Forward spare parts supply chain for the Chinese market

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Abstract

This research project, conducted at Royal Philips in Best, investigates the Chinese spare parts supply chain configuration in terms of total costs, material availability and waiting time. The configuration of the Chinese supply chain, without Hong Kong and Taiwan, is examined. The key variables in this configuration are the replenishment and the emergency shipments, where for both variables the location, time, and related costs are iterated. For each supply chain configuration the performance is evaluated by means of the basestock optimization model of Kranenburg and Van Houtum (2009). Kranenburg and Van Houtum's model is employed because it allows lateral transshipments and emergency shipments. This mathematical model is adjusted according to the characteristics of the current supply chain. Next, the adjusted model is complemented with a Greedy heuristic to approach the optimal basestock levels. While finding these optimal basestock levels, the model is subject to a service level constraint, which is the material availability.

The application of the model applied in this research shows the dependency between the control parameters. These control parameters are tested to improve the current supply chain configuration. This research answers the question whether Regional Distribution Center (RDC) Singapore should also be used for replenishment or whether this RDC could be entirely disregarded. Moreover, both the benefits of faster replenishment and slower emergency shipments are evaluated.

Keywords: Single-echelon, Multi-Item, Multi-Location, Spare parts control, Capital Goods, Full pooling, Inventory modeling, Greedy heuristic, Lateral transshipments, Emergency shipments.

Executive Summary

This master thesis project is conducted at Royal Philips (henceforth Philips), which is a leading health technology company. This research has been proposed by the SPS department (Service Parts Supply chain department) as they want to reduce the costs related to the spare parts of the medical equipment for the Chinese supply chain. These spare parts are used to guarantee the up-time of medical equipment in hospitals located in China. To minimize the total costs of the current supply chain with the material availability as service level constraint, four alternative supply chain configurations are proposed, and subsequently the resulting performance is evaluated. In the proposed alternative cases, the configuration of the replenishment and emergency shipments are varied. In addition, the settings of the planning tool, currently used by Philips, are evaluated.

Introduction

Hospitals and clinics heavily depend on their medical equipment. They make use of these devices for both planned and unplanned treatments. The reliance on, and availability of this equipment is crucial and of the utmost importance since human lives may depend on it. It is therefore of crucial importance that the spare parts are quickly accessible at the right location at the right time. The more efficient and systematized these procedures become, the better for Philips. Philips sells to the hospitals both the capital goods and the service contracts. Service contracts ensure the availability of the capital goods and the presence of an FSE (Field Service Engineer) when the spare parts are prompted.

Since the world is changing fast, supply chain configurations need to be evaluated and assessed, especially taking into consideration the emerging markets. The most important emerging market is China, which experiences a yearly growth of 8%. This strongly impacts the supply chain network. In addition, continuous improvement programs are applied by Philips to align the current supply chain with the changing market need. Besides the strong growth and the quest for continuous improvement, Philips experiences difficulties with the clearance and the material availability of spare parts in China.
It is the intention of the SPS department to have a better insight into the Chinese market. Therefore, the main topic of this research is to study and analyze the Chinese supply chain. The current spare parts supply configuration is first evaluated to find possible improvements.

Current supply chain configuration

The spare parts supply chain of Philips comprises warehouses at different hierarchy levels. Therefore, the supply chain can be characterized as a multi-echelon supply chain. The Chinese supply chain starts at one of the three RDCs located in Louisville, Roermond, and Singapore, whereafter the parts are shipped to one of the two bonded LDCs (Local Distribution Centers) located in Beijing and Shanghai. From the LDCs, the parts are either directly shipped to the customer or they are stocked in a key market warehouse before being shipped to the customer. All spare parts are rooted to either one RDC or to all three. In the latter case, the network root is virtual. The spare parts demand is expected to be satisfied in 90% of the cases from stock. Thus, a 90% material availability is used as service level constraint in China.

Alternative supply chain configurations

Each alternative configuration focuses on optimizing the main performance indicators, namely the total costs and the output of the aggregate mean waiting time (AWT) with a material availability constraint. In addition, a low total value of parts on stock is desired. Furthermore, the function of RDC Singapore is questioned by changing the supplying location of the emergency shipments to either the root location or to only RDC Roermond and RDC Louisville. Currently, all the emergency shipments are supplied from RDC Singapore. In addition, both the options of replenishment from RDC Singapore and replenishment from the root location with emergency speed is researched.
In general, increasing the supplying speed results in higher costs while decreasing the supplying speed results in lower costs. With these adjusted configurations, four additional case studies are formulated. Table 1 represents the five cases with the corresponding input parameters.

Input	Initial case	Alt. case 0	Alt. case 1	Alt. case 2	Alt. case 3
Replenishment	Root location	RDC SGP	Root location	Root location(F)*	RDCs RMD & LVL
Em. shipments	RDC SGP	RDC SGP	Root location	RDC SGP	RDCs RMD & LVL
Virtual rooted	RDC SGP	RDC SGP	RDC SGP	RDC SGP	RDC LVL
SGP rooted	RDC SGP	RDC SGP	RDC SGP	RDC SGP	RDC RMD

Table 1: Input parameters for the five case studies. * = Fast replenishment

Results

The current supply chain network configuration is examined for a subset of 1000 SKUs (Stock Keeping Units). These costs are divided into emergency shipment costs (43%), lateral transshipment costs (5%), replenishment costs (23%), and holding costs (29%). As these percentages demonstrate, the total lateral transshipment costs are relatively small. The total emergency shipment costs are relatively high because of the high emergency shipment costs per SKU i.e. the parts first have to be replenished and handled in RDC Singapore before shipment to China. Besides the emergency shipment costs, the relatively high holding costs are caused by the long replenishment time in combination with the high material availability. When the material availability rises even higher, the percentage holding costs of the total costs rises as well. The AWT with the current material availability constraint is considered as relatively short, 0.43 days.

The current situation is examined by adjusting several control parameters. These adjustments did not result in a better overall solution. Namely, decreasing the replenishment time by changing the replenishment location from the root location to replenishment from RDC Singapore, resulted in a large increase in total costs (66%). In addition, decreasing the replenishment time by replenishment with emergency speed also resulted in a large increase in total costs (76%). Moreover, the emergency shipment location is also examined. The change from emergency shipments supplied from RDC Singapore to emergency shipments supplied from the root location resulted in a 6% decrease in total costs while the AWT increased with 58%. Likewise, when RDC Singapore is disregarded, the virtual rooted and RDC Singapore rooted parts are supplied from either RDC Roermond or RDC Louisville. As a consequence, the same pattern in output is recognized, the total costs decreases with 3% while the AWT increases with 73%. Therefore, none of these alternative cases are recommended to implement directly.

The planning tool (MCA planning tool) used by Philips for calculating the basestock levels with different service level constraints requires to provide for each of the 644 groups of SKUs a specific material availability constraint. This material availability constraint has to be manually entered per group by a planner. In addition, the material availability is calculated per service area (LDC Beijing and LDC Shanghai) instead of for the whole economic region (China). As a result, the overall material availability of the economic region and therefore the total material availability of the total set of spare parts in China is determined by calculating the average material availability for each service location over these 644 groups. This results in a total material availability which has to satisfy the material availability constraint. When the material availability does not satisfy the target, the planner manually adjusts the material availability of the groups until the material availability target is met. This method is sub-optimal and very laborious and therefore far from optimal i.e. the initial case compared with the output of the planning tool with the same input variables results in a 26% decrease in total costs. In addition, when the initial case is compared with the original output, the total costs are even further reduced namely with 34% with maintaining the material availability constraint and an excepted AWT.

Recommendations

1. The main conclusion is that the current supply chain configuration, compared with the alternative supply chain configurations, performs really well taking the most important performance indicators into account i.e. the total costs, the AWT and the material availability. These variables can be optimized, however, the variables have a strong dependency. Therefore, when one of these output parameter values is optimized, other output parameters are neglected. Because of this, is it recommended not to change the supplying location or speed of the emergency shipments nor the supplying location or speed of the replenishment shipments, the current supply chain configuration still performs better.

2. The material availability constraint does not take the emergency shipment time and lateral transshipment time into account. On the contrary, a waiting time constraint would take this into account. Therefore, the service level constraint is recommended to change from a material availability constraint to a waiting time constraint. For this moment, however, the best option to increase the material availability is by literally increasing the material availability constraint. When the material availability is increased to 95%, the total costs would increase with only 7% while the AWT decreases with 50%.

3. When RDC Singapore is disregarded, all the shipments are supplied from RDC Roermond and RDC Louisville. This results in lower total costs with an increase in AWT due to the increase in emergency shipment time. Disregarding RDC Singapore could have a large impact on the smaller markets being supplied from RDC Singapore, they would also have to change their supply chain. For China, disregarding RDC Singapore would affect all the emergency shipments and both the RDC Singapore rooted and virtual rooted parts replenishment. As a consequence, a hybrid solution is introduced between disregarding RDC Singapore entirely and the current situation. This solution means that RDC Singapore is scaled down and only the virtual parts and RDC Singapore rooted parts are supplied from RDC Singapore. The other parts are either emergency shipped from the root location or from neighbouring countries. The emergency shipment supply from neighbouring countries would result in a spare parts pooling system. However, this option still needs to be investigated and could result in major issues with the import and export of parts. In addition, high emergency shipment costs are an expected consequence of the pooling system. Therefore,

further research about a spare parts pooling system with neighbouring countries in combination with a scaled down RDC Singapore, is needed. To conclude, disregarding RDC Singapore would not be beneficial without this pooling system between the neighbouring countries and is therefore not recommended to directly implement. The hybrid solution could be an option when a scale down of RDC Singapore is desired. Otherwise, is it recommended to stay with the current replenishment and emergency shipment configuration.

4. Research the possibilities of integrating the key market warehouses (Chengdu, Guangzhou, Beijing, and Shanghai) into the MCA planning tool. The current situation aggregates the demand of the key market warehouses to one of the two LDCs. The demand allocated to the key market warehouses is closer to the customer, and therefore, faster at the site of the customer and more beneficial. This can make a significant difference in service for the customer.

5. The adjusted spare parts inventory control model used and applied in this research, originating from Kranenburg and Van Houtum (2009), is recommended to test the performance of similar markets.

6. The MCA planning tool requires to provide for each of the 644 groups of SKUs a specific material availability constraint. This material availability constraint is manually entered per group. In addition, the material availability is calculated per service area (LDC Beijing and LDC Shanghai) instead of the economic region (China). This method is sub-optimal and very laborious. Therefore, when only one aggregate material availability constraint for China is used and lateral transshipments are accounted for, the optimal basestock levels be determined by the optimization heuristic to efficiently calculate the basestock levels of each SKU. Summed up, decrease the number of groups. When only one aggregate material availability constraint for the entire economic region is taken into account and the lateral transshipments are accounted an impressive 34% reduction in total costs can be realized.

Preface

This thesis is the result of my graduation project, that I have conducted at Royal Philips in Best, in completion of the Master Operations Management & Logistics at Eindhoven University of Technology. I am glad for the opportunity to graduate at this company. I would like to thank all the people that made this project possible, for their interest in my project, and support.

First, I would like to thank my supervisors from the university. In particular I want to express my gratitude to my first supervisor Herman Blok. I really enjoyed and appreciated our meetings. I would like to thank for your critical eye and precision. I also want to thank you for your flexibility in planning our meetings, I always enjoyed them. Thank you for your support and guidance throughout this project. Further, I also want to thank Geert-Jan van Houtum for helping me in the beginning of the project for defining the research questions and for providing really good feedback after the concept version.

Second, I want to thank Philips for giving me the opportunity to write this thesis, for showing me around in the company, and providing me with this project. A special thanks to Japke van der Wal, who supervised me during the project, and always triggered the question why something happened; "People can say a lot but try to verify it with data". Thanks for constantly triggering me, asking the questions that got me start thinking again, and helped me to see the helicopter view of the project. Again, thank you for your guidance and for getting the best out of me.

Finally, I want to thank my family and friends who unconditionally supported me during the entire project. I want to thank my friends for being good sparring partners. I also want to thank them for the long evenings in the library, for working together on our theses, and having dinner together. This really encouraged me making the best efforts for finishing my thesis. To conclude, in memory of my nephew and grandfather who unfortunately passed in the last months.

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1 Introduction and research question

Hospitals and clinics depend heavily on their medical equipment. They make use of these devices for both planned and unplanned treatments. The reliance on, and availability of these machines is crucial and of the utmost importance since human lives may depend on it. This having said, equipment downtime is very expensive since hospitals use this medical equipment in their primary processes (Driessen et al., 2015). In the industry, this medical equipment is are characterized as capital goods. Driessen et al. (2015) classify the downtime of capital goods into, on the one hand, diagnosis and maintenance time; and on the other hand, maintenance delay caused by unavailability of the required resources. The original equipment manufacturer provides after sales support services to perform the maintenance activities. This service often guarantees either to fix the problem within a certain time limit or the presence and aid of a service engineer at the location of the machine in question within an agreed time frame. Therefore upon failures, the spare parts should be quickly accessible at the right location; and the FSE (Field Service Engineer) should be available and operational in the shortest period of time possible when prompted. The more efficient and systematized these procedures become, the better this will be for Royal Philips.

This master thesis researches the spare parts supply chain and it compares different configurations of the spare parts supply chain. Several components of this supply chain may be considered for reconfiguration; such as: the service level, the replenishment location, the emergency shipment location, and the replenishment and emergency shipment time.

The outline of this chapter looks as follows; First, Section 1.1 recounts the history of Royal Philips and the company background. It also describes summarily the goal and role within Royal Philips of the Service Parts Supply Chain Department along with its partners. Section 1.2 goes about the Chinese spare parts supply chain. In Section 1.3, a brief explanation of the replenishment logic is given. In Section 1.4, the research questions will be discussed while in Section 1.5 the thesis scope is defined. Finally, Section 1.6 provides the outline of the report.

1.1 Company background

This section briefly describes the company background. Section 1.1.1 recounts the history of Royal Philips, its foundation, later expansion and the company profile while Section 1.1.2 mainly focuses on a more detailed description of the SPS department.

1.1.1 Royal Philips

Royal Philips (henceforth Philips) was founded in Eindhoven in 1891. It started with the production of carbon-filament lamps. Soon, Philips broadened its activities and added research to the business. A laboratory, called NatLab was established; which has served as the company's main research center. Over the years, the research center moved to the south of the city marking the beginning of the High Tech Campus in Eindhoven. With a history spanning well over a century, Philips has been continuously expanding its horizons, including the production of many more electronic products. Currently, Philips is, among others, a manufacturer of medical devices with a turnover of 24.5 billion in 2016 and a corresponding net income of 1.5 billion. Moreover, Philips currently employs nearly 115.000 FTEs and operates with 95 production sites in 25 different countries. Furthermore, its sales and services are exploited in approximately 100 countries.

The company's vision is making the world healthier and more sustainable through innovation. This is in line with its mission to "improve the quality of people's lives through technology and enable meaningful innovations as co-creator" (Philips, 2017). Additionally, Philips wants to be a strategic partner for the Philips businesses and complementary, be an open participant in the innovation ecosystem.

1.1.2 Service Parts Supply Chain Department

The present research is performed for the SPS department (Service Parts Supply Chain department). It is the objective of the SPS department to maximize the spare part availability against minimal costs. This work is carried out by optimizing inventory levels and strategically allocating the spare parts. The SPS department is also responsible for the total spare parts supply chain; for both, the forward and the reverse flow. The forward flow, for Philips in general, covers the chain starting at the Philips factories and external suppliers, and it ends at the customers. The customers are either the FSE (Field Service Engineer) or the Key Market (KM). Along with this task, SPS is responsible for regulating the reverse flow starting at the customers, going by a blue room and ending at a Regional Distribution Center (RDC), a Local Distribution Center (LDC) or a Forward Stocking Location (FSL). RDCs, LDCs and FSLs are all owned and operated by UPS; but controlled by the SPS department.

The main function the SPS department has is the reliable and cost effective delivery of high quality service parts worldwide. In essence, their goal is to obtain a high service level against reasonable costs. SPS carries out this work with three strategic partners: Accenture, UPS and Sanmina. All the transactional activities of the spare parts management are outsourced to Accenture. UPS is the responsible partner for transport and warehousing of the spare parts. Sanmina, in turn, is responsible for the re-utilization of the spare parts. The activities performed by Sanmina are: the repair, testing and repacking of the spare parts in order to become ready for use. Between these three partners SPS stands as controller. This partnership is visualized in figure 1.

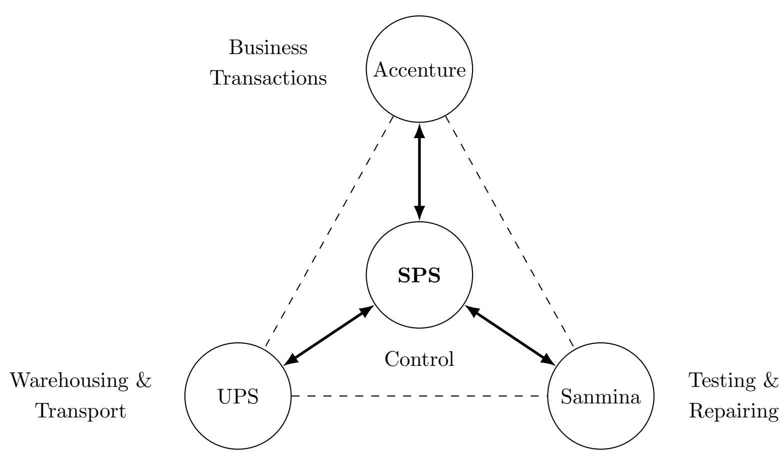

Figure 1: Visualization of structural relationship of partnerships

1.2 Service parts supply chain for China

The service parts supply chain comprises three regions: AMEC (US, Canada, and Latin America), APAC (Asia-Pacific) and EMEA (Europe, Middle East, and Africa); each region having its own RDC. For AMEC, RDC Louisville; for APAC, RDC Singapore; and for EMEA, RDC Roermond. All the spare parts are supplied by one of these root RDCs. The parts rooted to only one RDC are produced in the same region (e.g. produced in Germany, rooted to RDC Roermond). In addition all spare parts are rooted to either one warehouse or to all three. In the latter case the network root is virtual. When a part is virtually rooted, the demand in one of the three regions is replenished from its own RDC. For example, when Spain request a replenishment for a virtually rooted part, the part is supplied from RDC Roermond. The root location is, in most cases, RDC RMD (Roermond)(46%) and RDC LVL(25%) (Louisville). Only a small share of these parts is rooted in RDC SGP (Singapore)($< 1\%$).

The Chinese spare parts cycle involves two different flows; namely, the forward flow and the reverse flow. The forward flow starts at either the supplier or at a business unit factory owned by Philips. From here, the parts flow to one of the RDCs. Thereafter, the part will be either shipped directly to respectively LDC Beijing and LDC Shanghai or otherwise shipped to RDC Singapore. The flow from the two different LDCs can either go directly to the customer or first to one of the four key market warehouses. The locations of these key market warehouses are: Chengdu, Guangzhou, Beijing, and Shanghai.

The reverse flow starts at the customer, whereafter the (defective or unsealed) spare parts flow to the blue-room. After this, the part can either flow back to a warehouse, or flow to a repair vendor / scrap vendor. This process is visualized in figure 2.

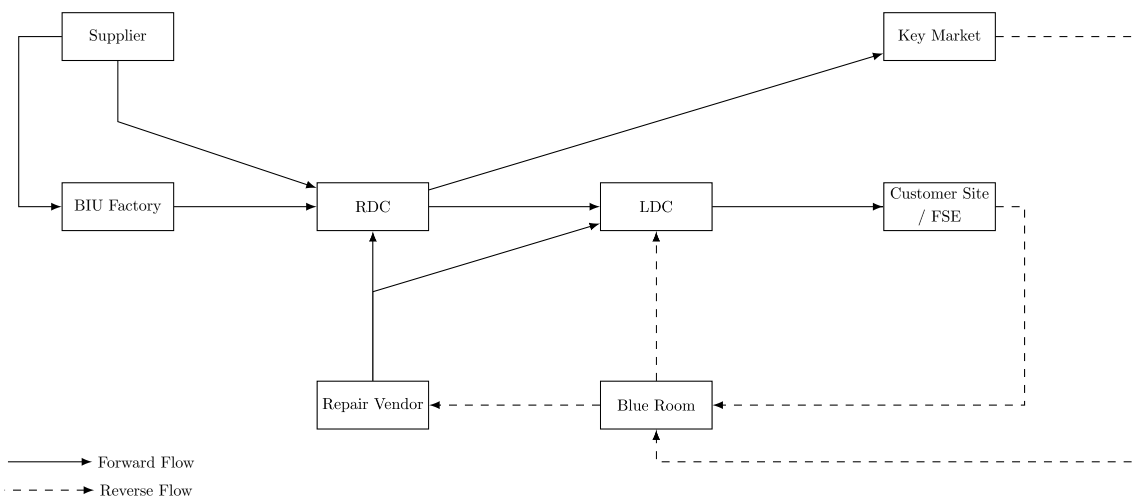

Figure 2: Visualization of the Chinese spare parts flow

1.3 Replenishment logic

The spare parts replenishment policy applied by the SPS department is the (s,S)-inventory policy. Whenever the inventory position becomes under the reorder level (ROL), the difference between the inventory position and the target stock level (TSL) is reordered. This quantity is also called the reorder quantity

(ROQ). Since for most SKUs (Stock Keeping Units) the ROQ is equal to 1, the replenishment policy boils down to the (S-1,S)-inventory policy. All these parts are replenished by the TARN logic. This is an acronym for Transship, Allocate, Repair and New buy. Whenever a part is out of stock, the warehouses at the same echelon are checked first for excess parts. If no excess parts are on stock there, the warehouses on a higher echelon are checked. These warehouses on a higher echelon will deliver only if they have unrestricted parts on stock, parts that are not yet assigned. When these warehouses, located more centrally, are low on stock, the parts are kept centrally. Then, the replenishment demand is continued to the repair shop. When this part is planned to be released at the repair shop, the part is considered to be shipped. If no parts are planned to be released, a new-buy order is executed.
The program Philips uses to coordinate this is the MCA tool, which optimizes the ROL and TSL within each group of SKUs. Within this group, the system optimization approach is used to allocate the parts especially taking into account the historic demand. In this way, the expensive slow movers in the group of SKUs have a lower material availability than the inexpensive fast movers. In Section 2.7, the MCA optimization and basestock level allocation method is discussed in more detail.

1.4 Research Questions

The main goal of the SPS department is to have the correct spare parts at the right place and at the right time, against minimal costs. Since the world is changing fast, old configurations need to be evaluated and assessed, especially taking into consideration the emerging markets. The most important emerging market is China, which experiences a yearly growth of 8% per year. This fact has a strong impact on the supply chain network. Besides the strong growth and the search for continuous improvement, Philips experiences a lot of difficulties with the clearance in China.

It is the intention of the SPS department to have a better insight into the Chinese market. Therefore, the main topic of this research will be to study and analyze the Chinese supply chain. The current spare parts supply chain configuration will first be evaluated in order to find possible improvements. Some of the initial choices made in the past concerning network design are being questioned due to the dynamic environment in which SPS operates. In addition, the transportation rates may have changed, thus giving room to alternative solutions. The key market in China is particularly interested in options to reduce the inventory levels due to the high holding costs and the high value of total stock on hand. The SPS department aspires to research an alternative design for the replenishment supply chain, with lower total logistic costs but keeping the same or higher material availability.

The current replenishment network for China is a two- or multi-echelon network with RDC Singapore as emergency shipment location and the SKU's root location as replenishment location. The key market and the FSEs are the final customers. The SPS department is therefore interested to see how an improved inventory planning strategy for China would affect the target stock levels and the total costs with a fixed material availability.

Based on this interest, the following questions are formulated:

1. What is the structure of the Chinese spare parts supply chain?

2. What are the service level constraints China has to deal with?

3. How does China perform with the current setup?
4. How does China perform with both replenishment and emergency shipments supplied from RDC Singapore?
5. What alternative configurations could be beneficial in terms of total costs, material availability, total value of stock on hand, and aggregate mean waiting time?

1.5 Scope

The scope of this research is divided into three different segments. First, in Section 1.5.1, the scope is described in terms of the geographical area. In Section 1.5.2 the SKUs (Stock Keeping Units) are considered. Finally, in Section 1.5.3, the relevant network flow is discussed.

1.5.1 Geographical area

This research solely focuses on the mainland of China. The semi-independent province of Taiwan is excluded because in this area, the import and export of service parts experiences significant smaller delays. Hong Kong, the autonomous territory south of the Chinese mainland is also excluded in this research because of the fewer import restrictions. Therefore, both Hong Kong and Taiwan are independently planned from China.

1.5.2 Service parts

The focus of this research is on all the SKUs (Stock Keeping Units), except the FCO segmented parts. The SKUs segmented as FCO (Field Change Order) parts are excluded in this research. These parts are shipped independently from the demand and also in larger quantities. A case of a field change order could be for example a cooling system, the cooling system of a certain type of MRI scanner has a possibility of a gas leak. In this case, all these cooling systems would have to be replaced; and the order for these new cooling systems would be disconnected from the normal stream.

1.5.3 Network flow

Only the forward flow will be taken into account in this research. The reverse flow, which deals with defective or unsealed parts, is left out of scope. Both flows experience problems with the clearance. However, in addition to the clearance problems, also issues with the material availability are experienced. Therefore, only the forward flow will be taken into account.

1.6 Outline Report

The remaining part of this report is structured in five chapters. This first chapter addresses the history of the company and it gives an introduction to this research. Chapter 2 deals with the current setup for the service parts supply chain. Chapter 3 explains the model applied to optimize the stock levels. Chapter 4 discusses the results of the different case studies. Finally, in Chapter 5, a conclusion is drawn; and some concrete recommendations and suggestions are offered for Philips' consideration.

2 Current setup

This chapter addresses the current spare parts supply chain configuration for China. Section 2.1 describes the current configuration. Moreover, Section 2.2 explains the demand fulfillment procedure. Furthermore, Section 2.3 breaks down the total costs, putting the emphasis on the holding and shipment costs. In Section 2.4, the demand rates are discussed. In addition, Section 2.5 describes the shipment leadtimes; and finally, in Section 2.6 the different product segmentations are described.

2.1 Configuration

The spare parts supply chain of Philips comprises warehouses at different hierarchy levels. Therefore, the supply chain can be characterized as a multi-echelon supply chain. The Chinese supply chain starts at one of the three RDCs whereafter the parts are shipped to one of the two LDCs (Beijing or Shanghai). From the LDCs, the parts are either shipped directly to the customer or otherwise they are stocked in a key market warehouse before being shipped to the customer. All parts are rooted to one of these warehouses: 46% of the different SKUs is rooted in Roermond; 25% of the SKUs is rooted in Louisville; only 1% of the SKUs is rooted in Singapore; and 29% of the SKUs has a virtual root. The parts segregated on volume result in 34%, 26% and 1% respectively supplied from the RDC in Roermond, Louisville and Singapore. In addition, 39% of the volume of the parts is supplied from the virtual root location. Since China is located in the APAC region, the virtual parts for the Chinese market are supplied from RDC Singapore.

2.2 Demand fulfillment

All the Chinese demand follows the same demand fulfillment procedure. First, the stock is checked at the local warehouse experiencing the demand. When this warehouse is out of stock, the demand is referred to a different key market warehouse or LDC on the same echelon. If neither of these warehouses can deliver, RDC Singapore is checked for stock. If again, RDC Singapore is out of stock, the demand is referred to RDC Roermond or RDC Louisville. Whenever the parts are supplied from an external country, the delivery goes through one of the LDCs to the customer.

2.3 Cost Structure

The total supply chain costs can be divided into holding costs, shipment costs and clearance costs. The shipment costs, in turn, can be split up into replenishment costs, lateral transshipment costs, and emergency shipment costs. The cost components are discussed in Section 2.3.1, Section 2.3.2, and Section 2.3.3.

2.3.1 Holding costs

The holding costs are a major contributor to the total costs. The holding costs can be split up into warehousing costs, investment costs, and acquisition costs for the risk of that part of becoming obsolete. The warehousing costs include the inbound handling costs, the storage costs, and the outbound handling costs. The handling costs are charged per orderline and are linear with the amounts shipped. The storage costs are based on the volume of each SKU. In contrast, both the obsolescence costs and the investment costs are based on the SKU's value. Since the costs related to the SKU's value are predominant, the holding costs per SKU are approximated by charging 20% of the SKU's value by the SPS department. Even though the relation with the SKU's value and the holding costs is not linear, the assumption of charging 20% holding costs based on the SKU's value may be justified since 92% of the costs is based on the value and only 8% is based on warehousing costs.

2.3.2 Shipment costs

As we said before, the shipment costs can be split up into replenishment costs, lateral transshipment costs, and emergency shipment costs. The shipment costs can be divided into transportation costs to China and, sometimes, for parts rooted to RDC Roermond and RDC Louisville, handling costs in Singapore and replenishment costs to Singapore.

The transportation costs for each specific lane need to be calculated. These costs mainly depend on the shipment speed and on the chargeable weight of the SKU. The chargeable weight CW is based on the maximum of the volume (length (l), width (w), and height (h)) and actual weight (aw) in kilograms. This is formulated as follows; $CW = max(\frac{l*w*h}{6000}, aw)$. The slowest transportation times are used for the replenishment. These rates with the lowest urgency are charged per CW i.e. UPS Economy Airfreight. On the contrary, the fastest shipment times are used for the emergency shipments. Therefore, for the transportation service with the highest urgency UPS Parcel Express is used. The lateral transshipments are carried out by a Chinese carrier.

The replenishment costs depend on the supplying warehouse, the receiving warehouse, the SKU's characteristics, and the replenishment urgency. When the SKUs are replenished from the root location, only the transportation costs need to be taken into account. However, when the part is not replenished from the root location, handling costs and additional shipment costs are taken into account as well. Figure 3 represents the replenishment lanes in the current configuration. This figure shows the direct replenishment lanes for the parts supplied from the root location. The transportation rates are linear per chargeable weight, starting at 30 kg. Since nearly every combination of SKUs is heavier than 30kg, the costs are assumed to be linear per 0.5 kg starting at a minimum CW of 0.5 kg.

The emergency shipments are all supplied from RDC Singapore. The emergency shipment costs for the parts rooted to RDC Singapore and the virtually rooted parts consist only of the transportation costs from RDC Singapore to China. On the contrary, the parts rooted to RDC Roermond and RDC Louisville include replenishment costs to RDC Singapore, handling costs in RDC Singapore, and emergency transportation costs to China. These lanes are graphically shown in Figure 4. The emergency shipment rates provided in this figure are only provided to give an indication of the costs per CW. The replenishment rates from RDC LVL to RDC SG and from RDC RMD to SGP are linear. The emergency shipment transportation rates are not linear, the rates are provided in the appendix in Table 20. These rates are provided per 0.5 kg of chargeable weight.

The lateral transshipments are either shipped from LDC Beijing to LDC Shanghai or the other way around. In conversation with the Chinese planners, it was decided to use the average shipment time of 24 hours to model this later on. The carrier charges the CW per kilogram starting with a minimum of 10 kg. However, since this threshold is nearly always reached by combining different SKUs, the transportation costs are assumed to be linear per 0.5 kg.

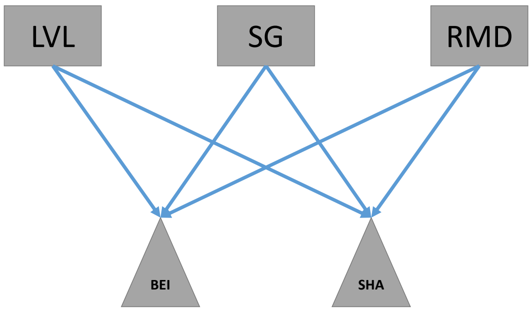

Figure 3: Initial Case, SKU replenishment.

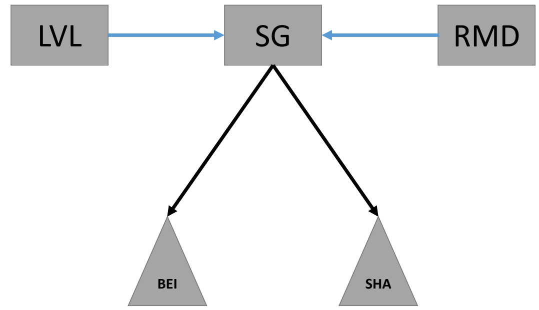

Figure 4: Initial Case, SKU emergency shipment.

2.3.3 Clearance

The custom clearance in China is an important factor in the spare parts supply chain. All parts need to pass two different clearance types. The first clearance type is the more expensive and more difficult one. The clearance costs are in general 20% of the part's value. All the parts need to pass this type of clearance when physically entering China. This clearance takes a couple of days and it depends on the part, the day in the week (week vs. weekend), and on the Chinese holidays. The Chinese national holidays are shown in Table 2. In addition, Figure 6 and Figure 7 represent the average monthly replenishment and emergency shipment times supplied from the root location to China. When Table 2 is compared with Figure 6 and Figure 7, a correlation between the Chinese holidays and peak transportation times can be visualized. Especially, the peaks in October and February representing the National Days and Chinese New year are emphatically present. The peak in June, with the Dragon Boat festival is only visible in the emergency shipment leadtimes. When comparing these figure, please note the different values on the y-axis.

The second clearance type is the national clearance. This type of clearance is performed only once a month after the sales for all the parts sold during that period. The national clearance is performed after the sales thanks to the function of the bonded warehouses (LDC Beijing and LDC Shanghai). These bonded warehouses have the qualification of selling and shipping the parts right after the first clearance and before the second clearance. Therefore, the administrative task of the national clearance is performed after the sale. Without the bonded warehouses, the national clearance has to be performed right after the first clearance and would cost an additional 3 to 4 working days for regular parts. However, if a CCC (China Compulsory Certification) license is required, it is not possible to clear the parts in without a bonded warehouse. Therefore, bonded warehouses are considered to be essential and of high value.

The impact of the clearance time on the transportation time is processed as additional replenishment or emergency shipment time for each lane. The clearance costs cannot be omitted and therefore left out of the scope of this project.

2.4 Demand rates

The demand rates per year are determined by summing up the demand over 2016 for each SKU. LDC Beijing and LDC Shanghai satisfy respectively 85% and 15% of the yearly Chinese demand. The difference of demand satisfied by LDC Beijing and LDC Shanghai is caused by difference in service area. LDC

Chinese holidays:	Date
Labour Day	1-2 May 2016
Dragon Boat Festival	9-11 Jun 2016
Mid Autumn Festival	15-17 Sept 2016
National Day	1-9 Oct 2016
New years eve	31 Dec-2 Jan 2016-2017
Chinese new Year	27 Jan-2 Feb 2017
Qingming	2-4 April 2017

Table 2: Chinese holidays

Beijing serves three key market warehouses (i.e. Beijing, Chengdu, and Guangzhou) in addition to the demand directly shipped to the customers. LDC Shanghai only serves its own the key market warehouse (Shanghai). Figure 5 shows the shipments to the key market warehouses.

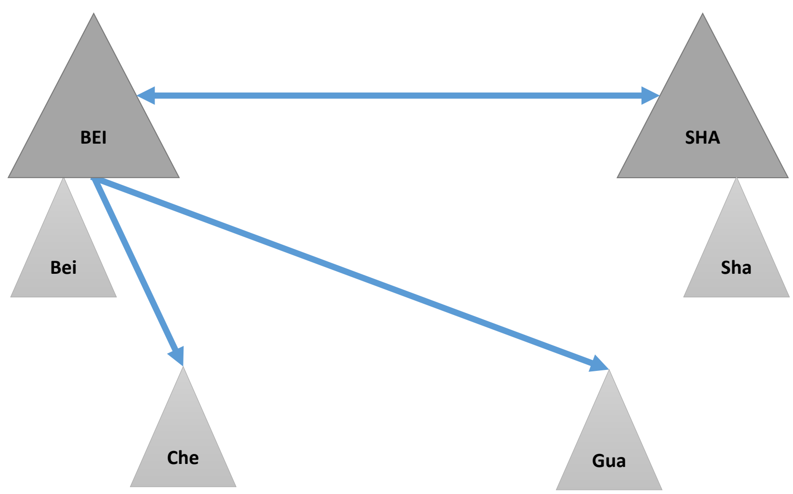

Figure 5: Demand stream from LDC Beijing and LDC Shanghai to their key market warehouses.

2.5 Shipment leadtimes

The shipment leadtimes are determined by averaging historical leadtimes for both the replenishment and emergency shipments. The leadtimes used for this analysis are the leadtimes from May 2016 to May 2017 from the root location to one of the bonded warehouses. The leadtime is defined as the time it takes from the initiation of the order until the completion, the arrival and ready for delivery, of the order. No distinction is made for replenishment and emergency shipment leadtimes between from the root location to LDC Beijing and LDC Shanghai since the difference is insignificant. The average replenishment leadtime per month for each lane is determined and shown in Figure 6. The total average of the total replenishment times or emergency shipment times are used as average replenishment leadtime or average emergency shipment leadtime. This results for the lanes RMD-CN, LVL-CN, and SGP-CN in 13.3 days, 12.3 days, and 6.2 days respectively. The applied replenishment leadtimes in the MCA planning tool for the lanes RMD-CN, LVL-CN, and SGP-CN are 17 days, 18 days, and 8 days respectively. These increased leadtimes are used to guarantee the delivery with a 90% certainty.

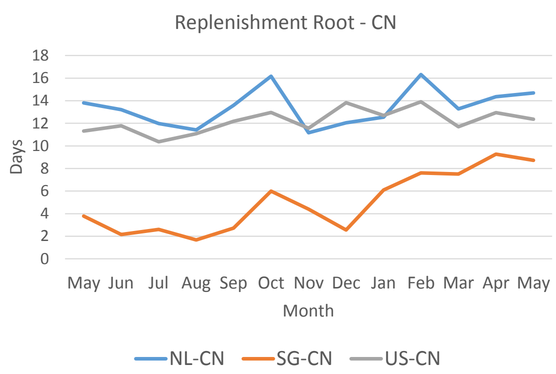

Figure 6: Average monthly replenishment time from RDC Roermond (NL), RDC Louisville (US), and RDC Singapore (Singapore), to China

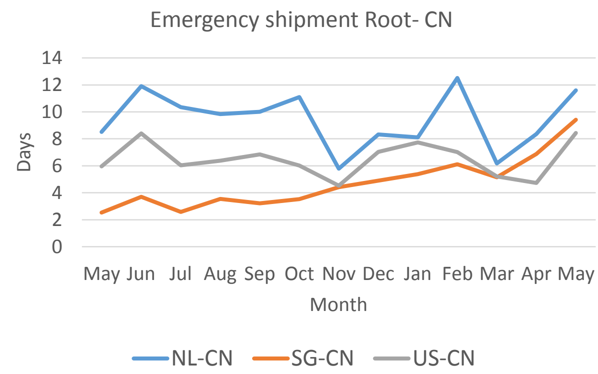

Figure 7: Average monthly emergency shipment time from RDC Roermond (NL), RDC Louisville (US), and RDC Singapore (SG), to China.

2.6 Product segmentation

Each part is by the SPS department allocated to a segment. The parts can be subdivided into either repairable or consumable parts; or in parts segmented to demand and SKU's characteristics. The repairable parts are repaired after failure, whereas the consumables are scrapped. The segments based on both the demand and the SKU's characteristics are shown in Table 3.

Segment	Definition	Perc. of demand	Perc. of SKUs
CCP	Customer Critical Parts	18.8%	8.4%
EOL	End Of Life	1.7%	2.6%
FCO	Field Change Order	-	-
HCFM	High Cost Fast Movers	8.6%	5.7%
LCFM	Low Cost Fast Movers	49.3%	34.2%
LTB	Last Time Buy	1.3%	3.2%
NPI	New Product Introduction	6.6%	3.3%
Slow	Slow moving	11.9%	41.3%
TO	Tools for repair or installation	1.0%	0.9%
Tubes	Tubes	0.9%	0.3%

Table 3: Spare parts segmentation

2.7 Material availability

The material availability is defined as the percentage of the demand complete and on time available in the economic region where the request originates. China, without Hong Kong and Taiwan, is one economic region. The material availability constraint for the Chinese market is 90%, determined by the SPS department. This material availability target is planned for both LDC Beijing and LDC Shanghai separately. However in the realization, the material availability is met when at least one of the two warehouses has on hand stock. Therefore, the lateral transshipment costs and lateral transshipment time are not taken into account but the parts are transshipped from LDC Beijing to LDC Shanghai and the other way around. As a consequence, the material availability for one location is not used as aggregate constraint for both warehouses. In addition, all the SKUs are again divided in 644 subgroups. These groups are unique for each combination of the modality (MRI, Xray, CT etc), the root location, and the segment. The material availability for each group is manually inserted. When all these material availabilities are determined, the MCA tool calculates an overall material availability what could be lower or higher than the desired material availability. Thereafter, the planner can adjust the material availabilities of the different groups to decrease or increase the aggregate material availability of for each service region. The material availability of the SKUs in each group are optimized with the given material availability constraint. As a result, the total material availability for all the groups together is just a weighted average.

The applied replenishment leadtimes in the MCA planning tool for the lanes RMD-CN, LVL-CN, and SGP-CN are 17 days, 18 days, and 8 days respectively. The incentive of SPS to use these leadtimes is to assure the delivery of the part on time with 90% certainty. In reality, the average replenishment leadtimes are for RMD-CN, LVL-CN, and SGP-CN are 13.3 days 12.3 days, and 6.2 days. The increased leadtimes together with the manual allocated material availabilities lead to an increase in the overall material availability. The material availability is expected to be larger than the target material availability because the used leadtimes are not averages but leadtimes assuring an on-time delivery of 90%. Therefore, the planners of the SPS department manually decrease the overall material availability target to 86% to approximate the 90% final material availability.

The material availability used as constraint for all the parts, versus a material availability constraint for each subgroup, is in terms of total costs at least as good as the material availability constraint for each subgroup. However, in general only one aggregate material availability is much better. Therefore, in the current configuration and the alternative configurations, the material availability is used as an aggregate constraint for the economic region China.

3 Spare parts inventory model.

This chapter describes the inventory replenishment model used to describe the current situation. First, in Section 3.1 spare parts inventory models with both emergency shipments and lateral transshipments are introduced. Thereafter, in Section 3.2 the applied spare parts inventory model is explained. The assumptions for this model are given and elaborated on in Section 3.3. Finally, the evaluation and the optimization methods are described in Section 3.4 and Section 3.5 respectively.

3.1 Introduction

The current Chinese spare parts supply chain has a multi-item, multi-location setup and this needs to be modelled appropriately. The demand at a local warehouse can be satisfied in three different ways: from stock, by means of an emergency shipments, or by means of a lateral transshipments. Lateral transshipments are stock movements between warehouses of the same echelon (Paterson et al., 2011). This means there is a possibility for shipments between the warehouses in Beijing and Shanghai.

The model explained in this chapter is used for two purposes. First, this model is used to generate the performance of the current configuration of the Chinese supply chain. Second, alternative configurations of the Chinese supply chain are proposed and calculated with this model. The main objective of this research is to minimize the network wide costs, using a material availability constraint. The material availability is used as service level constraint because it is the main Chinese performance indicator used by Philips.
Here, as opposed to Kranenburg and Van Houtum (2009), the waiting time variable is not used as optimization constraint, the waiting time is only generated as output. The waiting time is dependent on the one hand on the lateral transshipment time and the emergency shipment time and on the other hand on the material availability and fraction of demand satisfied by a lateral transshipment. These shipment times are independent on the material availability.

Kranenburg and Van Houtum (2009) developed a single-echelon, multi-location, multi-item model with lateral transshipments and emergency shipments. In this model, two different types of local warehouses are distinguished i.e. regular local warehouse and main local warehouses. The main local warehouses can both request and perform a lateral transshipment whereas the regular local warehouses can only request one. This model from Kranenburg and Van Houtum (2009) is adjusted to be applicable to the current Chinese spare parts replenishment flow. Since both warehouses in China are able to supply lateral transshipments, only main local warehouses need to be considered. This leads to a full pooling situation.

In case of a demand at a local warehouse, the availability is checked. If this warehouse is out of stock, the other local warehouse is checked. When both warehouses are out of stock, an emergency shipment from one of the central warehouses takes place. It is assumed that the central warehouses are always able to deliver the requested parts. The moment none of the local warehouses have the particular part on stock, the material availability of the particular part at this moment is 0.

3.2 Model

Let I denote the (non-empty) set of SKUs. Let $J = \{1, 2\}$ denote the set of local warehouses and $K (\subseteq J)$ the set of main local warehouses. Both warehouses, LDC Beijing and LDC Shanghai are considered as main local warehouses. The total demand for SKU $i \in I$ at local warehouse $j \in J$ is assumed to follow a Poisson process with a constant rate $M_{i,j}$. The corresponding waiting time is zero whenever SKU $i \in I$ is on stock.

The moment a part is ordered at a local warehouse, a request for replenishment is submitted at the central warehouse allocated to supply this part. Since each SKU is supplied from only one of the three central warehouses, there is no necessity of introducing additional parameter indices. The replenishment time t_i^{rep} and the replenishment costs c_i^{rep} depend respectively only on the replenishment location versus both on the replenishment location and chargeable weight of each SKU. Therefore, the replenishment time can adopt only three different values. The chargeable weight CW used to calculate the transportation rates is based on the maximum of the volume (length (l), width (w) and height (h)) and actual weight (aw). This is formulated as follows; $CW = max(\frac{l*w*h}{6000}, aw)$.
Whenever local warehouse j does not have stock of the particular SKU, the demand is first tried to be satisfied by means of a lateral transshipment from the other local warehouse. The corresponding lateral transportation time from main local warehouse $k \in K$ $k \neq j$ to main local warehouse $j \in J$ is t^{lat} with c_i^{lat} as the corresponding costs, also dependent on the CW. If none of the local warehouses has stock on hand, an emergency shipment from one of the central warehouses takes place. The corresponding transportation time and costs, $t_i^{em}(\geq t^{lat}, k \neq j)$ and $c_i^{em}(\geq c_i^{lat} k \neq j)$, are dependent on respectively only the root location and on both the root location and the CW. The central warehouses are assumed to have infinite stock of all SKUs and are therefore always able to fulfill the demand. In addition, the emergency shipment time t_i^{em} and emergency shipment costs c_i^{em} are significantly larger than the t_i^{rep} and c_i^{rep} $i \in I$. Therefore, a replenishment shipment is preferred over an emergency shipment, in addition to the material availability as service level constraint. The costs of the emergency shipments delivered from Singapore, for the SKUs rooted in either Roermond or Louisville, are comprised of: the replenishment costs to Singapore, the handling costs in Singapore and the fast shipment costs for the lane from Singapore to China.
The holding costs c_i^{hol} are the costs to stock one SKU $i \in I$ for one year. This value is the same for both local warehouses and is approximated by taking 20% of the SKU's value. The moment the part is ordered, the part is assumed to be bought already. Therefore, the part may be treated as being on stock concerning the holding costs.

Kranenburg and Van Houtum (2009) assume fixed transportation costs for each distance, they assume the shipment costs are mainly dependent on the distance. However, in Philips' case, the shipment costs are mainly dependent on the CW of the part. Therefore, the CW per part is multiplied by the shipment rate for each lane and are specific for each SKU.

All the warehouses are assumed to be controlled by a basestock policy. The basestock level for SKU $i \in I$ in local warehouse $j \in J$ is denoted by $S_{i,j}$. $S_i = (S_{i,1}, S_{i,2})$, $i \in I$ denotes the vector of basestock levels for SKU i. The basestock policy for the whole system is denoted by:

$$S = \begin{pmatrix} S_{1,1} & S_{1,2} \\ S_{2,1} & S_{2,2} \\ \vdots & \vdots \\ S_{|I|,1} & S_{|I|,2} \end{pmatrix}$$

With respect to the fulfillment of a demand for SKU $i \in I$ for a local warehouse $j \in J$, the following notation is used:

- $\beta_{i,j}(S_i)$ The fraction of the demand of SKU i at local warehouse j delivered directly on demand from stock.
- $\alpha_{i,j}(S_i)$ The fraction of demand for SKU i delivered to local warehouse j by means of a lateral transshipment by local warehouse $j-3$.
- $\theta_{i,j}(S_i)$ The fraction of the demand of SKU i delivered to local warehouse j by the allocated central warehouse by means of an emergency shipment.

The total fractions of demand for SKU $i \in I$ together should be one. This comprises three fractions: the total demand for SKU $i \in I$ delivered directly upon request, the total fraction of demand delivered by an emergency shipment for SKU $i \in I$, and the total fraction of demand delivered by means of a lateral transshipment for SKU $i \in I$. This is shown in the following formula:

$$\beta_{i,j}(S_i) + \theta_{i,j}(S_i) + \alpha_{i,j}(S_i) = 1 \tag{1}$$

The mean waiting time $W_{i,j}(S_i), i \in I, j \in J$ for SKU i requested at local warehouse j can be determined by multiplying the different fractions of demand by the corresponding shipment times. This results in the following equation:

$$W_{i,j}(S_i) = t^{lat}\alpha_{i,j}(S_i) + t_i^{em}\theta_{i,j}(S_i) \tag{2}$$

The mean waiting time $W_i(S_i)$ for each SKU $i \in I$ at the same echelon can be determined by multiplying the mean waiting time $W_{i,j}(S_i), i \in I, j \in J$ by the fraction of the demand satisfied at local warehouse i divided by the total demand of the SKU i. The yearly demand in China for each SKU can be denoted with $M_i = \sum_{j \in J} M_{i,j}$. The total yearly demand for all SKUs is denoted with M. The mean waiting time $W_i(S_i)$ can be calculated as follows:

$$W_i(S_i) = \sum_{j \in J} \frac{M_{i,j}}{M_i} W_{i,j}(S_i) \tag{3}$$

In addition, the aggregate mean waiting time $W(S)$ for the system can be calculated.

$$W(S) = \sum_{i \in I} \frac{M_i}{M} W_i(S_i) \tag{4}$$

The total inventory holding costs for each SKU $i \in I$ at local warehouse $j \in J$ can be calculated by multiplying the basestock level of each SKU i by the holding costs per part $c_i^{hol} S_{i,j}$.
The total holding costs for SKU $i \in I$ is given by the following formula.

$$\sum_{j \in J} c_i^{hol} S_{i,j} \tag{5}$$

The total transportation costs for SKU $i \in I$ are equal to:

$$\sum_{j \in J} M_{i,j} \Big(c_i^{rep}(1 - \theta_{i,j}(S_i)) + c_i^{lat} \alpha_{i,j}(S_i) + c_i^{em} \theta_{i,j}(S_i) \Big) \tag{6}$$

The total costs per year for SKU $i \in I$ is denoted with $C_i(S_i)$.

$$C_i(S_i) = \sum_{j \in J} c_i^{hol} S_{i,j} + \sum_{j \in J} M_{i,j} \Big(c_i^{rep}(1 - \theta_{i,j}(S_i)) + c_i^{lat} \alpha_{i,j}(S_i) + c_i^{em} \theta_{i,j}(S_i) \Big) \tag{7}$$

The total costs for the whole system can be calculated by summing up the different costs over SKU $i \in I$, $C(S) = \sum_{i \in I} C_i(S_i)$. The objective is to minimize the total costs for all SKUs together with an MA (material availability) constraint, MA^{obj}.

$$MA(S) = 1 - \frac{\sum_{i \in I} \sum_{j \in J} \theta_{i,j}(S_i) M_{i,j}}{M} \tag{8}$$

$$\begin{aligned} P \qquad min \qquad & C(S) \\ s.t. \qquad & MA(S) \geq MA^{obj} \\ & S \in \phi \end{aligned} \tag{9}$$

$$\phi = \{S = (S_{i,j})_{i \in I, j \in J} | S_{i,j} \in \mathbb{N}_0, \forall i \in I \, and \, j \in J\}$$

3.3 Assumptions

1. **The stock in all local warehouses is controlled by a basestock policy.**
   The selected subset used in the case studies contains only SKUs with ROQ=1.

2. **The demand and the demand overflow are both Poisson processes.**
   This is a common assumption in the literature on spare parts inventory models. In addition, in 2015 Huyps (2015) studied this assumption with a generic χ^2 test. This test can be used to compare two data samples. In addition, Huyps used the monthly demand with four years of data and randomly selected five different SKUs which were used to perform the analyses. With these data Huyps tested each SKU with five different tests. None of these tests rejected the assumption, which can therefore not be rejected.

3. **The central warehouses are assumed to have infinite stock.**
   The central warehouses are the three RDCs respectively Roermond, Louisville and Singapore. Dependent on the case study, percentages of the demand are met from each central warehouse. The material availability of each SKU, at the root location, is at least 95%.

4. **Replenishment transportation leadtimes are generally distributed.**
   Alfredsson and Verrijdt (1999) have shown by simulation that the researched two-echelon model is, to a large extent, insensitive to the replenishment leadtime distribution. Therefore, the leadtimes are assumed to be generally distributed.

Notation	Description
i	Index for each SKU $i \in I$.
I	Set of SKUs.
j	Index for each local warehouse $j \in J$.
J	Set of local warehouses.
C_i^{lat}	Lateral transshipment costs for each SKU i from the local warehouses to each other.
C_i^{rep}	Replenishment costs for SKU $i \in I$.
C_i^{em}	Emergency shipment costs for SKU $i \in I$.
C_i^{hol}	Holding costs for each SKU $i \in I$.
t^{lat}	Lateral transshipment time.
t_i^{rep}	Replenishment time for SKU $i \in I$.
t_i^{em}	Emergency shipment time for SKU $i \in I$.
$M_{i,j}$	Demand rate for SKU $i \in I$ at local warehouse $j \in J$.
M_i	Total yearly demand for SKU $i \in J$.
M	Total aggregated yearly demand for all the SKUs over the two local warehouses.
$C_i(S_i)$	Total costs per year for each SKU $i \in I$.
$C(S)$	Total costs per year for all the SKUs together.
$\beta_{i,j}(S_i)$	Fraction of the demand for SKU $i \in I$ at local warehouse $j \in J$ delivered directly from stock.
$\alpha_{i,j}(S_i)$	Fraction of the demand for SKU $i \in I$ delivered to local warehouse $j \in J$ via a lateral tansshipment by local warehouse $j - 3$.
$\theta_{i,j}(S_i)$	Fraction of the demand for SKU $i \in I$ delivered at local warehouse $j \in J$ by means of an emergency shipment.
MA^{obj}	Material availability objective.
$MA(S)$	Aggregate mean material availability.
$W_{i,j}(S_i)$	Mean waiting time for SKU $i \in I$ at local warehouse $j \in J$.
$W_i(S_i)$	Mean waiting time for SKU $i \in I$
$W(S)$	Aggregate mean waiting time.

Table 4: Notation description

3.4 Evaluation

An approximate evaluation is used to determine the different fractions of demand satisfied by either a lateral transshipment $\alpha_{i,j}(S_i)$ or directly from stock $\beta_{i,j}(S_i)$. The fraction of demand delivered by an emergency shipment $\theta_{i,j}(S_i)$ is evaluated exactly. The evaluation can be performed for each SKU $i \in I$ separately. The choice for an approximate evaluation is justified because of the good performance in calculation time and accuracy. The numerical analyses of the exact and approximate evaluation performed by Kranenburg and Van Houtum (2009) of asymmetric instances with $(J \leq 4)$ are compared. The difference between the exact and approximate evaluation is the same as the difference between the $\beta_{i,j}(S_i)$ and the $\alpha_{i,j}(S_i)$ because the fraction of demand satisfied by an emergency shipment is exact. With a maximum basestock of 2, absolute errors are less than 1%. From the numerical results, we can conclude that this approximation works well. The optimal basestock levels for the subset are expected to mainly contain values ≤ 2 since the majority of the spare parts has a low yearly demand and is relatively expensive to hold on stock. Therefore, we conclude that this evaluation is assumed to perform well evaluating the current Chinese supply chain.

The Erlang loss queuing model $M|G|c|c$ is used to represent the number of servers in the system. Let $L(c, \rho)$ denote the loss probability in the Erlang loss model where $c \in \mathbb{N}_0$ represents the number of servers and $\rho(> 0)$ represents the offered load which is by convention $L(0, \rho) = 1, \rho > 0$. $L(c, \rho)$ returns the probability of blocking and therefore not being able to satisfy the demand from stock. This probability is the chance that the offered load (replenishment time * the demand) is bigger than the number of servers (the basestock level). The Erlang loss formula is decreasing and convex in ρ and therefore expected to converge.

$$L(c, \rho) = \frac{\frac{\rho^c}{c!}}{\sum_{x=0}^{c} \frac{\rho^x}{x!}} \tag{10}$$

Between the two local warehouses, there is a possibility for lateral transshipments. These lateral transshipments are regarded as an extra demand process for a local warehouse and are assumed to behave as a Poisson process. The extra demand is approximated in an iterative process with $\hat{M}_{i,\tilde{k},k}$ as the rate with which main $\tilde{k}$ requests a lateral transshipment from main k. The equation for the $\hat{M}_{i,\tilde{k},k}$ is provided in Formula 11. This formula is built up from four different elements i.e. $\alpha_{i,\tilde{k}}(S_i)$, $M_{i,\tilde{k}}$, $\beta_{i,k}(S_i)$, and $\hat{M}_{i,\tilde{k},k}$. $\alpha_{i,\tilde{k}}(S_i)$ as the fraction of the demand for SKU $i \in I$ at local warehouse $\tilde{k} \in K, \tilde{k} \neq k$, that is delivered by means of a lateral transshipment. Moreover, $M_{i,\tilde{k}}$ denotes the direct demand process at local warehouse $k \in K$ for SKU $i \in I$. In addition, $\beta_{i,k}(S_i)$ denotes the fraction of demand for SKU i at local warehouse k that is delivered immediately upon request. Finally, $\hat{M}_{i,\tilde{k},k}$ as the overflow demand rate with which main $\tilde{k}$ requests a lateral transsshipment from main k. This fraction $\hat{M}_{i,\tilde{k},k}$ is derived from two fractions with the same outcome. The first fraction is $\alpha_{i,\tilde{k}}(S_i)M_{i,\tilde{k}}$, the total fraction of the demand rate at local warehouse $\tilde{k}$ supplied by a lateral transshipment from main k. The second fraction is $\hat{M}_{i,\tilde{k},k}\beta_{i,k}(S_i)$, the total demand of local warehouse k that is satisfied by means of a lateral transshipment. Since the total fraction of the demand at local warehouse $\tilde{k}$ supplied by a lateral transshipment is the same as the total demand of local warehouse k satisfied by means of a lateral transshipment (only two local warehouses), the following holds $\alpha_{i,\tilde{k}}(S_i)M_{i,\tilde{k}} = \hat{M}_{i,\tilde{k},k}\beta_{i,k}(S_i)$, therefore:

$$\hat{M}_{i,\tilde{k},k} = \begin{cases} \frac{\alpha_{i,\tilde{k}}(S_i)M_{i,\tilde{k}}}{\beta_{i,k}(S_i)}, & S_{i,k} > 0 \\ 0 \quad , & otherwise \end{cases} \tag{11}$$

The formal evaluation algorithm described in Table 5 is an iterative procedure to approximate the $\beta_{i,k}(S_i)$ and the $\alpha_{i,k}(S_i)$. This procedure starts with determining the $\theta_{i,k}(S_i)$, with $\theta_{i,k}(S_i) = L(\sum_{k\in K} S_{i,k}, \sum_{k\in K} M_{i,k}t)$ (Step 1). Thereafter, an initial value for $\beta_{i,k}(S_i)$ and $\alpha_{i,k}(S_i)$ is determined with the assumption of no lateral transshipments between the two local warehouses $k \in K$, $\beta_{i,k}(S_i) = 1 - L(S_{i,k}, M_{i,k}t)$ and $\alpha_{i,k}(S_i) = 1-(\beta_{i,k}(S_i)+\theta_{i,k}(S_i))$ (Step 2). In this first iteration step, $\hat{M}_{i,k}$ and $M_{i,k}$ are assumed to be equal because both $\beta_{i,k}(S_i)$ and $\alpha_{i,k}(S_i)$ are dependent and therefore, $\hat{M}_{i,k} = M_{i,k}$. Then, the $\hat{M}_{i,k}, k \in K$ and $\hat{M}_{i,\tilde{k},k}, k, \tilde{k} \in K, \tilde{k} \neq k$, are approximated in this iterative process. Formula 11 is used to determine $\hat{M}_{i,\tilde{k},k}$ and $\hat{M}_{i,k} = M_{i,k} + \hat{M}_{i,\tilde{k},k}$. Thereafter, the Erlang Loss model is applied for both local warehouses to approximate $\beta_{i,k}(S_i) = 1 - L(S_{i,k}, \hat{M}_{i,k}t)$ and with this value $\alpha_{i,k}(S_i) = 1 - \beta_{i,k}(S_i) + \theta_{i,k}(S_i)$ is determined (Step 3). As a result, a first approximation is made to determine $\hat{M}_{i,\tilde{k},k}$, $\hat{M}_{i,k}$, $\beta_{i,k}(S_i)$, and $\alpha_{i,k}(S_i)$ for both local warehouses (Step 4). This iterative procedure is repeated for both local warehouses until the $\hat{M}_{i,k}$, for each local warehouse, finds convergence (Step 5). This means in practice until $\hat{M}_{i,k}$ does not change more than ϵ, a really small positive number. After convergence, the approximated value for $\alpha_{i,k}(S_i)$ can be determined with $\alpha_{i,\tilde{k}}(S_i) = \beta_{i,\tilde{k}}(S_i)\frac{\hat{M}_{i,k,\tilde{k}}}{M_{i,k}}$ (Step 6).

Evaluation Algorithm	
Step 1	For both local warehouses $k \in K$, $\theta_{i,k}(S_i) = L(\sum_{k\in K} S_{i,k}, \sum_{k\in K} M_{i,k}t)$
Step 2	For both local warehouses $k \in K$, $\beta_{i,k}(S_i) = 1 - L(S_{i,k}, M_{i,k}t)$, and $\alpha_{i,k}(S_i)) = 1 - (\beta_{i,k}(S_i) + \theta_{i,k}(S_i))$
Step 3	For *one main* $k \in K$:
Step 3-a	Determine $\hat{M}_{i,\tilde{k},k}$ using formula 11, and $\hat{M}_{i,k} = M_{i,k} + \hat{M}_{i,\tilde{k},k}$.
Step 3-b	$\beta_{i,k}(S_i) = 1 - L(S_{i,k}, \hat{M}_{i,k}t)$, and $\alpha_{i,k}(S_i) = 1 - (\beta_{i,k}(S_i) + \theta_{i,k}(S_i))$
Step 4	Repeat Step 3 for the other main $k \in K$.
Step 5	Repeat Step 3 and 4 until $\hat{M}_{i,k}$ does not change more than ϵ for each $k \in K$, with ϵ small.
Step 6	For both mains $k \in K$, $\alpha_{i,\tilde{k}}(S_i) = \beta_{i,\tilde{k}}(S_i)\frac{\hat{M}_{i,k,\tilde{k}}}{M_{i,k}}$.

Table 5: Evaluation Algorithm

3.5 Optimization

The Greedy heuristic tries to find a feasible solution with as low costs as possible for Problem (P). This algorithm essentially exists of three different parts. The first part is the initialization part, the second part optimizes the costs regardless of the constraints, and the third part finds the optimal solution taking the service level constraint into account by finding the optimal fraction. This fraction is the difference in improvement towards the constraint and the downturn in costs. Wong et al. (2005) have shown the performance of the exact evaluation with the application of the Greedy heuristic and a local search algorithm. The performance of this combination was significantly strong. Kranenburg and Van Houtum (2009) performed additional experiments without the local search algorithm. The set of SKUs tested, contained both 50 and 100 SKUs for respectively 2, 3, or 4 warehouses. This resulted in a maximum gap of 3.7% compared to the lower bound obtained by the Dantzig-Wolfe decomposition. In addition, Kranenburg and Van Houtum (2009) found that the gap is decreasing when the number of instances increase. This implies the strong performance of the Greedy heuristic.

In the initialization step, the basestock levels $S_{i,j}$ are set to 0. The second step is the cost minimization step where the stock levels are increased as long as the total costs decreases. The basestock levels, in this step, are increased separately for each SKU $i \in I$. These basestock levels are increased until the costs cannot be decreased further. When this level is reached, the optimal basestock levels in terms of total costs are determined.

$$\Delta_j C_i(S_i) = C_i(S_i + e_j) - C_i(S_i) \tag{12}$$

Here, e_j denotes the j-th unit vector with dimension $|I|$. The basestock levels $S_{i,j}, i \in I, j \in J$ are again increased iteratively. The feasible solutions are divided into a subset $\phi^{feas} = \{S \in \phi | MA(S) \geq MA^{obj}$ for all $j \in J\}$.

The distance to the feasible solution is denoted with $d(S)$.

$$d(S) = MA^{obj} - MA(S) \tag{13}$$

The decrease in distance to the feasible solution per SKU is given by $-\Delta_{i,j} d(S)$, $e_{i,j}$ is an $|I| * |J|$ matrix with a 1 on the (i,j)'th position and zeros on all the others).

$$\Delta_{i,j} d(S) = d(S + e_{i,j}) - d(S) \tag{14}$$

Let $\Gamma_{i,j}$ denote the decrease in distance to the feasible solutions per unit of increase in costs. The combination of SKU i and local warehouse j with the highest ratio $\Gamma_{i,j}$, is the so-called "biggest bang for the buck". This increase in basestock level is chosen and increased by one, $S_{i,j} + 1$. This step is performed iteratively until the constraint is met.

$$\Gamma_{i,j} = \frac{-\Delta_{i,j} d(S)}{\Delta_j C_i(S_i)} \tag{15}$$

The formal Greedy heuristic is described in Table 6. The three steps discussed earlier in this chapter correspond with the three steps described in this table.

Greedy heuristic	
Step 1	Set $S_{i.j} = 0, i \in I, j \in J$
Step 2	For each SKU $i \in I$:
Step 2-a	Calculate $\Delta_j C_i(S_i), j \in J$ (Formula 12);
Step 2-b	While $\min_{j \in J}\{\Delta_j C_j(S_i)\} \leq 0$:
a)	Determine j' such that $\Delta_{j'} C_i(S_i) \leq \Delta_j C_i(S_i), j \in J$;
b)	Set $S_{i,j'} = S_{i,j'} + 1$;
c)	Calculate $\Delta_j C_j(S_i), j \in J$
Step 3	
Step 3-a	Calculate $\Delta_{i,j} C(S), \Delta_{i,j} d(S)$, and $\Gamma_{i,j}, i \in I, j \in J$
Step 3-b	While $d(S) > 0$:
a)	Determine i' and j' such that $\Gamma_{i',j'} \geq \Gamma_{i,j}, i \in I, j \in J$;
b)	Set $S_{i',j'} = S_{i',j'} + 1$;
c)	Calculate $\Delta_{i,j} C(S), \Delta_{i,j} d(S)$, and $\Gamma_{i,j}, i \in I, j \in J$

Table 6: Greedy heuristic

3.6 Model verification

The programming procedure of the model discussed in the previous section is iteratively programmed in Matlab. First the $\theta_{i,j}, \alpha_{i,j}$, and $\beta_{i,j}$ are calculated and verified with a verified example. The configurations of this example are similar to the configurations in the current supply chain network (i.e. asymmetric instances with two main local warehouses). These examples are provided by Kranenburg and Van Houtum (2009). Subsequently, these value are used for the optimization procedure on SKU level and then on subset level.

4 Case studies

This chapter addresses five different case studies and their performances. Each case study is composed with different supply chain network configurations. The first case (i.e. the initial case) discusses the performance of the current supply chain configuration. The second, third, fourth, and fifth case (i.e. alternative case 0 to 3), represent additional supply chain configurations. These alternative configurations are based on either decreasing the total value of stock on hand or decreasing the total costs. In addition, the necessity of RDC Singapore is evaluated. Table 7 represents the five case studies with the corresponding input parameters. The case studies are all evaluated with a material availability of 85%, 90%, and 95%. The output of this analysis is compared in terms of total costs, aggregate mean waiting time (AWT), and total value of parts on stock. In addition, the output of each case study is compared with the output of the initial case. The initial case is also compared with the output generated by the MCA planning tool, with the original input and with the same input as in the initial case. Furthermore, four extreme cases with expensive, cheap, heavy, and light SKUs are compared. These outcomes are tested for sensitivity by respectively decreasing and increasing the input parameter values by 50%. Finally,

This chapter is structured in ten sections. In Section 4.1, the chapter is introduced and the input parameters are explained. In Section 4.2 to Section 4.6, an elaboration on the five case studies is given and the corresponding results are provided. Thereafter, in Section 4.7, the five case studies are compared in terms of total costs, waiting time, material availability and total value of stock on hand. In Section 4.8, the output of the MCA planning tool is compared with the output of the initial case. In Section 4.9, four cases with extreme subsets are evaluated. Finally, in Section 4.10, the total costs of the initial case and the alternative cases are tested on sensitivity by changing the control parameter values.

Input	Initial case	Alt. case 0	Alt. case 1	Alt. case 2	Alt. case 3
Replenishment	Root location	RDC SGP	Root location	Root location(F)	RDCs RMD & LVL
Em. shipments	RDC SGP	RDC SGP	Root location	RDC SGP	RDCs RMD & LVL
Virtual rooted	RDC SGP	RDC SGP	RDC SGP	RDC SGP	RDC LVL
SGP rooted	RDC SGP	RDC SGP	RDC SGP	RDC SGP	RDC RMD

Table 7: Input parameters for the five different case studies.

4.1 Introduction

The main objective of each case study is to minimize the total costs with a material availability constraint. The material availability constraint for the total Chinese demand is set to 90% by the SPS department. The evaluation in terms of total costs and waiting time, for each case study, is obtained by a subset of the total set of SKUs. The subset is preferred to analyze over the total set of SKUs due to run time limitations. The Greedy heuristic in specific increases the total calculation time when the size of the subset increases. This relation between the size of the subset and the calculation time is shown in Figure 9, the size in hundreds and the calculation time in seconds.

For each case study, the same subset is used to evaluate and optimize the basestock levels. The subset is selected, based on the segmentation of the SKUs. The fraction represented by one segment in the total set is represented in the same fraction in the subset (e.g. 8.4% are CCP parts, both in the total set as in the subset). These parts are randomly selected per segment. The size of the chosen subset is 1000 SKUs which is assumed to be sufficient to represent the total set of 6592 SKUs because the characteristics of

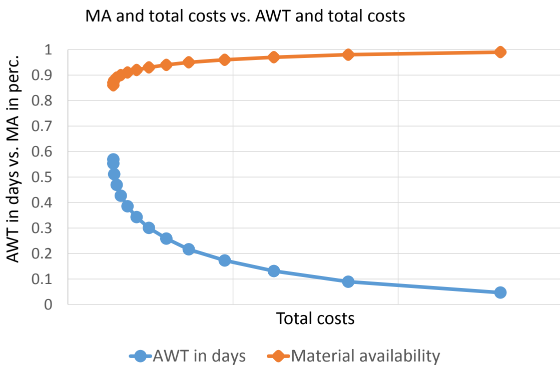

Figure 8: The total costs for a material availability constraint and the corresponding AWT in the initial case.

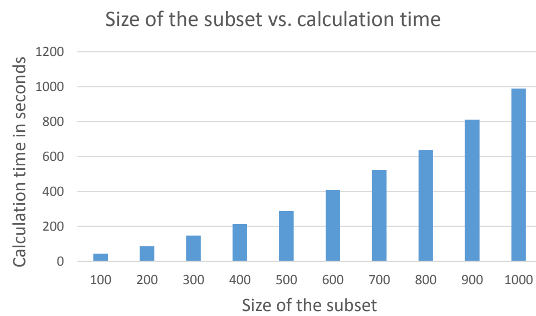

Figure 9: The calculation time for the initial case with the number of SKUs varying from 100 to 1000, and the calculation time from 0 - 990 seconds.

both sets are similar as represented in the appendix in Table 18. The total demand for the selected subset is 15,340 parts with 16.62 parts per SKU, an average SKU value of \$916.98, an average weight of 7.73 kg, and an average volume of 58,124 cm^2. The total Chinese demand experienced over 2016 was 109,534 parts with an average demand, value, weight, and volume of 15.43, \$954.54, 8.16 kg, and 52,830 cm^2 respectively. The total demand in the subset requested from LDC Beijing and LDC Shanghai is 12,521 and 2,819 parts respectively. The total demand requested from LDC Beijing and LDC Shanghai in 2016 was 93,862 and 15,672 parts respectively.

4.1.1 Input parameters

The control parameter values for each case input are unique. The difference between the case studies is mainly obtained by changing the shipment time, the shipment costs, the shipment supplying location, and the shipment speed.

The parameter values are determined by using historical data. The yearly demand $M_{i,j}$ for each SKU $i \in I$ is the demand experienced in 2016. The indices i, j represent the 1000 SKUs and the two local warehouses, $|I| = 1000$ and $|J| = 2$. The replenishment shipment time t_i^{rep} and emergency shipment time t_i^{em} are determined by averaging respectively the replenishment and emergency shipment times over the period from May 2016 to May 2017. The lateral transshipment time is set to 24 hours in consultation with the local market planners. These shipment times are assumed to be independent on the characteristics of the parts such as the weight and size. The replenishment costs c_i^{rep} are determined by the rates obtained from UPS Economy Airfreight rates and the chargeable weight of each part rounded up by 0.5kg. Moreover, the emergency shipment costs c_i^{em} are determined by the UPS Parcel Express service rates and the chargeable weight rounded up to 0.5kg. Furthermore, the lateral transshipment costs are also determined by the chargeable weight and the corresponding shipment rate. The holding costs c_i^{hol} are 20% of the part's value. The part value varies between \$0.10 and \$50,700.

4.2 The current supply chain configuration.

The current supply chain configuration is evaluated in this section. The main performance indicators are the AWT (aggregate mean waiting time), the material availability, the total value of parts on stock, and the total costs. Each performance indicator has main control variables contributing to the performance. For example, the waiting time is mainly determined by the material availability, the emergency shipment time, the lateral transshipment time, and the lateral transshipment frequency. Since the number of lateral transshipments is relatively small, mainly the emergency shipment time and material availability determine the AWT. Another example is the total value of parts on stock, this value is mainly determined by the replenishment time and material availability.

The current spare parts supply chain configuration is based on low cost replenishment with fast emergency shipments. Therefore, the replenishment is directly shipped from the root location and all the emergency shipments are shipped from the RDC the most nearby, RDC Singapore. The replenishment costs for each lane are based on the CW of each SKU. The replenishment lanes and the corresponding costs per CW for RDC Roermond, RDC Louisville, and RDC Singapore are shown in Figure 10. In turn, the emergency shipment costs are based on the transportation costs from RDC Singapore to China and, for the parts rooted to RDC Roermond and RDC Louisville, handling costs in RDC Singapore and replenishment costs to RDC Singapore. The emergency shipment costs are not linear namely transportation costs for a part with CW 0.5 kg are much higher per kilogram than a part with CW 50kg. These emergency shipment rates are shown in the appendix in Table 20. The emergency shipment lanes and costs are represented in Figure 11. In addition, the replenishment time from the root locations RMD, LVL, and SGP to China are 13.3 days, 12.3 days, and 6.2 days respectively. Moreover, the emergency shipment time from SGP to China is 4.2 days on average.

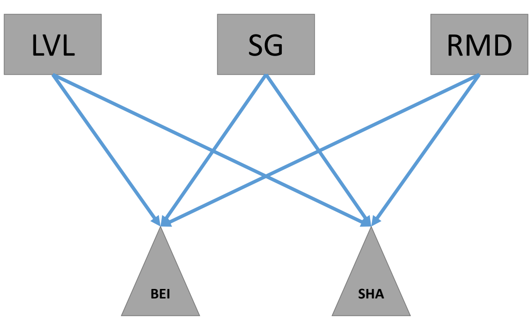

Figure 10: Initial Case, SKU replenishment.

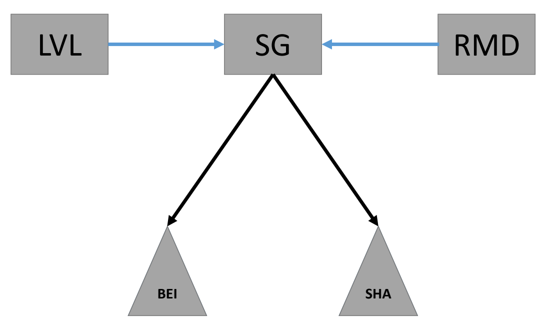

Figure 11: Initial Case, SKU emergency shipment.

4.2.1 Results

The total costs of the current situation are divided into different cost drivers namely the emergency shipment costs, the lateral transshipments costs, the replenishment costs, and the holding costs. The total costs, existing of these four costs drivers, are determined with a material availability constraint. The higher the material availability, the higher both the replenishment costs and holding costs, because more parts are kept on stock and therefore more replenished parts. In addition, when the material availability increases, the number of emergency shipments decreases. Therefore, the total emergency shipment costs also decrease. However, both the holding costs and the emergency shipment costs per part increase. The number of lateral transshipments is expected to decrease when the material availability increases because more demand is directly satisfied from stock. However, the higher the stock levels become, the more expensive the parts on stock become, and therefore, also the more expensive the lateral transshipment costs per part. Therefore, when the material availability rises, the number of lateral transshipment may decrease while the shipment costs per part increase.

When the optimal cost level is reached, an increase in material availability will cause an increase in total costs. The optimum configuration is expected to be reached when the holding costs, the replenishment costs, and the lateral transshipment costs are balanced with the emergency shipment costs.

The material availability in the current configuration is 90%, the remaining 10% is delivered by means of an emergency shipment. The current material availability is higher than the cost optimal material availability. Therefore, the holding costs are emphatically present. The total costs are divided into 43% emergency shipment costs, 5% lateral transshipment costs, 23% replenishment costs, and 29% holding costs. For three different material availabilities 86%, 90%, and 95%, the number of lateral transshipments slightly decreases while the total lateral transshipment costs increase. Therefore, the lateral transshipment costs per part increase. The total number of lateral transshipments for a 86%, 90%, and 95% material availability is 118, 112, and 109. For an increase in material availability, the replenishment costs increase faster than linear, the holding costs increase much faster than linear while the emergency shipment costs decrease faster than linear. However, the decrease in emergency shipment costs does not outweigh the increase in lateral transshipment costs, replenishment costs, and holding costs. Therefore, the total costs increase.

The AWT is mainly determined by the material availability and the emergency shipment time. When the material availability is changed from 90% to 95%, the amount of parts emergency shipped is bisected. Therefore, the AWT is also nearly bisected from 0.43 days to 0.22 days. The reverse holds for the lower 86% material availability. Therefore, the AWT for a material availability of 86%, 90%, and 95% is 0.57 days, 0.43 days, and 0.22 days respectively.

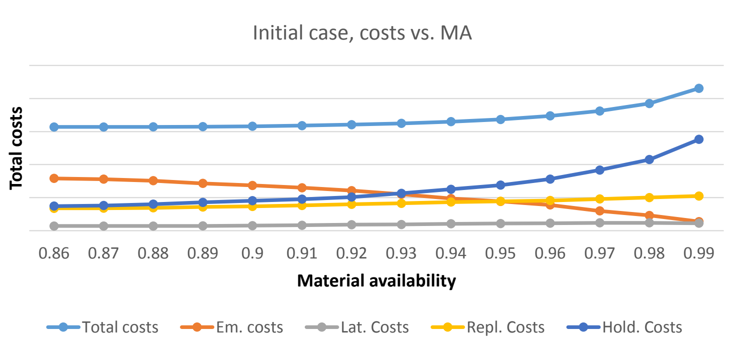

Figure 12: The total costs split-up in the emergency shipment costs, lateral transshipment costs, replenishment costs, and holding costs for an increasing material availability constraint.

The evaluation of the different cost drivers with an increasing material availability constraint are shown in Figure 12. This figure clearly shows that for an increasing material availability, the total costs increases, the emergency shipment costs decrease, the lateral transshipment costs increase, the replenishment costs increase, and the holding costs increase.

The material availability constraint is compared with the total costs and the AWT in days as output for the current configuration. The correlation between these three variables is graphically demonstrated in Figure 8. This figure shows that the optimal costs for the current configuration is at a material availability of 86%. The AWT is denoted in days whereas the material availability is denoted as a value between zero and one, both on the y-axis. The x-axis denotes the total costs. The total output for the current configuration is provided in Table 8.

Output	86% MA	90% MA	95% MA
Total costs	100%	100%	100%
Emergency shipment costs	50%)	43%	26%
Lateral transshipment costs	4%)	5%	6%
Replenishment costs	22%	23%	26%
Holding costs	24%	29%	41%
Total number of parts on stock	1,672	1,851	2,171
Total number of lat. trans.	118	112	109
Total value of parts on stock	110%	145%	205%
AWT	0.57 days	0.43 days	0.22 days

Table 8: Results, current configuration - Replenishment by root location and emergency shipments from RDC Singapore.

4.3 Alternative configuration 0 - Replenishment and emergency shipments supplied from SGP.

The control parameters in alternative case 0 are set in such a way that the total value of stock on hand and the corresponding holding costs are decreased in value compared to the current situation, even though it may result in higher replenishment costs. The most important control parameter determining the total value of stock on hand for a fixed material availability is the replenishment time. The replenishment time in the current situation can be decreased in basically two different ways. The first possibility is to reduce the transportation time for each replenishment. The second option, to decrease the replenishment time is to change the replenishment location i.e. to replenish everything from RDC Singapore. Therefore, in this alternative configuration, all the parts are replenished from the closest RDC to China i.e. RDC Singapore. As a result, the replenishment location is changed from the root location to RDC Singapore whereas the virtual parts and the RDC Singapore rooted parts are still replenished form RDC Singapore. The effect of changing the replenishment location to RDC SGP is also a desired configuration by the Chinese market planners, they question whether the implementation of this configuration could be more beneficial than the initial case in terms of total costs, AWT, and total value of stock on hand.

The difference between the current configuration and alternative configuration 0 is that the parts rooted in respectively RDC Roermond and RDC Louisville are first shipped to RDC Singapore, handled in the warehouse, and shipped to China for replenishment. Therefore, the replenishment costs could include three different cost fractions (i.e. the transportation costs from the root RDC to RDC Singapore, the handling costs in RDC Singapore, and the transportation costs from RDC Singapore to China). The replenishment time is 6.2 days which is a big decrease in transportation time compared to the initial 13.3 days and 12.3 days for the RDC Roermond and RDC Louisville rooted parts. The difference between the replenishment costs and the emergency shipment costs is the shipment priority from RDC Singapore to China. The replenishment lanes and the corresponding costs are shown in Figure 13. In addition, the emergency shipment lanes stay the same as the initial situation. These lanes are shown in Figure 14.

The total replenishment costs will increase in this configuration compared to the initial case because the parts rooted in RDC Roermond and RDC Louisville have higher replenishment costs. However, the shorter average replenishment time is expected to result in lower holding costs. The increase in replenishment costs is expected to outweigh the decrease in holding costs. As a result, the total costs are expected to increase.

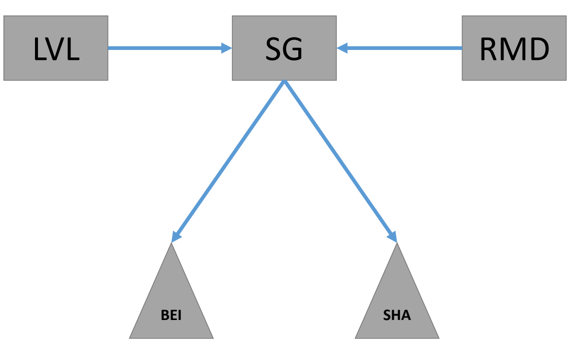

Figure 13: Alternative case 0, SKU replenishment.

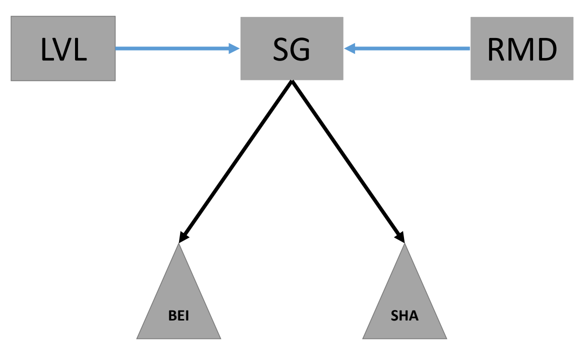

Figure 14: Alternative case 0, SKU emergency shipment.

4.3.1 Results

Alternative case 0 has, as expected, a weaker performance in terms of total costs compared to the initial case, both with a 90% material availability. The replenishment costs are more than tripled (361%) while the decrease in holding costs is much smaller, only 31%. This increase in replenishment costs is caused by the extra shipment costs to RDC Singapore and handling costs in RDC Singapore. The relation between the replenishment costs and the emergency shipment costs is changed. The added costs of an emergency shipment compared to a replenishment shipment are decreased for the parts rooted in RDC RMD and RDC LVL. Therefore, an emergency shipment could become more beneficial. As a consequence, the total emergency shipment costs have increased with 30%, even though the configuration remained the same. As a result, the total costs have increased with 66%. The total value of parts on stock experiences the same decrease in costs as the holding costs (17%).

The implementation of alternative case 0 could be beneficial in terms of the total value of parts on stock and total holding costs. However, a large increase in total costs can be expected, mainly due to the large increase in replenishment costs. The same conclusion is drawn for both an 85% and 95% material availability. An overview of the performance of alternative case 0, with the different cost drivers for an 85%, 90%, and 95% material availability, is shown in Table 9. In addition, the initial case with a 90% material availability is added to easily compare the differences between these cases.

Output	Init 90% MA	Result 85% MA	Result 90% MA	Result 95% MA
Total costs	100%	100%	100%	100%
Emergency shipment costs	43%	41%	34%	22%
Lateral transshipment costs	5%	3%	3%	5%
Replenishment costs	23%	48%	51%	55%
Holding costs	29%	8%	12%	19%
Total number of parts on stock	1,851	1,320	1,557	1,736
Total number of lat. trans.	112	140	142	134
Total value of parts on stock	145%	40%	60%	95%
AWT	0.43 days	0.64 days	0.43 days	0.22 days

Table 9: Results, alternative case 0 - Both replenishment and emergency shipments supplied from RDC SGP

4.4 Alternative configuration 1 - Replenishment and emergency shipments supplied from the root location.

The control parameter values of alternative case 1 are composed to decrease the total costs compared to the initial case. The emergency shipments are only handled once in this configuration. This results in delivery of both the replenishment and the emergency shipments supplied from the root location. The replenishment settings are the same in this case as in alternative case 1. On the contrary, the emergency shipments are supplied from the root location instead of RDC Singapore. This results in a cheaper route for the parts rooted in RDC Roermond and RDC Louisville. However, the emergency shipment times for the RDC Roermond and RDC Louisville rooted parts increase from 4.2 days to 8.9 days and 6.7 days supplied from Roermond and Louisville respectively to China. As a result, the AWT is expected to increase whereas the total emergency shipment costs are expected to decrease.
All the cost drivers are independent on the emergency shipment time. However, they are dependent on the emergency shipment costs, the lower emergency shipment costs are expected to only have a small positive influence on the replenishment costs and the holding costs. These replenishment and emergency shipment lanes are shown in Figure 15 and Figure 16.

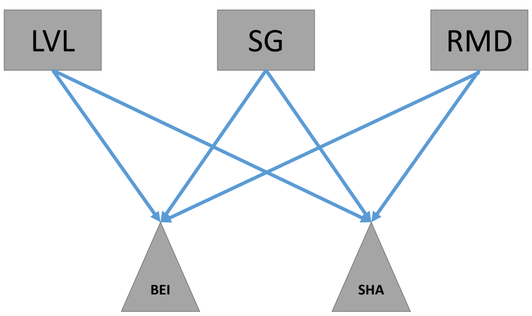

Figure 15: Alternative case 1, SKU replenishment.

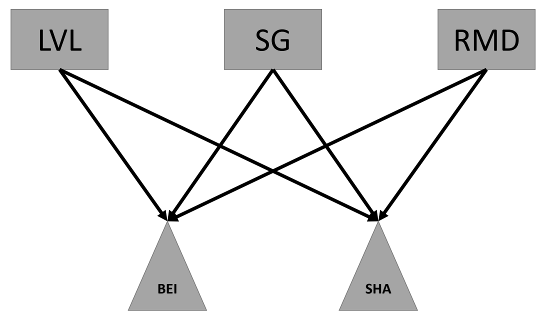

Figure 16: Alternative case 1, SKU emergency shipment.

4.4.1 Results

The total costs of alternative case 1 are, as expected, lower than the initial case. This holds for each material availability of 85%, 90%, and 95%, compared with the initial case with the same material availability.
The total emergency shipment costs are the main contributor of the reduced total costs. For the three different material availabilities, the difference between the initial case and alternative case 1 is decreasing. For an 85% material availability, alternative case 1 is about 7% cheaper whereas for a 90% material availability, the difference between the total costs is reduced to 6% between the two configurations. Finally, for a material availability of 95%, the difference left is only 3%. This reducing advantage of alternative case 1 to the initial case in total costs with a rising material availability is caused by the reduced amount of emergency shipments i.e. for a material availability of 95%, only 5% emergency shipments are shipped.
The AWT for the initial case and alternative case 1 for an 86% and 85% material availability are 0.57 days and 0.99 days. The AWT for alternative case 1 with a 90% and 95% material availability is in both cases about 50% longer. The cost optimal material availability in the initial case is 86% while in this optimal level is already reach at an 83% material availability in alternative case 1. With these optimal material availabilities, the total costs of alternative case 1 are 8% lower than the initial case. However, a large difference in AWT is experienced i.e. 0.57 days versus 1.12 days. As a result, alternative case 1 does perform better in terms of total costs but, the corresponding AWT is much larger. Therefore, alternative case 1 is not regarded as a good alternative for the initial case. The results for the 85%, 90% and 95% material availability and the corresponding costs are presented in Table 10.

Material availability	86%	85%	90%	90%	95%	95%
Output	Init.	Alt. 1	Init.	Alt. 1	Init.	Alt.1
Total costs	100%	100%	100%	100%	100%	100%
Emergency shipment costs	50%	52%	43%	40%	26%	25%
Lateral transshipment costs	4%	4%	5%	6%	6%	7%
Replenishment costs	22%	22%	23%	25%	26%	27%
Holding costs	24%	22%	29%	29%	41%	41%
Total number of parts on stock	1,672	1,615	1,851	1,858	2,171	2,226
Total number of lat. trans.	118	116	112	110	109	107
Total value of parts on stock	120%	110%	145%	145%	205%	205%
AWT	0.57 days	0.99 days	0.43 days	0.67 days	0.22 days	0.34 days

Table 10: Results alternative case 1 - Emergency shipments and replenishment by root location

4.5 Alternative Configuration 2 - Replenishment supplied from the root location, emergency shipments supplied from SGP.

The configuration of alternative case 2 is designed to investigate the impact on speeding up the replenishment shipments in order to decrease both the total value of stock on hand and the corresponding holding costs. Therefore, the replenishment shipments are supplied from the root location with emergency shipment speed (i.e. UPS Parcel Express service). These shipment times are 8.9 days, 6.7 days, and 4.2 days for RDC Roermond, RDC Louisville, and RDC Singapore respectively compared to 13.3 days, 12.3 days, and 6.2 days in the initial case. The resulting holding costs and total value of parts on stock can be considered as a lower bound. The option with faster replenishment is that both the replenishment and emergency shipments are supplied from RDC Singapore with emergency speed. However, this scenario may be considered as too extreme and therefore unrealistic.

The emergency shipments for alternative case 2 are still supplied from RDC Singapore, just as in the initial case. Therefore, when the material availability stays the same and the optimal material availability is already met, the AWT is not expected to change a lot, since the lateral transshipments satisfy only a small percentage of the demand. The most important downside of this configuration is the expected strong increase in replenishment costs. The replenishment costs are about four times more expensive than the initial case while the shipment time is, in the best case, 50% shorter. The total emergency shipment costs are expected to decrease for shorter replenishment times, however, the total emergency shipment costs are expected to increase for higher replenishment costs. The emergency shipment costs are expected to increase since an emergency shipment becomes relatively cheaper compared to a replenishment. The total value of stock on hand is expected to decrease because the chance of demand during leadtime is decreased. As a result, lower basestock levels are required for the same material availability. Moreover, the lower holding costs are a direct result of the lower value of total stock on hand. Summed up, the total costs are expected to strongly increase since the lower holding costs are not expected to outweigh the combination of an increase in both replenishment costs and emergency shipment costs. The replenishment and the emergency shipment lanes with the corresponding costs per CW are shown in Figure 17 and Figure 18.

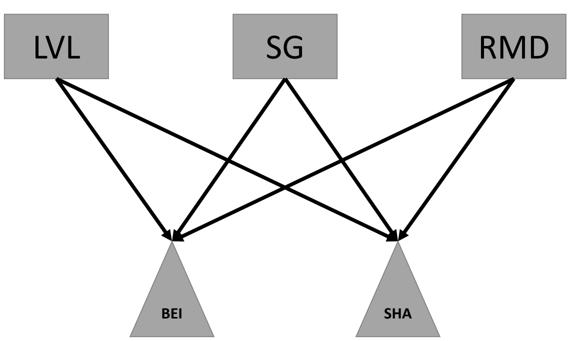

Figure 17: Alternative case 2, SKU replenishment.

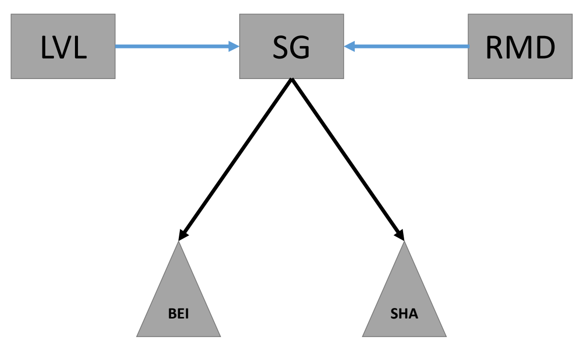

Figure 18: Alternative case 2, SKU emergency shipment.

4.5.1 Results

The total costs of alternative case 2 are significantly higher than the total costs of the initial case with the same material availability. The total costs increases with 76%. This increase is mainly due to the 277% increase in replenishment costs. In contrast, both the total value of stock on hand and with this the holding costs are decreased with 29%. This decrease in holding costs is does not outweigh the increase in replenishment costs. As a result, the current replenishment time and costs compared to the faster and more expensive replenishment costs results in a strong increase in total costs. Therefore, this configuration is not regarded as a good alternative for the initial case. The results are shown in Table 11.

Output	Init 90%	Result 85%	Result 90%	Result 95%
Total costs	100%	100%	100%	100%
Emergency shipment costs	43%	45%	36%	23%
Lateral transshipment costs	5%	2%	2%	3%
Replenishment costs	23%	45%	50%	56%
Holding costs	29%	8%	12%	17%
Total number of parts on stock	1,851	1,467	1,670	1,915
Total number of lat. trans.	112	159	155	149
Total value of parts on stock	145%	40%	60%	85%
AWT	0.43 days	0.64 days	0.43 days	0.22 days

Table 11: Results, alternative case 2 - Emergency shipments from SGP, replenishment from the root location emergency speed

4.6 Alternative configuration 3 - Replenishment and emergency shipments supplied from RDC Roermond and RDC Louisville.

The parameter settings of alternative case 3 are selected to research the impact of disregarding RDC Singapore entirely. When RDC Singapore is disregarded, all the replenishment and emergency shipments are supplied from the other two RDCs i.e. RDC Roermond and RDC Louisville. The virtual parts are shipped from RDC Louisville because of the shorter shipment time. The RDC Singapore rooted parts are first shipped to RDC Roermond upon request of SPS, before replenishment to China. Both the replenishment and emergency shipment times for the Singapore rooted and virtual rooted parts will increase from 6.2 days to 13.3 days and 12.3 days for replenishment and from 4.2 days to 8.9 days and 6.7 days for the emergency shipments respectively from RDC Roermond and RDC Louisville. In addition to the increase in shipment time, also both the replenishment and emergency shipment costs for the Singapore and virtual rooted parts increase. The replenishment costs stay the same for the RDC Roermond and RDC Louisville rooted parts. In addition, the emergency shipment costs decrease for these parts since they are not first shipped and handled in RDC Singapore.

This configuration is expected to have higher basestock levels for the virtual and Singapore rooted parts compared to the initial situation. The holding costs are expected to increase since the replenishment time increases. The replenishment costs are difficult to predict since the dependency between the emergency shipments has changed, even though the replenishment costs per part increase. In addition, the total emergency shipment costs are also difficult to predict since the RDC Roermond and RDC Louisville rooted emergency shipment costs are expected to decrease and the total emergency shipment costs for the virtual rooted and RDC Singapore rooted parts are expected to increase.
The AWT is expected to strongly increase because the emergency shipment time has increased for all the parts compared to the initial case. Moreover, the total value of stock on hand and the total holding costs are also expected to increase because of the longer replenishment times.
The replenishment and emergency shipment lanes for alternative case 3 with the corresponding costs are shown in Figure 19 and Figure 20.

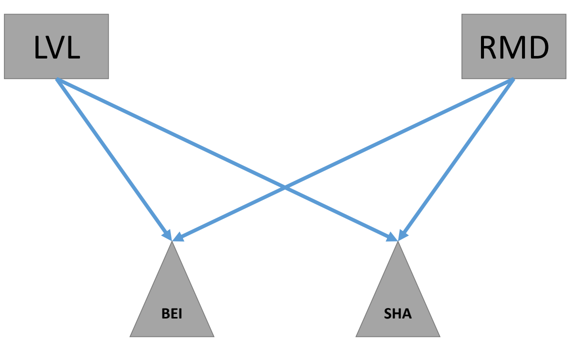

Figure 19: Alternative case 3, SKU replenishment.

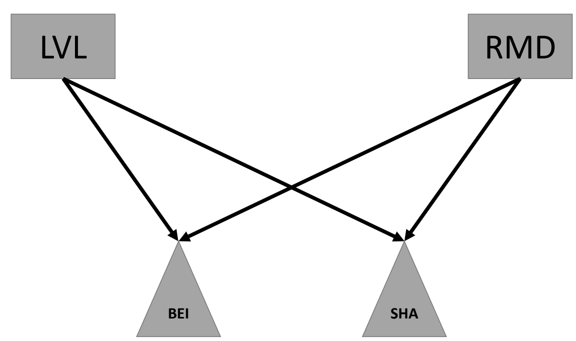

Figure 20: Alternative case 3, SKU emergency shipment.

4.6.1 Results

The total costs of alternative case 3 are lower than the initial case. A difference of 3% is realized for a 90% material availability. The advantage in total costs of alternative case 3 decreases when the material availability increases. With an 85% material availability, a total costs difference of 4% is realized whereas for a 95% material availability, a total costs difference of only 1% is realized. This decreasing advantage of alternative case 3 over the initial case, for an increasing material availability, is caused by the decreasing fraction of demand satisfied by an emergency shipment. The benefits of the lower emergency shipment costs decrease, when the material availability increases. In addition, a higher material availability increases the total value of stock on hand and therefore the holding costs. The increased replenishment time also increases the total value of stock on hand and therefore also the holding costs.

The AWT is strongly increased, from 0.43 days in the initial case to 0.70 days in alternative case 3. The same increase holds for the 85% and 95% material availability. The total replenishment costs are surprisingly decreased in alternative case 3 compared to the initial case while the replenishment costs per parts have increased. This is caused by the new relation between the replenishment and the emergency shipments. The total costs for the initial case and alternative case 3 are presented in Table 12.

Material availability	86%	85%	90%	90%	95%	95%
Output	Init.	Alt. 3	Init.	Alt. 3	Init.	Alt. 3
Total costs	100%	100%	100%	100%	100% 100%	
Emergency shipment costs	50%	46%	43%	40%	26%	25%
Lateral transshipment costs	4%	5%	5%	5%	6%	5%
Replenishment costs	22%	22%	23%	23%	26%	24%
Holding costs	24%	26%	29%	32%	41%	46%
Total number of parts on stock	1,672	1,747	1,851	2,006	2,171	2,410
Total number of lat. trans.	118	106	112	108	109	103
Total value of parts on stock	110%	130%	145%	160%	205%	230%
AWT	0.57 days	1.12 days	0.43 days	0.75 days	0.22 days	0.38 days

Table 12: Results, Alternative case 3 - RDC Singapore is disregarded, both replenishment and emergency shipments are supplied from RDC Roermond and RDC Louisville.

4.7 Comparison

The total costs is the most important performance indicator for Philips. However, the AWT and the material availability are also essential for a good performing supply chain. To research this, the five case studies are compared with the current 90% material availability in terms of total costs and waiting time. These results are aligned in Table 13 to have a better overview. Consequently, Table 14 compares each case in percentage difference with the initial case, to easily visualize the difference in performance.

Output	Initial case	Alt. case 0	Alt. case 1	Alt. case 2	Alt. case 3
Material availability	90%	90%	90%	90%	90%
Total costs	100%	100%	100%	100%	100%
Emergency shipment costs	43%	34%	40%	36%	40%
Lateral transshipment costs	5%	3%	6%	2%	5%
Replenishment costs	23%	51%	22%	50%	23%
Holding costs	29%	12%	29%	12%	32%
Total number of parts on stock	1,851	1,557	1,858	1,670	2,006
Total number of lat. trans.	112	142	111	155	108
Total value of parts on stock	145%	60%	145%	60%	160%
AWT	0.43 days	0.43 days	0.67 days	0.43 days	0.75 days

Table 13: Comparison of the results of the five different case studies with a 90% material availability

4.7.1 The initial case versus alt. case 1 and alt. case 3.

The best performing case in terms of total costs is alternative case 1 with both replenishment and emergency shipments supplied from the root location. The total costs are 6% lower. However, this case has a 56% longer AWT than the initial case. Moreover, alternative case 3 saves 3% in total costs compared to the initial case. The AWT for the current configuration is 0.43 days whereas the waiting time for both alternative case 1 and alternative case 3 are 0.67 days and 0.75 days respectively. The current situation with a material availability resulting in the same waiting times would result in the cost optimal situation in both cases i.e. 86% material availability with 0.57 days waiting time but with 5% and 2% higher costs. Furthermore, with a material availability of 95% for both alternative case 1 and alternative case 3 have 3% and 1% lower total costs respectively. The corresponding AWT for alternative case 1 and alternative case 3 are 0.34 days and 0.38 days while the initial case has 0.22 days AWT. The costs of the current configuration with the same AWT results for alternative case 1 and alternative case 3 in a 3% and 4% increase in costs respectively. Therefore, when a high level of material availability and a low corresponding waiting time is desired, the current configuration still performs the best.

4.7.2 Conclusion

Each case performs strong in a different area but overall has he initial case the best performance. The case with the lowest total emergency shipment costs is alternative case 1. The case with the lowest lateral transshipment costs is the initial case. Furthermore, the case study with the lowest replenishment costs is alternative case 3. Consequently, the case with the lowest holding costs is the alternative case 0. Finally the cases with the lowest total AWT time is the initial case, alternative case 0 and alternative case 2. Finally the alternative case 1 and alternative case 3 both have lower total costs than the initial case.

In conclusion, the initial case performs the best considering the total package. A possible change could be a higher material availability. The total costs for a 95% material availability would increase with 7% whereas the waiting time decreases with 50%. This could be an interesting option if a higher material availability and lower waiting times are desired.

Output	Initial case	Alt. case 0	Alt. case 1	Alt. case 2	Alt. case 3
Total costs	100%	166%	94%	176%	97%
Emergency shipment costs	100%	130%	87%	148%	89%
Lateral transshipment costs	100%	115%	117%	188%	101%
Replenishment costs	100%	361%	101%	377%	95%
Holding costs	100%	69%	95%	71%	110%
Total number of parts on stock	100%	69%	95%	71%	110%
Total number of lat. trans.	100%	127%	99%	138%	96%
Total value of parts on stock	100%	76%	102%	75%	116%
AWT	100%	100%	158%	‘101%	176%

Table 14: Comparison between the five cases in percentages. These values are all obtained with a 90% material availability constraint.

4.8 MCA planning tool output

The initial case is compared with two basestock levels calculated by the MCA planning tool i.e. the MCA original case and the MCA adjusted case. The MCA original case contains the MCA output for currently applied settings in real life. In addition, the MCA adjusted case contains the output from the MCA planning tool without restrictions other than the 90% material availability constraint for each of the 644 groups and the two service areas. To compare the basestock level allocation method discussed in this thesis with the method used by the MCA planning tool, the same replenishment leadtimes, and demand is used. These leadtimes are the "effective leadtimes" used by the MCA tool and are for each SKU different. The demand is the "Network average monthly forecast" which is multiplied by 12 to convert it to yearly demand in the model used in this thesis. The used leadtimes are even larger than the proposed leadtimes of 17 days, 18 days, and 8 days for respectively RMD-CN, LVL-CN, and SGP-CN. But in order to compare them properly, the same leadtimes are used for each SKU.

The MCA original case contains manually entered material availabilities for separate SKUs, for separate segments, and for each of the 644 groups. Therefore, the material availability of the SKUs manually entered will have the entered material availability which is in general quite high, as a result, the other SKUs in the same group have a really low material availability because the group total material availability has to be met. The optimization for all the basestock levels for each group is optimized by the MCA tool. This method may result in skewed results, the expensive parts may have relatively high material availabilities and the cheap parts relatively low. Therefore, the total costs are expected to be higher than the MCA adjusted case. However, the MCA adjusted case also contains these 644 groups, but they are all assigned with the same 90% material availability constraint. This technique applied for the MCA adjusted case is expected to result in a slightly better performance in total costs since the same input variables are used, except less restrictions for separate SKUs which increases the space for optimization for the optimal basestock levels per group. Both the MCA original case and the MCA adjusted case calculate the material availabilities for the service area separately, whereafter the total material availability in the economic region (China) can be calculated. Thus, there is a possibility for lateral transshipments but they are not calculated in advance, they are only used to calculate the material availability after the event of economic region. As a result the lateral transshipment time and costs are not take into account. Moreover, in the MCA adjusted case, less expensive parts are expected to be stocked compared to the MCA original case. However, the when the MCA adjusted case is compared with the initial case, each group still contains a material availability constraint and each service area used a separate material availability. Therefore, also in the MCA adjusted case, more expensive parts and less inexpensive parts are expected to be on stock compared to the initial case. As a result, the adjusted case is expected to decrease the total costs compared to the MCA original case, however, the total costs in the adjusted case are still expected to be much higher in terms of total costs than the initial case.

4.8.1 Results

The difference in total costs between the initial case and the MCA adjusted case is large. The initial case is 26% less expensive than the MCA adjusted case with the same material availability and with even the same waiting time. The difference in total costs is mainly caused by the decreased total holding costs, a decrease of 42% is experienced in the initial case. In addition, the total number of parts on stock stayed relatively constant. As a consequence, the average part value on stock has strongly increased. The reason behind the increased holding costs can be found in the optimization part of the groups and service area (LDC Beijing vs. LDC Shanghai). In this way, each group is separately optimized instead of aggregately optimized which results in a sub-optimal solution. In addition, a total material availability is used for each service area instead of only one total material availability constraint for the economic region. The comparison in total costs between the MCA original case and the MCA adjusted case results in 11% lower costs for the MCA adjusted case. This decrease is the result of only leaving out all the separate restrictions for different SKUs and segments. The basestock levels of both the MCA adjusted case and the MCA original case are determined to have at least a 90% material availability.
The material availability and the total costs are calculated by inserting the basestock levels from the MCA adjusted case and the MCA original case with both the demand and the replenishment leadtimes in the applied model in this thesis. This calculation takes the possibility of both the lateral transshipments and emergency shipments into account. Therefore, the calculated material availability is expected to be higher. In addition, the material availability for a group can be very high i.e. a group containing slow mover SKUs and only one 1 SKU is experiences demand, still the 90% material availability holds. As a result, the material availability of this group could be close to 100%. Therefore, the realized material availability is higher than the 90% i.e. the calculated material availability is 95.5%. This material availability is compared with the initial case with the same demand, same replenishment leadtimes, and with a 95.5% material availability constraint. In addition, the optimal basestock levels for the initial case with the same input but with a 99% material availability are calculated. This results in a large increase in total costs. However, still being more beneficial in terms of total costs than the MCA adjusted case. The total costs decrease with the initial case with 99% material availability results in a 5% decrease in costs compared tot the MCA adjusted case. The cost drivers and other performance indicators for all the cases are shown in Table 15.

Summed up, by only releasing the restrictions in the MCA original case and providing each group with the same material availability, the total costs decrease with 11%. But the large advantage can be found in omitting the group restrictions and focusing on only one material availability constraint for the whole economic region (China). When this is done, the total costs from the MCA original case can be reduced to the total costs in the initial case which is a 34% decrease in total costs. When the total costs of the MCA adjusted case are compared with the total costs of the initial case with the same input, 26% percent in total costs can be saved. In addition, the possibility for lateral transshipments is taken into account for all the three cases. When this would not be the case, even a larger percentage of the total costs could be saved. Therefore, when both the option and costs of lateral transshipments are implemented in the model and only one material availability constraint is used, a really large costs reduction of at least 26% can be realized.

Output	Init. case 99%	Init. case 95.5%	MCA adj. case	MCA orig. case
Diff	84.2%	66.0%	88.6%	100%
Total costs	100%	100%	100%	100%
Emergency shipment costs	5%	18%	10%	7%
Lateral transshipment costs	4%	6%	3%	3%
Replenishment costs	20%	23%	18%	16%
Holding costs	71%	53%	69%	74%
Total number of parts on stock	3,252	2,617	2,577	3,351
Total number of lat. trans.	138	181	145	180
Total value of parts on stock	355%	265%	345%	370%
MA	99%	95.5%	95.5%	95%
AWT	0.05 days	0.20 days	0.19 days	0.22 days

Table 15: Comparison of the optimal basestock levels of the initial case and the calculated basestock levels of the MCA adjusted case and the MCA original case with the same input variables.

4.9 Extreme cases

Four extreme cases are compare to get a better idea about the dependencies between the parts. The CW and the value of each SKU has a large influence on the optimal supply chain configuration. The cheap parts are inexpensive to hold since the holding costs are based on the parts value. On the contrary, expensive parts are very expensive to hold. Therefore, the cheap SKUs have in general a high material availability and the expensive SKUs a low material availability. Even though the CW and the value of an SKU are strongly correlated to each other, the range in value is larger than the range of CW. Therefore, the expensive parts still have a low material availability. The cheap SKUs are also relatively light and therefore cheap to ship and the expensive parts also relatively heavy and therefore expensive to ship. Figure 16 demonstrates the impact of having only extreme SKUs in a subset. This figure shows the large difference in total costs even when a correction is made for the number of parts in the subset. The same relation with heavy, light, expensive and cheap parts can be found in the tested subset earlier mentioned in this chapter. Therefore, a representative subset for the total set is important.

Input	Cheapest	Most expensive	leightest	Heaviest
Number of parts	40	404	24	24
Number of SKUs	10	10	10	10
Average value an SKU	0.0002%	100%	0.0038%	31.31%
Average CW of an SKU	0.5	130	0.5	603
Average CW of a part	0.5	122	0.5	519
MA constraint	90%	90%	90%	90%
Output				
Diff in total Costs	0.008%	100%	0.007%	17%
Total Costs	100%	100%	100%	100%
Emergency Shipment costs	0.30%	5%	4%	14%
Lat. transshipment costs	0.04%	3%	1%	2%
Replenishment costs	96.6%	18%	68%	21%
Holding costs	3.06%	17%	27%	63%
Tot. value of parts on stock	15.3%	85%	135%	315%
Tot. parts on stock	33	20	20	11
AWT	0.00 days	0.40 days	0.02 days	0.45 days
Average costs per part	0.03%	35.63%	0.04%	100%

Table 16: The results of four extreme cases are aligned. The cases are configured with the ten cheapest, most expensive, lightest, and heaviest SKUs.

4.10 Sensitivity analysis

The sensitivity analysis is performed for the initial case and alternative case 0 to 3. The most important parameter values are respectively decreased and increased in value to examine the sensitivity of the total costs. The analyses are all performed with a 90% material availability degree due to the fact that this material availability is currently used. The input variables taken into account are: c_i^{rep}, c_i^{em}, c_i^{hol}, t_i^{rep}, and t_i^{em}. For the case studies, each input variable is respectively decreased and increased by 50%. For increasing the replenishment costs holds that whenever $c_i^{rep} * 1.5 > c_i^{em}$, c_i^{em} else $c_i^{rep} * 1.5$. The same principle holds for decreasing the emergency shipment costs. Whenever $c_i^{em} * 0.5 < c_i^{rep}, c_i^{rep}$ else $c_i^{em} * 0.5$. This also holds for decreasing the replenishment time and increasing the emergency shipment times. Whenever $t_i^{rep} * 0.5 < t_i^{em}, t_i^{em}$ else $t_i^{rep} * 0.5$ and whenever $t_i^{em} * 1.5 > t_i^{rep}, t_i^{rep}$ else $t_i^{em} * 1.5$. The only exception for this analyses is made for the emergency shipment costs and replenishment costs supplied from RDC Singapore, only the last transportation part from RDC Singapore to China is respectively increased or decreased with 50%. Again, if the total value of the decreased costs are lower than the corresponding replenishment costs, the replenishment costs are used. The replenishment costs to RDC Singapore and handling costs in RDC Singapore stay the same. This choice is made to make the sensitivity analysis more realistic.

The relation between on the one hand the emergency shipment costs and on the other hand the lateral transshipment costs, the replenishment costs, and the holding costs can cause the optimal material availability to change. In case that this relation between the costs cause the material availability, in the cost optimal situation, to rise, then the AWT is affected and decreased. This change in optimal material availability occurred a couple of times in the sensitivity analysis. The increased emergency shipment costs in the initial case caused a shift in the optimal material availability; the AWT is decreased to 0.35 days. In addition, the 50% reduction in holding has led to a reduction in AWT in the initial case, alternative case 1 and alternative case 3 resulting in 0.30 days, 0.60 days, and 0.59 days respectively. This is due to the lower costs of the combination of holding costs, lateral transshipment costs, and replenishment costs. Otherwise, the AWT is mainly determined by the emergency shipment time and material availability constraint, only a small percentage of the demand is satisfied by a lateral transshipment. Thus, the AWT reacts as expected on the change in emergency shipment time in the sensitivity analysis and stays relatively constant. The AWT for the changed emergency shipment times are shown in Table 22 in the appendix.

The difference in performance between the case studies observed in the previous section are also observed in the sensitivity analysis except for two cases. The relation between the total costs of the different cases are discussed earlier in this chapter are nearly always consistent with the same change in input parameter values in the sensitivity analysis. The total costs of the initial case are in each input parameter value change lower than both alternative case 0 and alternative case 2. In addition, alternative case 1 performs always better in total costs than the initial situation. The total costs of alternative case 3 are lower than the initial case except for two cases i.e. the increased emergency shipment costs and the decreased holding costs. The total costs for each case study are shown in Table 21 in the appendix.

When the replenishment leadtimes are increased with 50% for the initial case with a 90% material availability, the total costs increase with 6%. This could be the case when the market desires to plan on longer replenishment to guarantee the delivery of the spare part within a certain time frame. When the initial case with average replenishment leadtimes and with a 95% material availability is compared with the outcome of the increased leadtimes, the same amount of total costs are realized. However, the increased material availability solution would be preferred over solution with the increased replenishment leadtimes. The difference between these solutions is that in the case the replenishment leadtimes are increased, the material availability of the cheap parts are increased, whereas for an increased material availability with average replenishment leadtimes, the material availability of the more expensive parts is increased.

The output of the sensitivity analysis is calculated in total costs per case study. This output is compared for each case study individually (i.e. the output of the normal parameter values are compared with the changed parameter values). This comparison is shown in Table 23 in the appendix. The biggest differences within each case study is marked as bold in Table 23. These markings clearly show that decrease in holding costs and the decrease in emergency shipment costs have the biggest influence on the total costs. This is due to the fact that the holding costs are also a large contributor to the total costs.

5 Conclusion & Recommendations

The research questions posed in Section 1.4 are answered with help of the results elaborated on in Chapter 2 and Chapter 4. Chapter 4 assessed the performance of the current supply chain network configuration and of the proposed alternatives. Potential improvements are obtained by adjusting the emergency shipment location, time, and costs, but also the replenishment location, time, and costs. Moreover, the material availability is changed. Furthermore, the performance of the initial case is compared with the performance of the MCA planning tool. In addition, a sensitivity analysis is conducted, in which the most important cost drivers are changed in value. By iterating over different input parameter values, the impact on total costs is investigated. The interpretation and application of the results to reality are discussed in Section 5.1. In Section 5.2 concrete recommendations and suggestions are offered for Philips' consideration.

5.1 Conclusion

What is the structure of the Chinese spare parts supply chain?
The Chinese supply chain starts at one of the three RDCs, whereafter the parts are shipped to one of the two bonded local warehouses (LDC Beijing or LDC Shanghai). From the LDCs, the parts are either directly shipped to the customer or they are stocked in a key market warehouse and then shipped to the customer. The key market warehouses Chengdu, Guangzhou, and Beijing, together with LDC Beijing are all considered as one location by the SPS department, and thus the SPS department does not distinguish between these locations for the calculation of base-stock levels. The same holds for both the inventory in LDC Shanghai and the inventory in key market warehouse Shanghai, they are also considered as one location by the SPS department. Therefore, only two local warehouses are considered in the model. Lateral transshipments are allowed between these local warehouses. The adjusted model of Kranenburg and Van Houtum (2009) combined with a Greedy heuristic is used to examine the current spare parts supply chain and calculate the optimal basestock levels with the corresponding optimal total costs. The model from Kranenburg and Van Houtum (2009) is supplemented with transportation costs that are dependent on both the CW and the lane of each part. In addition, the three RDCs are all assumed to always deliver the part when demand arrives. Therefore, the supply chain may be modelled as a single-echelon inventory system. The replenishment shipments are all supplied from the root location whereas the emergency shipments are supplied from RDC Singapore.

What are the service constraints China has to deal with?
The most important service level constraint in China is the material availability, which is the percentage of demand satisfied from stock (both LDC Beijing and LDC Shanghai). However, the material availability on its own is not a strong service measure since the emergency shipment time is not taken into account. Therefore, the material availability in combination with the AWT has to be considered as a performance indicator. In addition, the holding costs and the total value of stock on hand is important for the Chinese key market planners since this is a local performance indicator.

How does China perform with the current supply chain network setup?
The current supply chain configuration is examined with a subset of 1000 SKUs. The total costs are divided into emergency shipment costs (43%), lateral transshipment costs (5%), replenishment costs (23%), and holding costs (29%). As these percentages demonstrate, the main costs drivers are the emergency shipment costs and the holding costs. The total emergency shipment costs are high because of the high

emergency shipment costs per SKU. The holding costs are relatively high because of the long replenishment time and the 90% material availability. The waiting time is relatively short, which indicates that the waiting time for an SKU on average is fast. The total value of stock on hand is relatively high which is caused by the relatively slow replenishment time. In general, the performance of this case in terms of total costs, AWT, and material availability is good.

What alternative configurations could be beneficial in terms of total costs, material availability and waiting time?

How does China perform with both replenishment and emergency shipments supplied from RDC Singapore?
In this configuration, the supplying location for the replenishments has changed from the root RDC to RDC Singapore. Decreasing the replenishment leadtimes reduces the total holding costs and the total value parts on stock. On the contrary, decreasing the replenishment leadtimes strongly increases the replenishment costs. The benefits of this change are the decreased replenishment leadtimes and the corresponding stock on hand and holding costs. Nonetheless, the decreased replenishment leadtime and the reduced holding costs do not outweigh the increase in replenishment costs. As a result, the total costs increases. Therefore, it is not recommended to change the supplying location of replenishments to RDC Singapore.

What is the impact on the total costs and waiting time when the emergency shipments are supplied from the root location?
The emergency shipment location is changed from RDC Singapore to the root RDC of each SKU. This saves emergency shipment costs since only the transportation from the root RDC to China needs to be considered, the additional replenishment costs to RDC Singapore and handling costs in RDC Singapore are no longer the case. Therefore, the total emergency shipment costs decreases whereas the other costs parameters stay constant. Therefore, the total costs also decreases. However, the emergency shipment time is increased for the parts rooted in RDC Roermond and RDC Louisville resulting in an increased AWT. As a result, a 6% reduction in total costs is realized with 58% longer AWT. This is considered to be out of balance, and therefore not beneficial.

What are the benefits in terms of total costs and material availability when the replenishment speed is increased?
In the current configuration, the holding costs are a large contributor to the total costs. An increase in replenishment leadtime reduces the amount of parts on stock and the corresponding holding costs. Therefore, the replenishments are supplied with emergency speed from the root location with a maximum of 50% shorter leadtimes. The replenishment costs, however, are nearly tripled. This increase in replenishment costs has to be compensated with the lower holding costs. The reduction in holding costs is not high enough to cover the increased total replenishment costs, which results in an increase in total costs. As a result, this option is not beneficial for China and therefore not considered as a good alternative configuration.

What are the benefits in terms of total costs and material availability when also in the MCA planning tool only one material availability constraint is used and lateral transshipments are taken into account?
The MCA planning tool requires to provide each of the 644 groups of SKUs with a separate material

availability constraint. This material availability constraint is manually entered per group by a planner. In addition, the material availability for all the groups together is calculated per service area (LDC Beijing and LDC Shanghai) instead of the economic region (China). The corresponding total material availability of the economic region is calculated as weighted average of both service areas instead of using the material availability as a constraint. Therefore, when instead of the material availability constraint for each separate group and for each separate service region, only one total aggregate material availability is used, the total costs can be reduced with 34%.

What are the supply chain network consequences when RDC Singapore is disregarded?
When RDC Singapore is disregarded, both the replenishment and emergency shipments are supplied from either RDC Roermond or RDC Louisville. Currently, the emergency shipments, the virtual rooted parts, and the Singapore rooted parts are all replenished from RDC Singapore. Consequently, the replenishment and emergency shipment costs for these new lanes need to be applied. The emergency shipment costs have decreased which results in lower total emergency shipment costs. Besides this, the replenishment costs have increased which surprisingly results in lower total replenishment costs. The total costs decreased with 3%, which is mainly due to the lower total emergency shipment costs. The percentages of the main cost drivers have changed namely, the emergency shipment costs 25%, the lateral transshipment costs 5%, the replenishment costs 24%, and the holding costs 46% compared to the initial case. Since the emergency shipment time is increased, the AWT is increased from 0.43 days to 0.75 days which is a 76% increase. In addition, if a higher material availability is desired, the cost advantage of this configuration decreases compared to the current situation, caused by the lower fraction of emergency shipments. Moreover, disregarding RDC Singapore has also a big impact on the other smaller markets in the APAC region. Therefore, disregarding RDC Singapore is not considered as a good alternative.

5.2 Recommendations

1. Based on the previous section, the main conclusion is that the current supply chain configuration performs really well taking the most important performance indicators into account (i.e. the total costs, the AWT and the material availability). These variables can be optimized, however, the variables have a strong dependency. Therefore, when one of these output variables is optimized, other output parameters are ignored.

   Two alternative cases are researched with faster replenishment options, replenishment from RDC Singapore and replenishment from the root location with emergency speed. Both options result in higher replenishment costs but in lower holding costs. However, the increase in speed and the resulting decrease in holding costs does not outweigh the higher shipment costs. Therefore, the total costs strongly increases which makes it not beneficial to change the replenishment route.

   Reducing the total costs by changing the emergency shipment location from RDC Singapore to the root location is beneficial in terms of total costs, however, the emergency shipment time has increased and the AWT, dependent on the emergency shipment speed, has increased as well. As a result, a cost optimal solution would have been found which would not be beneficial for the SPS department because of the longer AWT.

   Thus, it is not recommended to change the supplying location for the emergency shipments nor the supplying location or speed for the replenishment shipments, and stay with the current supply chain configuration.

2. The material availability constraint does not take the emergency shipment time and lateral transshipment time into account. On the contrary, a waiting time constraint would take this into account. Therefore, the service level constraint is recommended to change from a material availability constraint to a waiting time constraint. For this moment, the best option to increase the material availability is by literally increasing the material availability constraint. When the material availability is increased to 95%, the total costs would increase with only 7% while the AWT decreases with 50%.

3. When RDC Singapore is disregarded, all the shipments are supplied from RDC Roermond and RDC Louisville. This results in lower total costs with an increase in AWT due to the increase in emergency shipment time. Disregarding RDC Singapore could have a large impact on the smaller markets being supplied from RDC Singapore, they would also have to change their supply chain. For China, disregarding RDC Singapore would affect all the emergency shipments and both the RDC Singapore rooted and virtual rooted parts replenishment. As a consequence, a hybrid solution is introduced between disregarding RDC Singapore entirely and the current situation. This solution means that RDC Singapore is scaled down and only the virtual parts and RDC Singapore rooted parts are supplied from RDC Singapore. The other parts are either emergency shipped from the root location or from neighbouring countries. The emergency shipment supply from neighbouring countries would result in a spare parts pooling system. However, this option still needs to be investigated and could result in major issues with the import and export of parts. In addition, high emergency shipment costs are an expected consequence of the pooling system. Therefore, further research about a spare parts pooling system with neighbouring countries in combination with a scaled down RDC Singapore, is needed. To conclude, disregarding RDC Singapore would not be beneficial without this pooling system between the neighbouring countries and is therefore not recommended to directly implement. The hybrid solution could be an option when a scale down of RDC Singapore is desired. Otherwise, is it recommended to stay with the current replenishment and emergency shipment configuration.

4. Research the possibilities of integrating the key market warehouses (Chengdu, Guangzhou, Beijing, and Shanghai) into the MCA planning tool. The current situation aggregates the demand of the key market warehouses to one of the two LDCs. The demand allocated to the key market warehouses is closer to the customer, and therefore, faster at the site of the customer and more beneficial. This can make a significant difference in service for the customer.

5. The adjusted spare parts inventory control model used and applied in this research, originating from Kranenburg and Van Houtum (2009), is recommended to test the performance of similar markets.

6. The MCA planning tool requires to provide each of the 644 groups of SKUs with a separate material availability constraint. This material availability constraint is manually entered per group. In addition, the material availability is calculated per service area (LDC Beijing and LDC Shanghai) instead of the economic region (China). The overall material availability of the economic region, and therefore the total set of parts in China, is determined by calculating the average material availability for each service location for these 644 groups. Thereafter, the total material availability for the economic region is determined. This results in an aggregate material availability which satisfies the constraint or not. When the material availability does not satisfy the needs, the planner manually adjusts the material availability of the separate groups until the material availability target is met. This method is sub-optimal and very laborious. Therefore, when one aggregate material

availability constraint for China is used and lateral transshipments between the two service areas are accounted for, the optimal basestock levels can be determined by the optimization heuristic to efficiently calculate them for each SKU. Summed up, decrease the number of groups. When only one aggregate material availability constraint for the entire economic region is taken into account and the lateral transshipments are accounted an impressive 34% reduction in total costs can be realized.

Out of scope recommendations

- Investigate the SKUs with a similar a function and try to reduce the amount of these SKUs. Currently, 140 different SKUs are used with similar functions, when this could be decreased, the total supply chain would highly benefit from this change.
- Research the possibilities and applicability of General Multilevel Rationing (Abouee-Mehrizi et al., 2012). The clients with different service level contracts are treated differently in this setting. This model allocates the spare parts to a local warehouse with a higher priority in this critical level policy. The FCFS (First Come First Serve), SP (Shortest Processing time) and MR (Multilevel Rationing) policies are all special cases of this policy. The objective is to minimize the total holding and emergency shipment costs by customer prioritization.
- LDC Beijing or LDC Shanghai is strongly advised not to use as RDC for APAC or as warehouse for other countries than China. This is mainly due to the high import and export time and tariffs.

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Appendices

A List of abbreviations

Abbreviation	Definition	Abbreviation	Definition
AMEC	USA, Canada, and Latin America	LTB	Last Time Buy
APAC	Asia-Pacific	LVL	Louisville
AW	Actual Weight	MA	Material Availability
AWT	Aggregate mean Waiting Time	NL	The Netherlands
BEI	Beijing	NPI	New Product Introduction
CCP	Customer Critical Parts	RDC	Regional Distribution Center
CHE	Chengdu	RMD	Roermond
CN	China	ROL	Re-order Level
CW	Chargeable Weight	ROQ	Re-order Quantity
EMEA	Europe, Middle East, and Africa	SG	Singapore
EOL	End of Life	SGP	Singapore
FCO	Field Change Order	SHA	Shanghai
FSE	Field Service Engineer	SKU	Stock Keeping Unit
FSL	Forward Stocking Location	SPS	Service Parts Supply chain department
FTE	Full Time Equivalent	Slow	Slow moving part
GUA	Guangzhou	TARN	Transship, Allocate, Repair, New-buy
HCFM	High Cost Fast Mover	TO	Tools for repair or installation
KM	Key Market	TSL	Target Stock Level
LCFM	Low Cost Fast Mover	US	United States of America
LDC	Local Distribution Center		

Table 17: List of abbreviations.

B Set and subset characteristics

	Set	Subset
Number of SKUs	6,592	1,000
Total demand	109,534	15,340
Demand BEI	93,862	12,512
Demand SHA	15,672	2,819
Demand per SKU	16.62	15.34
Average weight	8.16 kg	7.73 kg
Average volume	52,830 cm^2	58,124 cm^2
Average value	\$954.54	\$916.98
Root:		
NL rooted	46.1%	44.7%
SG rooted	0.6%	0.8%
US rooted	24.7%	25.4%
Virtual rooted	28.7%	29.1%
Segmentation:		
CCP	8.4%	8.4%
EOL	2.6%	2.6%
HCFM	5.7%	5.7%
LCFM	34.2%	34.3%
LTB	3.2%	3.2%
NPI	3.3%	3.3%
Slow	41.3%	41.3%
TO	0.9%	0.9%
Tubes	0.3%	0.3%

Table 18: Set and subset characteristics.

C Replenishment rates

Confidential

Table 19: The transportation rates for the replenishment shipments.

D Emergency shipment rates

Confidential

Table 20: The transportation rates for UPS Parcel Express service

E Sensitivity analysis

Percentage difference provided in Table 23

Table 21: Sensitivity analysis, total costs for each inut parameter value change

Output	Initial case	Alt. case 0	Alt. case 1	Alt. case 2	Alt. case 3
Total Normal	0.43	0.43	0.67	0.43	0.75
Total Tem -50%	0.22	0.22	0.43	0.22	0.38
Total Tem +50%	0.56	0.63	1.01	0.57	1.12

Table 22: Sensitivity analysis, waiting time differentiation.

Output	Init.	Alt. 0	Alt. 1	Alt. 2	Alt. 3
Normal	100%	100%	100%	100%	100%
Crep -50%	87%	92%	85%	**71%**	88%
Crep +50%	112%	107%	112%	115%	112%
Trep -50%	93%	98%	93%	99%	92%
Trep +50%	106%	102%	106%	102%	109%
Cem -50%	85%	**88%**	**79%**	97%	**80%**
Cem +50%	111%	108%	115%	110%	115%
Tem -50%	100%	100%	100%	100%	100%
Tem +50%	100%	100%	100%	100%	100%
Chol -50%	**82%**	93%	82%	94%	**80%**
Chol +50%	113%	106%	113%	106%	116%

Table 23: Sensitivity analysis in percentages.