the actual demand information they have.*
    To simplify the expressions in the local control model, there is assumed that the end stock points will exchange the true customer demand information to the upstream stock point. This has to be assumed because otherwise anticipation of end stock points on expected shortages at the upstream stock point can occur through exchanging higher customer demand information than what actually occurs.
26. *Every customer demands one unit of a product*
    This assumption is made to ensure that no difference has to be made between the inter-arrival times and customers and demand per customer. Here, the demand is aggregated to a weekly level.
27. *Every customer has a demand of one unit.*
    To be able to determine the expected waiting time by making a relation between the expected shortages within a certain time period and the customer demand during that same time period,

this assumption needs to be made. It can be made because of the high demand rates compared to the order quantity per customer at Ricoh, and because customer demand comes from a lot of different origins.

Assumptions for current control model (see section 4.5)

28. *The only information shared in whole the supply chain is the mean customer demand as shared from the end stock points with the upstream stock point (see also Figure 16 for the current control model)*

    This information exchange is required for representing the current situation in the Ricoh supply chain.

29. *The target inventory level represents the time-average on-hand inventory level*

    This assumption is made to simplify the calculations and is a way to easily represent how the current inventory levels should be like.

Appendix J Variables used in optimization model

Variable	Explanation
a_0	The ratio between the maximum physical on-hand inventory level at stock point 0 (Δ_0) and the expected demand during the lead time L_i of stock point 0 ($E[X_0]$).
A_i	The inventory level target used in the current control model, expressed in weeks of average customer demand
μ_{D_i}	Mean of the weekly customer demand at stock point i for $i = 1, \dots, J$
$\sigma(D_i)$	Standard deviation of the weekly customer demand at stock point i for $i = 1, \dots, J$
$D_{i,t}$	Echelon demand in units at stock point i in a time period with length t
$ESPRC_0$	The expected shortage per replenishment cycle of stock point 0, as used in the local control model
$F_i(x)$	Probability distribution function of the random variable X_i
h_i	Inventory holding costs in euro's per product per time unit at stock point i and in pipeline to its successors (holding cost of the external supplier (Asian factories) towards stock point 0 will be neglected)
i	Index used for stock points, with $i \geq 0$ and $i = 0$ denotes the most upstream stock point
J	The number of end stock points
k_{i0}	Parameter used in approximation of order-up-to levels of a stock point
k_{i1}	Parameter used in approximation of order-up-to levels of a stock point
L_i	The actual lead time as perceived by the receiving stock point i. For $i = 0$ in all control models and $i = 1, \dots, J$ in the echelon control model this just includes the transportation lead time (l_i), but for the local and current control this includes the production lead time (l_i) plus the excepted waiting time (W_0), for $i = 1, \dots, J$
μ_{l_i}	Mean of the transportation/production lead time in weeks for a product in pipeline between the external supplier and the upstream stock point 0 for $i = 0$, and between stock point 0 and stock point i for $i = 1, \dots, J$ (see also Figure 16)
$\sigma(l_i)$	Standard deviation of the transportation/production lead time in weeks for a product in pipeline between the external supplier and the upstream stock point 0 for $i = 0$, and between stock point 0 and stock point i for $i = 1, \dots, J$ (see also Figure 16)
m_{i1}	First moment in approximation of the quasi-probability function $\beta_i(S_i)$ for stock point i
m_{i2}	Second moment in approximation of the quasi-probability function $\beta_i(S_i)$ for stock point i
p_i	Rationing fraction of stock point i for $i = 1, \dots, J$ (see formula 1)
R	Length of the review period in weeks
S_i	Order-up-to level in units used at stock point i
t	Time in weeks
W_0	Waiting time in time units at the upstream stock point for orders of end stock point in the local control model due to shortages at the upstream stock point
X_0	The total system demand during the upstream lead time L_0
X_i	• *Echelon control model:* $D_{i,L_i} + p_i Y_0 \; for \; i = 1, \dots, J$: the demand during lead time for end stock point i plus the fraction of the shortage at stock point 0 allocated to end stock point i (Y_0 is defined as given below) • *Local control model:* the demand during lead time L_i (which includes the expected waiting time $E[W_0]$ due to shortages at upstream stock point) and the review period R, and, for $i = 1, \dots, J$ • *Current control model:* demand during lead time L_i (which includes the expected waiting time $E[W_0]$ due to shortages at upstream stock point) for end stock point i, with $i = 1, \dots, J$

$\boldsymbol{Y_0}$	Shortage at the upstream stock point 0 in the echelon control model
$\boldsymbol{Z}$	System inventory costs based on mean inventory levels, just before arrival of a replenishment order
$\boldsymbol{\bar{Z}}$	Time-average system inventory costs
$\boldsymbol{Z^+}$	$\max\{Z, 0\}$ for any variable Z
$\boldsymbol{\alpha}$	Shape parameter in gamma distribution
$\boldsymbol{\beta_i}$	Target fill rate used at stock point i, defined as the fraction of the demand immediately satisfied from stock on hand
$\boldsymbol{\Delta_0}$	Maximum physical stock level at stock point 0
$\boldsymbol{\Gamma_{\alpha,\lambda}}$	Gamma distribution with parameters α and λ
$\boldsymbol{\lambda}$	Scale parameter in gamma distribution
$\boldsymbol{\Psi_i}$	Mean inventory at stock point i in units, just before the arrival of a replenishment order
$\boldsymbol{\bar{\Psi}_i}$	Time-average inventory in units at stock point i
$\boldsymbol{\tilde{\Psi}_i}$	Time-average inventory in units in the pipeline to stock point i

Table 10: Explanation of all variables used in the model

Appendix K Derivations of formulas used in echelon control model

Note that in this Appendix formulas 16, 17, 25 till 28, and 30 till 35 are taken from the model of Van der Heijden (2000). Next, for the echelon control model derivations of formulas and additional formulas next to the description of section 4.3 is given. Explanation for all variables used is presented in Table 10 in Appendix J.

Echelon control (R, S)-model

$E[X_0]$ and $E[Y_0]$ are given by the following formulas:

$$E[X_0] = E\left[D_{0,L_0}\right] = \mu_{l_0} * \left[\sum_{j=1}^{J} \mu_{D_j}\right] \tag{16}$$

$$E[Y_0] = E[(X_0 - \Delta_0)^+] \tag{17}$$

To be able to evaluate this expression, X_0 will be approximated with a two-moment fit by using a gamma distribution with parameters α and λ. First, well known, see e.g. Van Berkum and Di Bucchianico (2007):

$$E[X_0] = \frac{\alpha}{\lambda}, and\ \sigma^2(X_0) = \frac{\alpha}{\lambda^2} \tag{18}$$

Rewriting these formulas results in the following parameters for the gamma distribution (De Kok, 2011):

$$\alpha = \frac{E^2[X_0]}{\sigma^2(X_0)}, and\ \lambda = \frac{\alpha}{E[X_0]} \tag{19}$$

where $\sigma^2(X_0)$, under the assumption that lead time and demand are independent random variables (assumption 20), can be determined as (Silver et al., 1998):

$$\sigma^2(X_0) = E[L_0] * \left[\sum_{j=1}^{J} \sigma^2(D_j)\right] + \sigma^2(L_0) * \left[\sum_{j=1}^{J} \mu_{D_j}\right]^2 \tag{20}$$

Because of the assumption of constant lead time (assumption 9), the following part of the equation remains:

$$\sigma^2(X_0) = \mu_{l_0} * \left[\sum_{j=1}^{J} \sigma^2(D_j)\right] \tag{21}$$

Then, De Kok (2011) derived the following two expressions (see formulas 22 and 23):

$$E[Y_0] = E[(X_0 - \Delta_0)^+] = \int_{\Delta_0}^{\infty} (y - \Delta_0) \frac{\lambda^\alpha y^{\alpha-1} e^{-\lambda y}}{\Gamma(\alpha)} dy$$
$$= \int_{\Delta_0}^{\infty} y \frac{\lambda^\alpha y^{\alpha-1} e^{-\lambda y}}{\Gamma(\alpha)} dy - \Delta_0 \left(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\right)$$
$$= \frac{\alpha}{\lambda} \int_{\Delta_0}^{\infty} \frac{\lambda^{\alpha+1} y^{\alpha} e^{-\lambda y}}{\Gamma(\alpha+1)} dy - \Delta_0 \left(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\right) \tag{22}$$
$$= \frac{\alpha}{\lambda} \left(1 - \Gamma_{\alpha+1,\lambda}(\Delta_0)\right) - \Delta_0 \left(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\right)$$

$$E[Y_0^2] = E[((X_0 - \Delta_0)^+)^2] = \int_{\Delta_0}^{\infty} (y - \Delta_0)^2 \frac{\lambda^\alpha y^{\alpha-1} e^{-\lambda y}}{\Gamma(\alpha)} dy$$
$$= \int_{\Delta_0}^{\infty} y^2 \frac{\lambda^\alpha y^{\alpha-1} e^{-\lambda y}}{\Gamma(\alpha)} dy - 2\,\Delta_0 \int_{\Delta_0}^{\infty} y \frac{\lambda^\alpha y^{\alpha-1} e^{-\lambda y}}{\Gamma(\alpha)} dy + \Delta_0^2 \left(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\right)$$
$$= \frac{\alpha(\alpha+1)}{\lambda^2} \int_{\Delta_0}^{\infty} \frac{\lambda^{\alpha+2} y^{\alpha+1} e^{-\lambda y}}{\Gamma(\alpha+2)} dy - 2\Delta_0 \frac{\alpha}{\lambda} \int_{\Delta_0}^{\infty} \frac{\lambda^{\alpha+1} y^{\alpha} e^{-\lambda y}}{\Gamma(\alpha+1)} dy + \Delta_0^2 \Big(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\Big) \tag{23}$$
$$= \frac{\alpha(\alpha+1)}{\lambda^2} \left(1 - \Gamma_{\alpha+2,\lambda}(\Delta_0)\right) - 2\Delta_0 \frac{\alpha}{\lambda} \left(1 - \Gamma_{\alpha+1,\lambda}(\Delta_0)\right) + \Delta_0^2 \left(1 - \Gamma_{\alpha,\lambda}(\Delta_0)\right)$$

Next, $\sigma^2(Y_0)$ can be determined as follows (well known, see e.g. Van Berkum & Di Bucchianico, 2007):

$$\sigma^2(Y_0) = E[Y_0^2] - E^2[Y_0] \tag{24}$$

In formula 6 (see section 4.3.3) $X_i = D_{i,L_i} + p_i Y_0 \; for \; i = 1, \dots, J$, where p_i represents the allocation fraction of an end stock point as determined by the rationing rule. Next, the expected value for X_i can be determined as follows:

$$E[X_i] = E\left[D_{i,L_i} + p_i Y_0\right] = E\left[D_{i,L_i}\right] + p_i * E[Y_0] \;\; for \; i = 1, \dots, J \tag{25}$$

To be able to solve this formula, the expression for $E[Y_0]$ as given in equation (22) has to be used.

Optimization formulas

The order-up-to level required to be able to solve equation (8) is given by the following function:

$$S_i'(\Delta_0) = m_{i1}'(\Delta_0) * \left\{1 - \frac{m_{i1}(\Delta_0)k_{i0}}{\sqrt{m_{i2}(\Delta_0) - m_{i1}^2(\Delta_0)}} + (k_{i0} - k_{i1}) * \left(1 + \frac{m_{i2}(\Delta_0)}{m_{i1}^2(\Delta_0)}\right)\right\} + m_{i2}'(\Delta_0) * \left\{\frac{k_{i0}}{2 * \sqrt{m_{i2}(\Delta_0) - m_{i1}^2(\Delta_0)}} + \frac{(k_{i0} - k_{i1})}{m_{i1}(\Delta_0)}\right\} \; for \; i = 1, \dots, J \tag{26}$$

where $m_{i1}(\Delta_0)$ and $m_{i2}(\Delta_0)$ refer to the first two moments of the approximation of the quasi-probability function $\beta_i(S_i)$ by a gamma distribution. These first two moments are given by the following expressions:

$$m_{i1} = E[X_i] + \frac{\sigma^2(D_i)}{2\mu_{D_i}} + \frac{1}{2}R\mu_{D_i} \; for \; i = 1, \dots, J \tag{27}$$

$$m_{i2} \approx E\left[X_i^2\right] + E[X_i] * \left\{\frac{\sigma^2(D_i)}{\mu_{D_i}} + R\mu_{D_i}\right\} + \frac{\left(R * (\mu_{D_i})^2 + \sigma^2(D_i)\right) * \left(R * (\mu_{D_i})^2 + \sigma^2(D_i)\right)}{3 * (\mu_{D_i})^2} \; for \; i = 1, \dots, J \tag{28}$$

where, under the assumption of independent customer demand at the different end stock points (assumption 7) and constant production lead time (assumption 10), $E[X_i]$ is given by equation (25), and:

$$\begin{aligned} E\left[X_i^2\right] &= E^2[X_i] + \sigma^2(X_i) = E^2[X_i] + \sigma^2\left(D_{i,L_i}\right) + \sigma^2(p_i Y_0) \\ &= E^2[X_i] + \mu_{l_i} * \sigma^2(D_i) + p_i^2 * \sigma^2(Y_0) \\ & for \; i = 1, \dots, J \end{aligned} \tag{29}$$

where $\sigma^2(Y_0)$ is given by equation (23). Next, the derivatives of the first two moments of equations (27) and (28) are given by the following equations:

$$m_{i1}'(\Delta_0) = -p_i[1 - F_0(\Delta_0)] \; for \; i = 1, \dots, J \tag{30}$$

$$m_{i2}'(\Delta_0) = -2p_i^2 E[Y_0(\Delta_0)] - p_i[1 - F_0(\Delta_0)] * \left\{\frac{\sigma^2(D_i)}{\mu_{D_i}} + \left(2\mu_{l_i} + R\right)\mu_{D_i}\right\} \; for \; i = 1, \dots, J \tag{31}$$

Moreover,

$$k_{i0} = \Phi^{-1}(\beta_i) \; for \; i = 1, \dots, J \tag{32}$$

$$k_{i1} = -1 - \ln(1 - \beta_i) \; for \; i = 1, \dots, J \tag{33}$$

Results

The formulas as given below are used in the calculations of the echelon control model results.

$$S_i \approx m_{i1} + k_{i0}\sqrt{m_{i2} - m_{i1}^2} + (k_{i1} - k_{i0}) * \left(\frac{m_{i2}}{m_{i1}} - m_{i1}\right) \; for \; i = 1, \dots, J \tag{34}$$

$$S_0 = \Delta_0 + \sum_{j \in succ(0)} S_j \tag{35}$$

$$\bar{Z}_{RIF}(\Delta_0) = h_0 * \left\{\overline{\Psi}_0(\Delta_0) + \sum_{j=1}^{J} \widetilde{\Psi}_j\right\} + 0.148 * \sum_{j=1}^{J} h_i \overline{\Psi}_i(\Delta_0) \tag{36}$$

$$\bar{Z}_{RESCM}(\Delta_0) = 0.852 * \sum_{j=1}^{J} h_i \overline{\Psi}_i(\Delta_0) \tag{37}$$

Appendix L Formulas of local control model

Explanation for all variables used is given in Table 10, Appendix J.

In equation (9; see section 4.4.2) the following formula has to be used in the calculations of X_i (Silver et al., 1998):

$$E[X_i] = E[L_i + R] * E[D_{i,1}] \ for\ i = 0, \dots, J \tag{38}$$

$$\sigma^2(X_i) = (E[L_i] + R) * \sigma^2(D_{i,1}) + E^2[D_{i,1}] * \sigma^2(L_i) \ for\ 0 = 1, \dots, J \tag{39}$$

For the end stock points the total replenishment lead time ($L_i + R$) includes the sum of the production lead time, the length of the review period, and the expected waiting of an order due to backorders at the upstream stock point. Here, L_i is still defined as the lead time as perceived by the receiving stock points. Within the local control model, for the end stock points L_i therefore includes, next to the production time (l_i), also the expected waiting time $E[W_0]$. However, for stock point 0, the lead time L_0 just includes the transportation lead time as used in the echelon model (Hopp & Spearman, 2008). Thus, for the end stock points:

$$E[L_i] = \mu_{l_i} + E[W_0] \ \ for\ i = 1, \dots, J \tag{40}$$

$$\sigma^2(L_i) = \frac{\beta_0}{1 - \beta_0} * E^2[W_0] \ for\ i = 1, \dots, J \tag{41}$$

where μ_{l_i} denotes the production lead time towards end stock point i (as also used in the echelon control model and W_0 represents the waiting time at the upstream stock point 0. Here, μ_{l_i} is an input parameter. Note that in using formula (41) there has to be assumed that the waiting time is deterministic.

$E[W_0]$ can be determined with the following formula (Hopp & Spearman, 2008):

$$E[W_0] = \frac{ESPRC_0}{D_{0,L_0+R}} \tag{42}$$

with:

$$ESPRC_0 = E[(X_0 - S_0)^+] = \int_{S_0}^{\infty} (x_0 - S_0)\, f_x(x_0) dx_0 \tag{43}$$

where $f_x(x_0)$ denotes the probability density function of the demand during lead time at stock point 0. Again, there is assumed that this demand is Gamma distributed, and a two moment fit approximation will be used. Equation (43) has a similar form as (22). Applying the same derivations as done for equation (22) will result in the following formula (Silver et al., 1998):

$$ESPRC_0 = E[(X_0 - S_0)^+] = \int_{S_0}^{\infty} (x_0 - S_0)\, f_x(x_0) dx_0 = \frac{\alpha}{\lambda}\Big(1 - \Gamma_{\alpha+1,\lambda}(S_0)\Big) - S_0\left(1 - \Gamma_{\alpha,\lambda}(S_0)\right) \quad (44)$$

Where α and λ are given by a function similar to equation (19), but now with demand during lead time and review period instead of demand during lead time only due to the local control model:

$$\alpha = \frac{E^2[D_{0,R+L_0}]}{\sigma^2(D_{0,R+L_0})}, and\ \lambda = \frac{\alpha}{E\left[D_{0,R+L_0}\right]} \quad (45)$$

Results

In the calculation of the results of the local control model again a two moment fit approximations for the demand during lead time (and review period) has to be made to be able to determine the outcome of the following equation:

$$\overline{\Psi}_i \approx \frac{1}{6} * E[(S_i - X_i)^+] + \frac{4}{6} * E\left[\left(S_i - D_{i,\frac{R}{2}} - X_i\right)^+\right] + \frac{1}{6} * E\left[\left(S_i - D_{i,R} - X_i\right)^+\right] \ \ for\ i = 0, \dots, J \quad (6')$$

Appendix M Formulas used in current control model

Explanation for all variables used is presented in Table 10, Appendix J.

For the current control model the time-average inventory level in the pipeline to stock point 0 can be determined by formula (4):

$$\widetilde{\Psi}_i = E\left[D_{i,L_i}\right] \ for\ i = 0, \dots, J \tag{4}$$

with:

$$E[X_0] = E\left[D_{0,L_0}\right] = \mu_{l_0} * \left[\sum_{j=1}^{J} \mu_{D_j}\right] \tag{16}$$

$$E\left[D_{i,L_i}\right] = E[L_i] * \mu_{D_i} \ for\ i = 1, \dots, J \tag{46}$$

where $E[L_i]$ includes the production time plus the expected delay of an order due to backorders at the upstream stock point, and is thus given by equation (40; see Appendix L). This expected waiting time is also needed in this current control model because the attained fill rate has an influence on total lead time result.

Next, the time-average on-hand inventory levels, based on the target inventory levels A_i, can be determined with the following formulas:

$$\overline{\Psi}_0 = A_0 * \left[\sum_{j=1}^{J} \mu_{D_j}\right] \tag{47}$$

$$\overline{\Psi}_i = A_i * \mu_{D_i} \ for\ i = 1, \dots, J \tag{48}$$

To be able to determine the order-up-to level and the fill rate, formulas of the (R, S) model as defined before will be used.

The order-up-to level required to attain the given time-average on-hand inventory level will be approximated based on the time-average on-hand inventory level used for all stock points in the local control model. This approximation is equal to the following formula, as given for the local control model.

$$\overline{\Psi}_i \approx \frac{1}{6} * E[(S_i - X_i)^+] + \frac{4}{6} * E\left[\left(S_i - D_{i,\frac{R}{2}} - X_i\right)^+\right] + \frac{1}{6} * E\left[\left(S_i - D_{i,R} - X_i\right)^+\right] \ for\ i = 0, \dots, J \tag{6'}$$

From this equation, $\overline{\Psi}_i$ is already determined by formula (48), and the demand during lead time (and review period) can be approximated with a two moment fit based on a gamma distribution. Note that in this current control model X_i is defined as the demand during the lead time towards this end stock point i. The only unknown variable remaining in equation (6') is S_i. Then, solving this equation (by making use of the Goal Seek function in Excel) will result in the value of S_i.

Last, the achieved fill rate can be determined by using formula (9; Van der Heijden, 2000):

$$\frac{E\left[\left(X_i + D_{i,R} - S_i\right)^+\right] - E[(X_i - S_i)^+]}{R\mu_{D_i}} = 1 - \beta_i \;\; for\ i = 0, \dots, J \tag{9}$$

Here, again a two moment fit by approximating the demand during lead time (and review period) with a gamma distributed will be used to be able to calculate the fill rate β_i. Recall that for the current control model X_i is defined as the demand during lead time L_i.

Appendix N Values for input parameters used in analysis

Table 11: Product characteristics of machines covered in analysis. Note: cpm = copies per minute - Confidential

Parameter	Model 2	Model 4	Dimension
N_0	4	4	*end stockpoints*
R	1	1	*week*
μ_{L_0}	10	10	*weeks*
σ_{L_0}	0	0	*weeks*
μ_{L_1}	2	2	*working days*[1]
μ_{L_2}	2	2	*working days*
μ_{L_3}	2	2	*working days*
μ_{L_4}	2	2	*working days*
h_0	79.89	100.45	*€ per unit per year*
h_1	92.38	121.58	*€ per unit per year*
h_2	103.35	140.46	*€ per unit per year*
h_3	120.00	132.55	*€ per unit per year*
h_4	123.59	151.43	*€ per unit per year*
β_0	0.95	0.95	*fill rate (only local control)*
β_1	0.9	0.9	*fill rate*
β_2	0.9	0.9	*fill rate*
β_3	0.9	0.9	*fill rate*
β_4	0.9	0.9	*fill rate*
μ_{D_1}	4.33	5.25	*units per week*
σ_{D_1}	4.28	3.95	*units per week*
μ_{D_2}	706.83	1.27	*units per week*
σ_{D_2}	184.17	1.80	*units per week*
μ_{D_3}	0.71	726.77	*units per week*
σ_{D_3}	0.82	141.49	*units per week*
μ_{D_4}	148.85	167.04	*units per week*
σ_{D_4}	39.84	42.91	*units per week*

Table 12: Start values of input parameters for the models

Note: $\sigma_{L_i} = 0$ for $i = \{1,2,3,4\}$.

Details about the calculations of the holding costs are provided in Appendix O.

[1] Note: 1 week = 5 working days

Appendix O Calculation of holding cost - Confidential

Cost of capital

The cost of capital is determined by the following formula:

$$Cost\ of\ capital = Product\ value * Interest\ rate$$

where the interest rate related to the cost of capital is given as 4.0%. In the table below the product values and the corresponding cost of capital are given. Note that for the upstream cost of capital the product value (of plotter, scanner and ARDF combined) is determined by multiplying the weighted average product value of the finished goods (based on demand data for the finished goods) with 75%, as assumed to be the product value upstream.

Table 13: Calculation of cost of capital - Confidential

Storage costs

The storage costs are determined as given in the tables below. Note that the storage costs for finished goods ("FG average") are determined by using: $\text{"FG average"} = 0.148 * \text{"FG at RIF"} + 0.852 * \text{"FG at RESCM"}\ for\ i = 1, \dots, J.$

Table 14: Storage costs calculation for Model 2 - Confidential

Table 15: Storage cost calculation for Model 4 - Confidential

Holding costs

Last, the general formula for the calculations of the holding costs is as follows:

$$Holding\ costs = Cost\ of\ capital + Storage\ costs$$

Table 16: Holding cost calculation – Confidential

Appendix P Results of optimization model for Model 2

Units per week	μ_{D_i}	σ_{D_i}	cv_{D_i}
FG1	4.33	4.28	0.988
FG2	706.83	184.17	0.261
FG3	0.71	0.82	1.155
FG4	148.85	39.84	0.268

Table 17: Demand characteristics for Model 2

Output parameter	Echelon control	Local control	Current control	Dimension
S_0	10,269.89[2]	11,049.00	10,793.13	*Units*
Δ_0	8,480.90	-	-	*Units*
S_1	109.68	17.63	20.20	*Units*
S_2	1288.76	1,763.51	3,258.47	*Units*
S_3	104.56	3.22	3.34	*Units*
S_4	285.99	372.95	686.20	*Units*
$\bar{\Psi}_0$	0.21	1.32	1.00	*Weeks*[3]
$\bar{\Psi}_1$	14.43	2.08	2.70	*Weeks*
$\bar{\Psi}_2$	0.63	0.57	2.70	*Weeks*
$\bar{\Psi}_3$	85.19	2.53	2.70	*Weeks*
$\bar{\Psi}_4$	0.68	0.58	2.70	*Weeks*
$\bar{Z}_{Modules}$	€ 14,276.97	€ 90,675.08	€ 68,759.50	*€ per year*
$\bar{Z}_{Production}$	€ 27,503.80	€ 27,516.74	€ 28,189.66	*€ per year*
$\bar{Z}_{Finished\ Goods}$	€ 71,644.07	€ 53,112.88	€ 240,090.43	*€ per year*
$\bar{Z}_{RIF}$	€ 52,394.71	€ 126,060.40	€ 132,518.12	*€ per year*
$\bar{Z}_{RESCM}$	€ 61,030.14	€ 45,244.31	€ 204,521.48	*€ per year*
$\bar{Z}_{Total}$[4]	€ 113,424.85	€ 171,304.71	€ 337,039.59	*€ per year*
β_0	-	94.66%	89.62%	*Percentage*
β_1	93.28%	86.85%	91.51%	*Percentage*
β_2	88.54%	88.04%	100.00%	*Percentage*
β_3	93.99%	86.68%	87.85%	*Percentage*
β_4	88.76%	88.02%	100.00%	*Percentage*

Table 18: Output of the three control models for Model 2

[2] Echelon order-up-to level
[3] Inventory level in terms of weeks of average customer demand
[4] Excluding In-Transit Asia – RIF for modules (In-Transit$_0$)

Appendix Q Results of optimization model for Model 4

Units per week	μ_{D_i}	σ_{D_i}	cv_{D_i}
FG1	5.25	3.95	0.752
FG2	1.27	1.80	1.417
FG3	726.77	141.49	0.195
FG4	167.04	42.91	0.257

Table 19: Demand characteristics for Model 4

Output parameter	Echelon	Local	Current	Dimension
S_0	10,558.33[5]	11,295.15	11,268.29	Units
Δ_0	8,868.74	-	-	Units
S_1	91.85	18.23	24.27	Units
S_2	87.81	6.80	6.07	Units
S_3	1,208.23	1,747.82	3,347.02	Units
S_4	301.70	415.83	769.28	Units
$\overline{\Psi}_0$	0.14	1.03	1.00	Weeks[6]
$\overline{\Psi}_1$	9.60	1.50	2.70	Weeks
$\overline{\Psi}_2$	39.32	3.32	2.70	Weeks
$\overline{\Psi}_3$	0.53	0.48	2.70	Weeks
$\overline{\Psi}_4$	0.61	0.56	2.70	Weeks
$\overline{Z}_{Modules}$	€ 12,662.63	€ 93,279.83	€ 90,438.27	€ per year
$\overline{Z}_{Production}$	€ 36,175.31	€ 36,180.05	€ 36,657.36	€ per year
$\overline{Z}_{Finished\ Goods}$	€ 79,502.34	€ 62,203.01	€ 325,647.72	€ per year
$\overline{Z}_{RIF}$	€ 60,616.06	€ 138,675.14	€ 175,339.73	€ per year
$\overline{Z}_{RESCM}$	€ 67,724.21	€ 52,987.75	€ 277,403.62	€ per year
$\overline{Z}_{Total}$[7]	€ 128,340.28	€ 191,662.89	€ 452,743.35	€ per year
β_0	-	94.72%	94.20%	Percentage
β_1	93.02%	87.11%	96.46%	Percentage
β_2	93.46%	86.43%	82.44%	Percentage
β_3	88.65%	88.22%	100.00%	Percentage
β_4	88.48%	88.05%	100.00%	Percentage

Table 20: Output of the three control models for Model 4

	Module	FG 1	FG 2	FG 3	FG 4
Echelon control	0.14	9.60	39.32	0.53	0.61
Local control	1.03	1.50	3.32	0.48	0.56
Current control	1.00	2.70	2.70	2.70	2.70

Table 21: On-hand inventory levels expressed in weekly average customer demand per stock point for Model 4

[5] Echelon order-up-to level
[6] Inventory level in terms of weeks of average customer demand
[7] Excluding In-Transit Asia – RIF for modules (In-Transit$_0$)

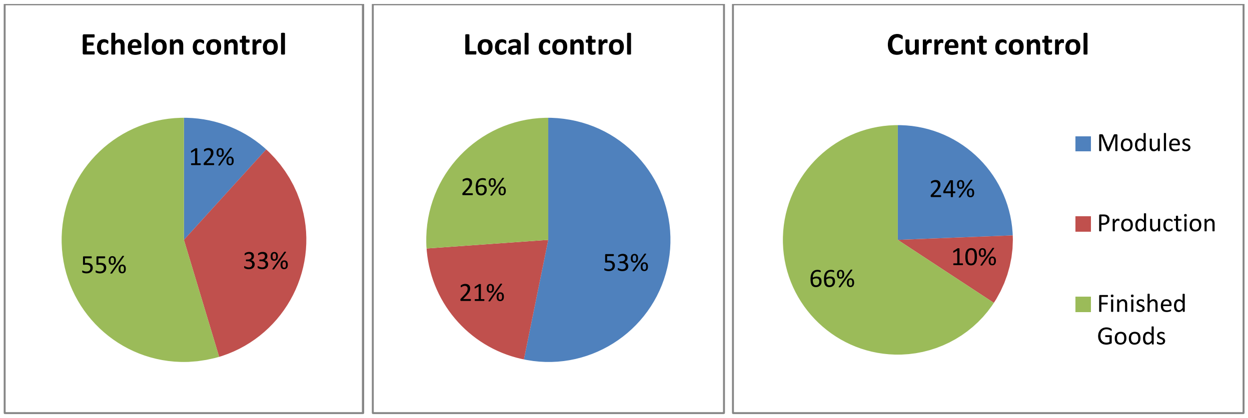


Figure 40: Location of inventory in supply chain, based on inventory levels in units for Model 4

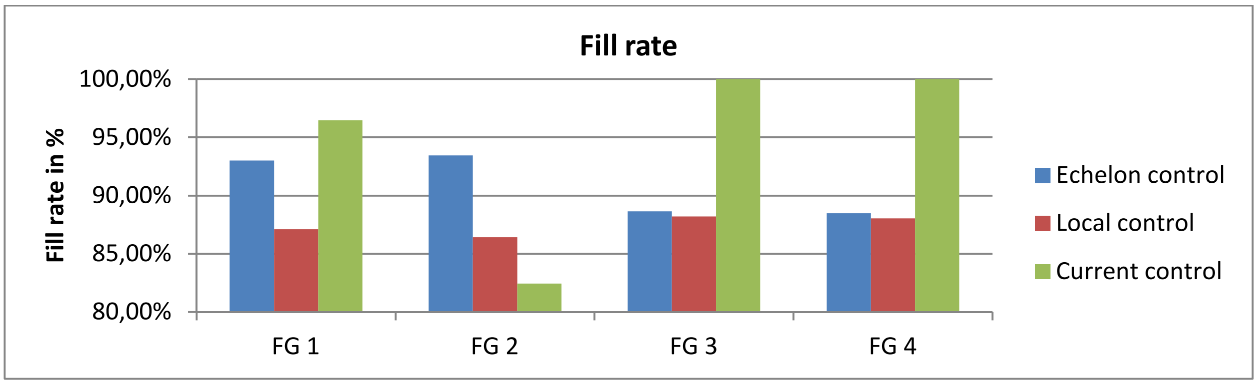


Figure 41: Fill rate results for Model 4

Holding costs per year	Echelon control		Local control		Current control	
RIF	€	60,616.06	€	138,675.14	€	175,339.73
RESCM	€	67,724.21	€	52,987.75	€	277,403.62
Total	€	128,340.28	€	191,662.89	€	452,743.35

Table 22: Holding costs results per organization per year for Model 4

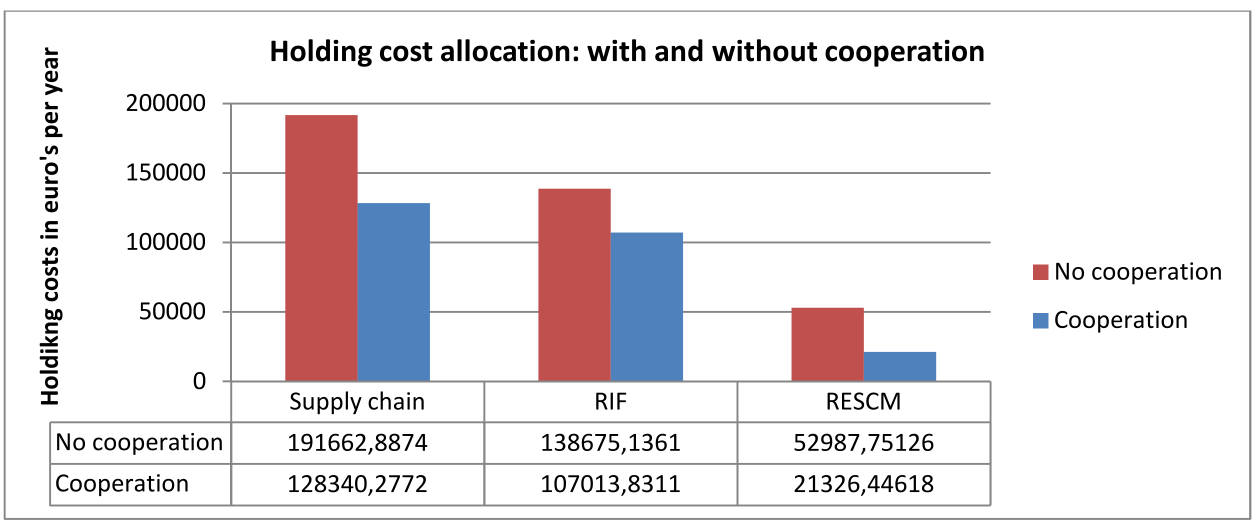


Figure 42: Cost allocation: costs results without cooperation (local control model) versus allocated costs in echelon control model (cooperation) for Model 4

Appendix R Graphs sensitivity analysis

Customer fill rate

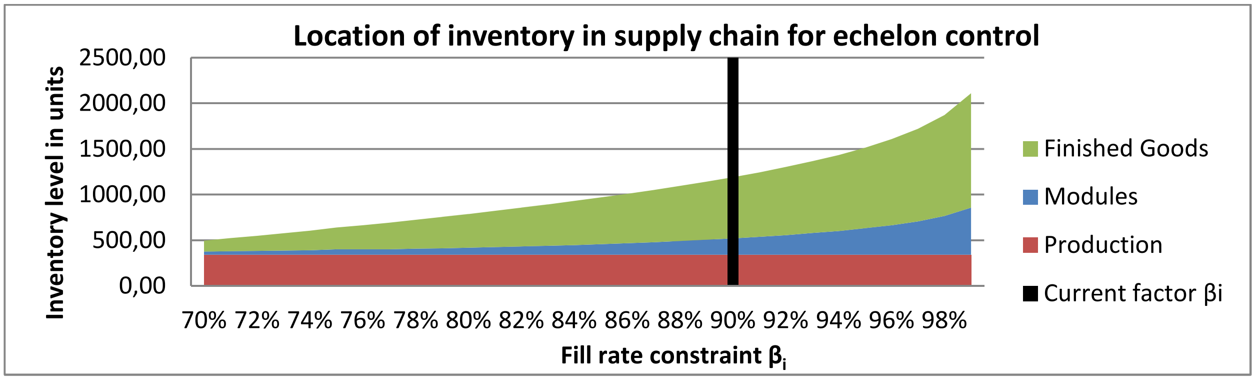


Figure 43: Sensitivity of location of inventory in supply chain on customer fill rate for echelon control for Model 2

Holding cost factor

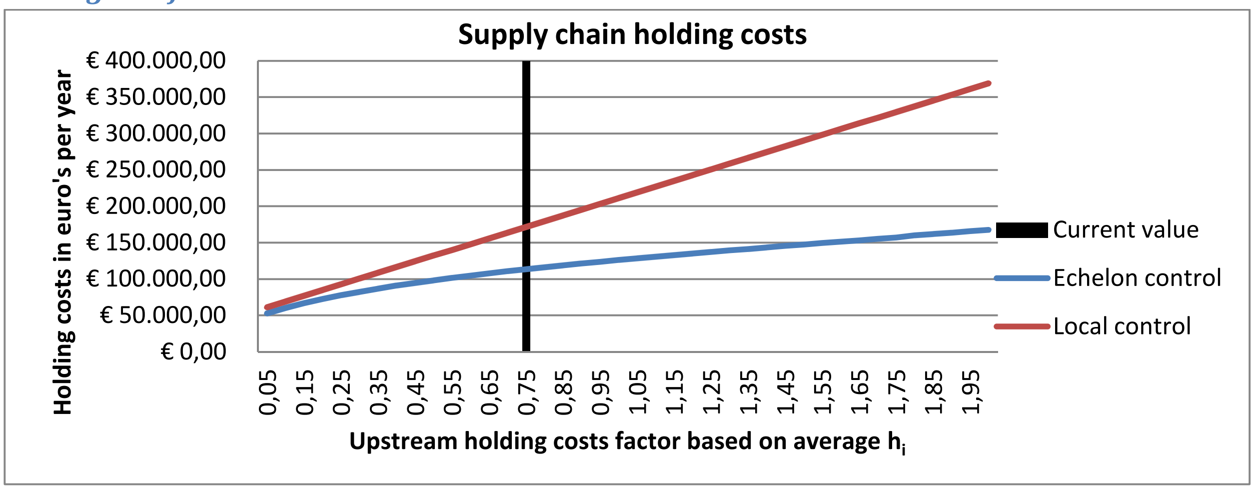


Figure 44: Sensitivity of supply chain holding costs on upstream holding costs for Model 2

Upstream lead time

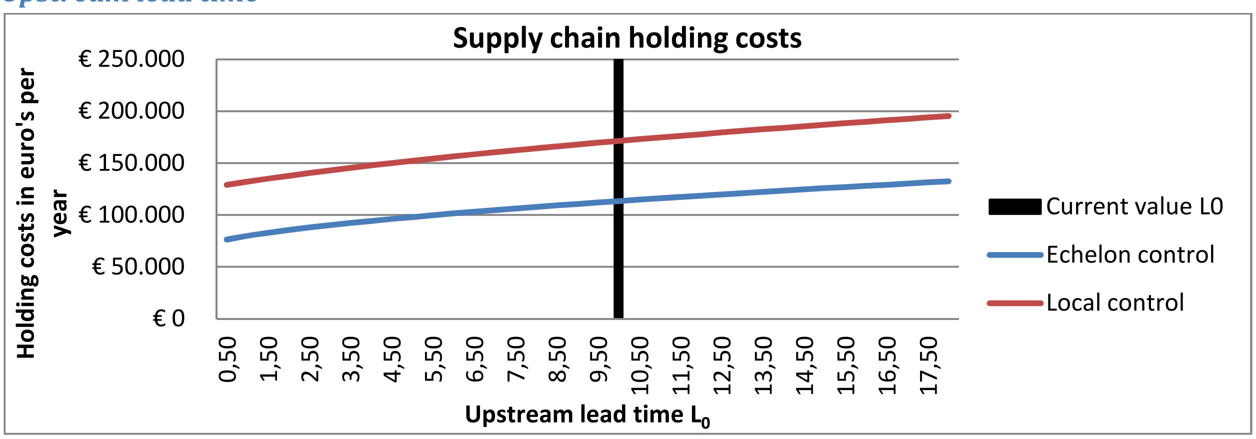


Figure 45: Sensitivity of supply chain holding costs on upstream lead time for Model 2

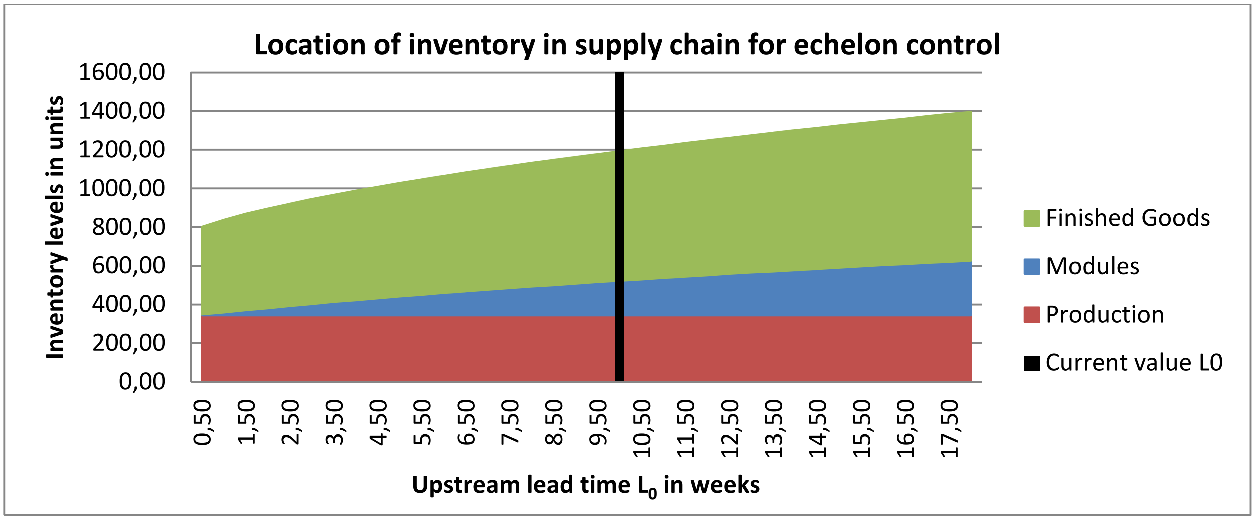


Figure 46: Sensitivity of inventory level per phase in the supply chain on upstream lead time for Model 2 in echelon control model

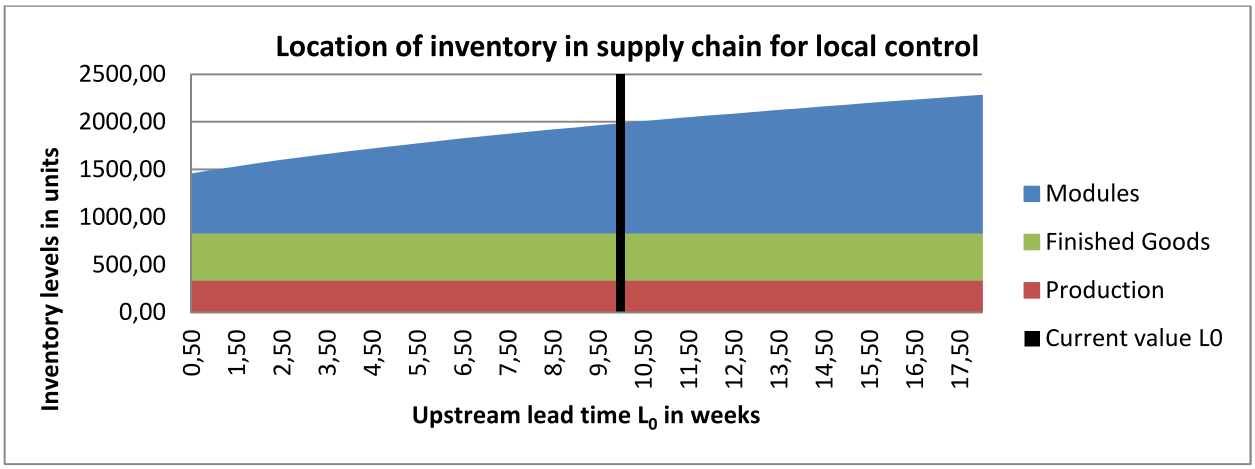


Figure 47: Sensitivity of inventory level per phase in the supply chain on upstream lead time for Model 2 in local control model

Variability of customer demand

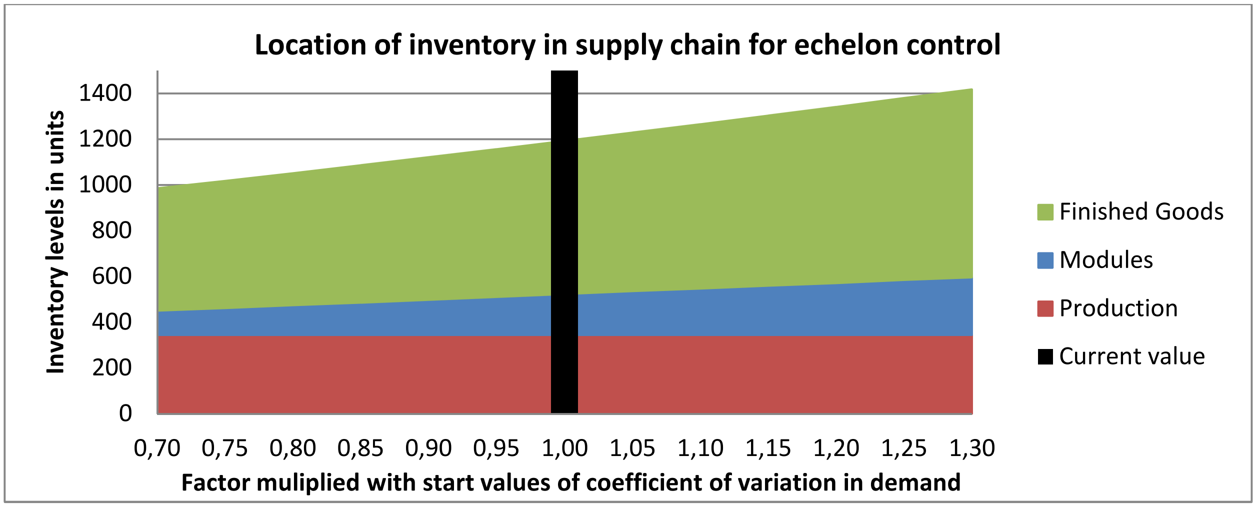


Figure 48: Sensitivity of inventory level per phase in the supply chain on customer demand variability for Model 2 in echelon control model

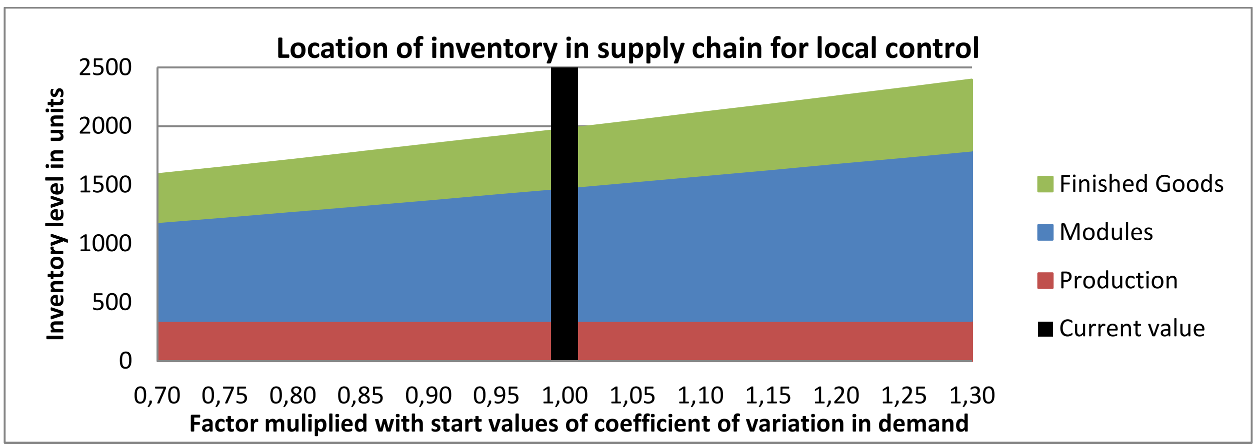


Figure 49: Sensitivity of inventory level per phase in the supply chain on customer demand variability for Model 2 in local control model

Appendix S Poster

Ricoh Europe SCM B.V., August 2012
Supervisors: M. Slikker, Z. Atan, M. Jimenez & S. Wischnewski

Technische Universiteit **Eindhoven** University of Technology

Inventory level and product availability improvement in a two-echelon divergent supply chain at Ricoh

Master thesis by Rob van Pelt (r.v.pelt@student.tue.nl)

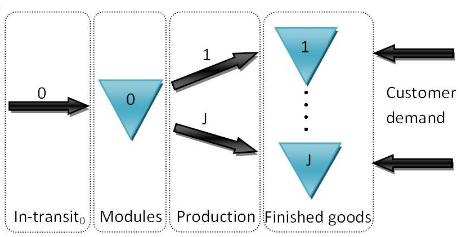
Introduction

This research is about a two-echelon divergent supply chain within Ricoh, where one specific basic product (module) can be assembled into different types of finished goods, and where two different parties are involved (factory and distribution centre). Problems experienced by Ricoh were high inventory levels, but sometimes also a low product availability. Possible causes identified were independent replenishment and lack of information sharing in the supply chain. This resulted into the following research question:

Which cost savings can Ricoh obtain when their inventory levels in Europe for machines assembled in a European factory are centrally controlled for a given product availability target under the limitations of the chosen model, and how can these cost savings be fairly allocated to the European factory and RESCM?

Methods

The following supply chain structure is used in the optimization model:

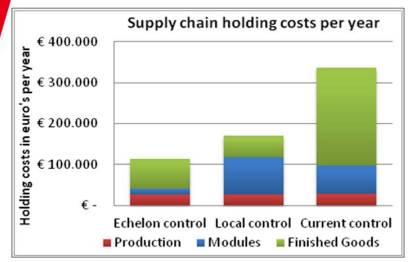


This distribution structure is analyzed with 3 different control models:

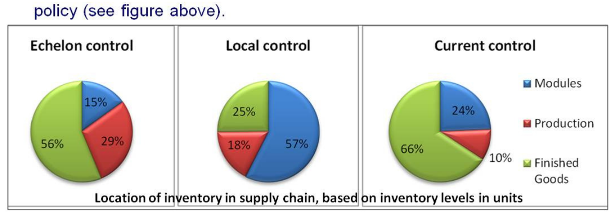
1. **Echelon control:** centralized decision making with full information exchange by making use of an (R,S)-inventory policy on supply chain level, based on Van der Heijden (2000). Supply chain holding costs are minimized under a target fill rate.
2. **Local control:** local decision making with limited information exchange and at every stock point an (R,S)-inventory policy with a target fill rate (adapted from Van der Heijden, 2000).
3. **Current control:** replenishment decisions are made locally and based upon inventory targets, with almost no information exchange.

The performance of these models was determined with time-average formulas. The two involved supply chain organizations should receive half of the cost savings in the echelon control model compared to local control, to make cooperation happen.

Results



When evaluated by supply chain holding costs, a decrease of 49.17% in costs could be achieved when moving from current control to local control, and a decrease of 66.35% in holding costs could be achieved when changing the current control to the echelon control policy (see figure above).



Echelon control is not beneficial for the finished goods' stock points, but the cost allocation proposal enabled cooperation. Regarding the location of inventory in the supply chain there were significant changes. In the current control model the majority of inventory was at the finished goods' stock points, while local control model suggested most of the inventory as module stock. In contrast, echelon control again resulted in majority of inventory as finished goods.

Conclusion

To answer the research question, there can be concluded that central control can lead to significant cost savings compared to the local and current control. Moreover, historical data analysis showed that the actual performance was even worse than the current control model results. The results of the echelon control model can be fairly allocated by splitting the supply chain cost savings between echelon and local control equally between the two parties involved.

Relevant for science is the comparison made between a central and decentralized decision-making approach for a period review order-up-to level under service level constraints. Moreover, lead time variability was added to the model of Van der Heijden (2000) and a cost savings allocation proposal is made. Further research should consider bigger supply chains, include an improved rationing rule for cases of shortages, and include more variables in the cost minimization function.

Reference: Van der Heijden, M. (2000). Near cost-optimal inventory control policies for divergent networks under fill rate constraints. *International Journal of Production Economics, 63*, 161-179.

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