MASTER

Comparing different service parts distribution network configurations to evaluate the effect on logistics costs

Borst, R.N.

Award date:
2016

July 2016

Comparing different Service Parts Distribution Network configurations to Evaluate the Effect on Logistics Costs

by
R.N. Borst

Student identity number 0848971

In partial fulfillment of the requirements for the degree of

**Master of Science
in Operations Management & Logistics**

Supervisors:
Dr.ir. J.J. Arts, Eindhoven University of Technology
Dr. H. Blok, Eindhoven University of Technology
Ir. J. van der Wal PDEng, Philips

Preface

This Master Thesis is the result of my graduation project as part of the Master Operations Management & Logistics at Eindhoven University of Technology. The project took place at Philips in Best from February to July 2016. I am glad that I had the opportunity to graduate within this company.

First and foremost, I want to express my gratitude to Joachim Arts, my first supervisor. His enthusiastic and constructive support was one of the key factors that made this project such a pleasant and informative experience. During some of the challenging periods he helped me when I got stuck in complexity. I truly appreciate his support. I also want to thank Herman Blok, my second supervisor. He provided me with valuable feedback on my report.

From Philips I would like to thank Japke van der Wal, my company supervisor. She helped me in understanding the processes of the SPS department and introduced me to several interesting people. In addition, I want to thank Henry van der Schoot for defining this interesting graduation project.

I would also like to thank Bram Kranenburg and Jan van Doremalen from CQM. In a series of meetings they helped me to scope the research assignment and shared their modeling knowledge. I also would like to thank Rio Groot for his support in collecting data as part of his Bachelor End Project.

Last but not least, I would like to thank my girlfriend, friends and family for their support.

Remco Borst

Abstract

In this research project, conducted at Philips in Best, we compared different Service Parts Distribution Network (SPDN) configurations in terms of total logistics costs. Total logistics costs includes inventory holding costs and transportation costs for shipments from DC to customer. With respect to the configuration of a SPDN we considered the number of Distribution Centers (DC-s), their geographical location and the allocation of customer demands to these DC-s. An inventory-transportation model, based on the model of Kranenburg and Van Houtum (2009), has been developed which can be used to compare different SPDN configurations.

The inventory-transportation model has been used in two case studies to compare the current SPDN configuration with an alternative SPDN configuration. A greedy algorithm is used to optimize stock levels such that the total logistics costs are minimized under the restriction that at least 95% of the aggregate demand for requested service parts is delivered Next Business Day.

Keywords: Spare parts, Inventory Control, Greedy Algorithm, Optimization, Capital Goods, Pooling Effects

Executive Summary

This report is the result of a Master Thesis Project at the Service Parts Supply Chain (SPS) department of Philips. The SPS department is responsible for the total service parts supply chain from Philips' factories and external suppliers to the customers. The SPS department's strategy is to maximize the service part availability, minimize the total cost of operation and minimize inventory levels. To realize this strategy, the SPS department operates a Service Parts Distribution Network (SPDN). Some of the initial design choices made with respect to the SPDN configuration in the region Europe, Middle East and Africa (EMEA) are being questioned due to the dynamic environment in which the SPS department operates. Both the geographical location and the rate of demand for service parts have been subject to change. In addition, inventory and transportation rates may have changed over time affecting the optimal SPDN configuration to perform its objective.

In this Master Thesis we compared the current SPDN configuration with an alternative SPDN configuration in terms of total logistics costs. Total logistics costs includes inventory holding costs and transportation costs for shipments from DC to customer. With respect to the configuration of an SPDN we considered the number of DC-s, their geographical location and the allocation of customer demands to these DC-s. This Master Thesis is geographically scoped on 18 countries in the region EMEA. The focus is on all service parts that need to be delivered Next Business Day (NBD).

Current SPDN configuration

The SPS department currently uses a two-echelon SPDN with one Regional Distribution Center (RDC) and four Local Distribution Centers (LDC-s) to fulfill demand that needs to be delivered NBD in our geographical scope. For 18 countries in the geographical scope the RDC is used primarily; approximately 97.2% of the total demand in EMEA is fulfilled by the RDC. The SPS department wants to investigate if there is an alternative SPDN configuration with lower total logistic costs. There is a special interest around the effect of applying a SPDN configuration in which stock is installed closer to the customer. By looking into an alternative SPDN design, the SPS department gains insight into the extent to which the current SPDN of the region EMEA is well designed in terms of the number and location of the DC-s to perform its objective.

Altenative SPDN configuration

In configuring the alternative SPDN, we considered installing a DC in the six countries that have the largest demand; FR, DE, IT, NL, ES and GB. We determined in which of these countries it is beneficial to install a DC in terms of transportation costs based on the analysis of domestic and cross-border transportation rates. For DE, IT, NL, ES and GB it is beneficial for the transportation costs to install a DC since demand for those countries may be fulfilled with domestic shipments. Domestic shipments are, dependent on the country, 39% to 60% percent lower compared to the lowest cross border rate. Based on these insights, we introduced an alternative SPDN configuration with five DC-s located in DE, IT, NL, ES and GB. Each of these DC-s shares their stock with another DC when a DC faces a stock out. In this way, the same level of risk pooling may be obtained as when using a network configuration with one single large DC such as the current SPDN configuration. The assignment of demand to the DC-s in the alternative SPDN configuration is based on the outbound transportation rates.

An inventory-transportation model, based on the model of Kranenburg and Van Houtum (2009), has been developed to compare different SPDN configurations. We made some adjustments to their model and changed the interpretation of some of the parameters. The inventory-transportation model has been used in two case studies to compare the current SPDN configuration with an alternative SPDN configuration. A greedy algorithm is used to optimize stock levels such that the total logistics costs are minimized under the restriction that at least 95% of the aggregate demand for requested service parts is delivered Next Business Day. We performed the case studies with a subset of 500 SKU-s of the complete set of SKU-s in order to maintain acceptable computation times.

Conclusion

The cost difference between the current SPDN and alternative SPDN equals -2,9%. This cost difference does not take into account the change in inbound transportation costs. It is likely that the inbound transportation costs will increase when moving from the current SPDN to the alternative SPDN. Inventory holding costs dominate in both SPDN configurations. Complete pooling between DC-s in the alternative SPDN configuration seems suitable since holding costs are large compared to transportation costs. Transportation costs are lower for the alternative SPDN configuration due to the lower transportation rates associated with domestic shipments.

Recommendations

Based on the conclusions, the main recommendation is to determine the change in inbound transportation costs when moving from the current SPDN configuration to the alternative SPDN configuration. It is important to determine this change and how it affects the total costs of both SPDN configuration and the resulting cost difference. In addition to this main recommendation, it is recommended to determine the change in warehousing costs when moving from the current SPDN configuration to the alternative SPDN configuration. In this research we assumed that warehousing costs such as inbound handling, outbound handling and storage does not change when the configuration of the SPDN changes. It seems that implementing the alternative SPDN configuration from a cost perspective is not recommended, since the cost difference is -2.9% and it will be further reduced by including inbound transportation. However, the alternative SPDN configuration may be interesting when demand requirements change in the future. When in the future demand needs to be fulfilled more quickly, for example Same Business Day instead of Next Business Day, the alternative SPDN configuration may be more cost effective due to the proximity of DC-s to the customers.

Contents

Chapter 1

Introduction & Research Questions

Many industries rely on the proper functioning of high value capital assets. Companies in these industries use capital assets in their primary processes (Driessen et al., 2015). Downtime of capital assets can lead to various negative consequences such as lost revenues, customer dissatisfaction and possible associated penalties. In general the consequences of downtime are very costly (Driessen et al., 2015). According to Öner et al. (2010), losses of operational interruptions due to failures of complex technical systems may even grow more than linearly in the duration of the operational interruption. Since the availability of capital assets is critical to the execution of primary processes, downtime needs to be minimized. Downtime can be divided into diagnosis and maintenance time on the one hand and maintenance delay caused by unavailability of the required resources on the other hand (Driessen et al., 2015). To shorten the time an asset spends in maintenance, the repair-by-replacement concept is often applied. This means that a failed part or a part that needs maintenance is taken out and replaced by a Ready-For-Use part. In many cases the original equipment manufacturer (OEM) of capital assets provides an after sales support service to perform these maintenance activities. This service consists in providing necessary service engineers and spare parts to existing, geographically dispersed customers when they experience problems with a purchased capital asset (Candas and Kutanoglu, 2007). In order to provide a successful after sales support service, it is important to design and operate a spare parts supply chain capable of serving geographically dispersed customers in a time-responsive manner. Designing a supply chain requires decisions on three traditional hierarchical levels and corresponding time horizons: strategical, tactical, and operational (Shen, 2007). Research on spare parts management is mostly focused on the tactical and operational level, such as inventory control, assortment management and demand forecasting (Wagner and Lindemann, 2008). Important decisions at the strategic level for a spare parts supply chain are the number of stock points, their geographical location and the allocation of customer demands to these stock points (Candas and Kutanoglu, 2007).

In this Master Thesis we will compare different Service Parts Distribution Network configurations in terms of total logistics costs. With respect to the configuration, we consider the number of Distribution Centers (DC-s), their geographical location and the allocation of customer demands to these DC-s. This chapter gives a general introduction to Philips and describes the research questions. In §1.1, an introduction to Philips is given. In §1.2, a description of the Service Parts Supply Chain is given. In §1.3, relevant literature is briefly mentioned and our research questions are presented. In §1.4, the scope of this Master Thesis Project is described. Finally, in §1.5 an outline of this report is given.

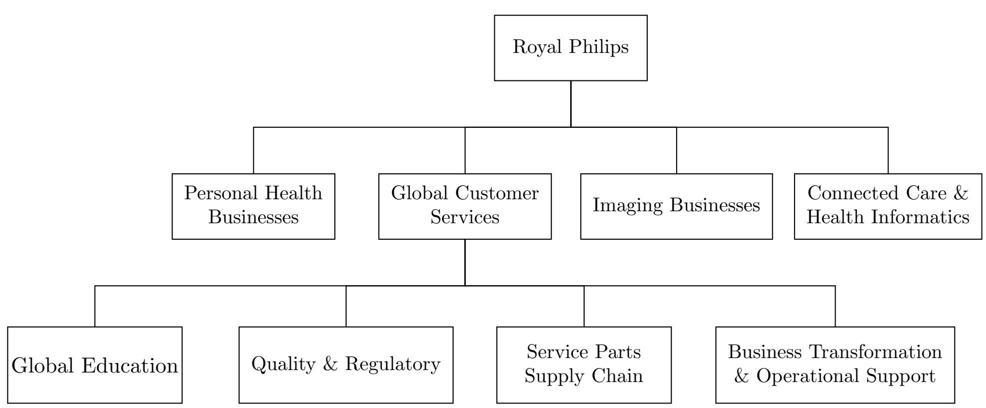
1.1 Company Background

In §1.1.1, a brief overview of Philips is given and the different types of businesses they are involved in. In §1.1.2, a description of the Service Parts Supply chain Department where this Master Thesis Project is conducted is provided.

1.1.1 Royal Philips

Royal Philips (commonly referred to as Philips) was founded in Eindhoven in 1891 by Gerard Philips and his father Frederik, later, Gerard's brother Anton joined Philips as well. Philips started out with the production of carbon-filament lamps and other electro-technical products. Soon, it was one of the largest light bulb producers in the world. Today, Philips has evolved into a diversified technology multinational, offering a variety of products. Headquartered in the Netherlands, Philips had a turnover of 24.2 billion euro and a profit of 659 million euro in 2015. The company employs approximately 113,000 employees, it has 95 production sites located in 25 different countries and sales and services in approximately 100 countries. The mission of Philips is to improve people‘s lives through meaningful innovation. Recently, Philips established two stand-alone companies: Royal Philips, active in the area of health technology, and Philips Lighting, active in the area of lighting solutions. Royal Philips consists of four different Business Groups. These Business Groups are Personal Health Businesses, Global Customer Services, Imaging Businesses and Connected Care & Health Informatics. Business Groups can be further broken down into so-called Business Innovation Units (BIUs). The Global Customer Services Group consists of four BIUs, namely Global Education, Quality & Regulatory, Service Parts Supply Chain and Business Transformation & Operational Support. A partial organization chart of Royal Philips is shown in Figure 1.1. In this research, we will focus on the Service Parts Supply Chain.

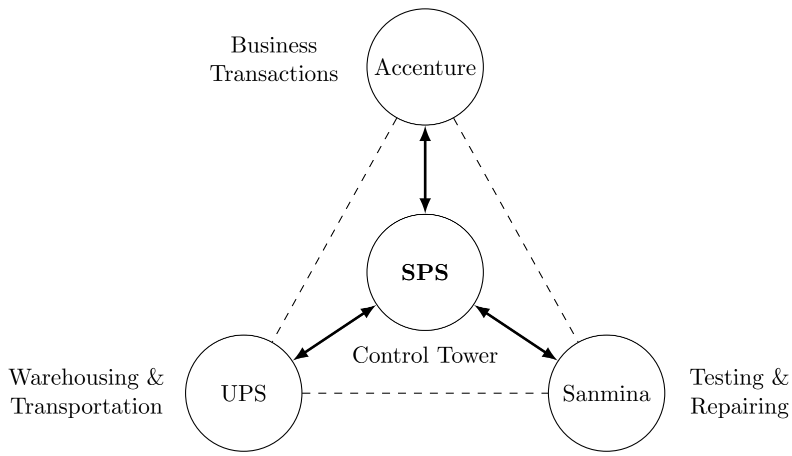
Figure 1.1: Partial organization chart of Royal Philips



1.1.2 Service Parts Supply Chain Department

The Service Parts Supply Chain (SPS) department is responsible for the total service parts supply chain from Philips' factories and external suppliers to the customers. The SPS department's strategy is to maximize the service part availability, minimize the total cost of operation and minimize inventory levels. To realize this strategy, the SPS department operates a Service Parts Distribution Network. The mission of the SPS department is to assure that the right part is at the right place at the right time and cost. The core competence of the SPS department is global inventory planning, the majority of the remaining business processes is either automated or outsourced. The SPS department has formed strategic partnerships with three important external parties: Accenture, UPS and Sanmina. The structural relationship of these partnerships is visualized in Figure 1.2.

Figure 1.2: Visulization of structural relationship of strategic partnerships



The SPS department outsources all transactional activities to Accenture. On an operational basis this involves adding and modifying data. Warehousing is completely outsourced to UPS. Transportation is also completely outsourced but to multiple different parties such as UPS, DHL, TNT and FedEx. Operations of the reverse supply chain such as testing, disposing and repairing defective service parts are outsourced to Sanmina. The SPS department operates as a control tower with regard to the service parts supply chain. The SPS department consist of eight different teams, each responsible for a separate part of the service parts supply chain.

1.2 Service Parts Supply Chain

In managing the service parts supply chain (SPSC), the SPS department distinguishes three regions. The first region is APAC which includes East Asia, South Asia, Southeast Asia, and Oceania. The second region is EMEA, which includes Europe, Middle East and Africa. Finally, the third region is AMEC, which includes America, Mexico, Latin America and Canada. More or less the same types of service parts supply chain is operated in each region. Two types of service parts flow through the SPSC: *repairables* and *consumables*. Repairables are repaired after they have failed. By contrast, consumables are directly scrapped after failure. The SPS department currently categorizes service parts into eight so-called part segments. These part segments are classified based on a part's value and demand rate. An overview of each part segment and its associated description is given in Table 1.1. The components that form the service parts supply chain are described in §1.2.1. The flow of service parts between the different components is discussed in §1.2.2. Finally, §1.2.3 characterizes the way inventory planning is carried out at the SPS department.

Table 1.1: Part Segments

Segment	Description
CCP	Customer Critical Parts
HCFM	High Cost Fast Movers
LCFM	Low Cost Fast Movers
Slow moving	Slow Movers
NPI	New Product Introduction
FCO	Field Change Order
Tools	Tools for repair or installation
LTB	Last Time Buy
EOL	End of Life
Tubes	Tubes

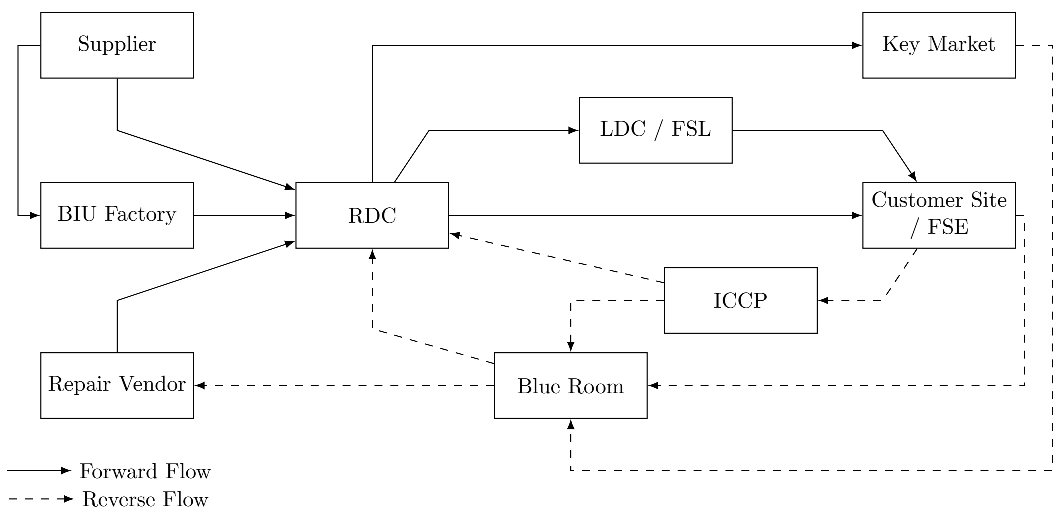
1.2.1 Components of the Service Parts Supply Chain

The service parts supply chain is build up from sources, Distribution Centers, customers, In-Country Collection-Point's and so-called Blue Rooms. Service parts are sourced at three different types of sources. A service part may be sourced at an *external supplier*. Philips sources service parts from external suppliers located at different regions in the world. A service part may also be sourced at a *Business Innovation Unit* (BIU) factory. A BIU factory can be seen as an internal supplier of service parts. Approximately 70% of the service parts is sourced internally at the BIU factories. Medical devices are assembled from parts manufactured by Philips itself as well as from parts purchased at external suppliers. Hence, parts manufactured by Philips serve both the assembly of medical equipment and act as a source of service parts for the service parts supply chain. Finally, a service part may also be sourced at one of the *Repair Vendors*. A Repair Vendor receives defective parts, performs a diagnosis and repairs the parts. Repaired parts are subsequently sent back to the *Regional Distribution Center* (RDC). For each region, the SPS department operates a two-echelon distribution network. The first echelon contains a single RDC. The second echelon contains multiple *Local Distribution Centers* (LDC-s) and multiple *Forward Stocking Locations* (FSL-s). Each RDC, LDC and FSL is owned and operated by UPS but controlled by the SPS department. An RDC contains a relatively large assortment of service parts. Each RDC is strategically located at a central point in a regions' transportation network. The RDC of the region APAC is located in Singapore (Singapore) near UPS's hub in Singapore. The RDC of EMEA is located in Roermond (The Netherlands) close to UPS's hub in Cologne. The RDC of AMEC is located in Louisville (America) near UPS's hub in Louisville. LDC-s are used to improve Next Business Day (NBD) delivery performance and for customs reasons. An LDC contains only a limited assortment of service parts. FSL-s are used to deliver service parts to important customers within 4 hours. These shipments are carried out by an external dedicated courier. An FSL contains only a very limited assortment of critical service parts and are often located close to a cluster of key customers. The SPS department has two different types of customers, a service part may be delivered to a *Field Service Engineer* (FSE) at a *so-called Pick-Up Drop-Off* (PUDO) location or at a customers' site such as a hospital, clinic or doctor practice. An FSE performs maintenance operations on medical equipment at the customers' site. It may also be sold to a *Key Market* (KM). A KM is an organization that maintains the end customer relationships for a single or collection of countries. When the SPS department sells a service part to a KM, the service part may be shipped directly to the end customer. Certain countries in the region EMEA contain a so-called *In-Country Collection-Point* (ICCP) in order to consolidate the return flow of service parts. At an ICCP location, defective parts are consolidated into batches to lower transportation costs. Each region contains one *Blue Room* (BR) where defective or unsealed service parts are inspected to decide whether a service parts needs to be scrapped, repackaged or repaired. A BR has the capability to repack unsealed service parts.

1.2.2 Flow of Service Parts

The service parts supply chain controlled by the SPS department contains a forward flow and a reverse flow. The reverse flow includes both *repairable* parts and *consumable* parts since in some cases a part cannot be scrapped locally. The flow of service parts through the service parts supply chain is roughly the same for each of the three regions: APAC, EMEA and AMEC. The flow of service parts in the current service parts supply chain is visualized in Figure 1.3. The forward flow comprises all service parts supply chain components that facilitate the flow of service parts from their source to the customer which may be either an FSE or a KM. By contrast, the reverse flow comprises all service parts supply chain components that facilitate the flow of service parts from the customers back to the RDC or Repair Vendor. Service parts are obtained from three different

Figure 1.3: Visualization of flow service parts



types of sources: External Suppliers, Philips BIU factories or Repair Vendors. Philips' BIU factories source parts for the manufacturing and assembly of medical equipment at external suppliers as well. Service parts flow from their source to the RDC. From the RDC, service parts flow either directly to a customer or indirectly via a LDC or FSL to the customer. In addition, service parts may flow directly from an RDC to a KM. Defective service parts flow from the customer either directly or indirectly via the ICCP to the BR. Sealed parts arriving at an ICCP flow directly back to the RDC, non-sealed or defective service parts at the ICCP flow to the BR for further inspection. Defective parts from a KM flow directly to the BR without any consolidation at an ICCP. After an inspection in the BR, a service part may either flow back to the RDC in case it is non-sealed but not defective or flow to the Repair Vendor in case it is defective and needs repair. Consumable service parts are scrapped. The most important component of the five components of the Service Parts Supply Chain from the SPS department's point of view are the Distribution Centers. In the remainder of this report, we will refer to this set of DC-s as the *Service Parts Distribution Network* (SPDN).

1.2.3 Inventory Planning

The SPS department applies a (s, Q)-ordering policy to manage service parts inventory across the different types of DC-s. In practice, this means that if the inventory position of a service part falls below its Reorder Level (ROL), a certain Reorder Quantity (ROQ) is ordered such that its inventory position is increased up to its Target Stock Level (TSL). The calculation of the ROL's, ROQ's and TSL's is done using a planning tool called MCA. MCA runs a *system-approach* optimization to determine TSL's and resulting ROL's and ROQ's on a part basis. For CCP parts, optimal stocking levels are set while satisfying a network fill rate of 98%. Non-CCP parts need to satisfy a lower network fill rate of 95%. As optimizations are run based on a system-approach, slow moving expensive parts are likely to have a lower fill rate than low value, fast moving parts. In this way, total inventory investments are minimized while satisfying the network fill rate constraints. When the inventory position of a service parts falls below its ROL, a replenishment is carried out using the so-called TARN-policy. TARN is an acronym for Transship, Allocate, Repair and New Buy. It specifies the order in which Philips wants to replenish their DC-s. The SPS department distinguishes between *rooted* and *virtual* part networks. In case of *rooted* networks, suppliers ship service parts to a single RDC and afterwards the parts are replenished to the other two RDC-s based on demand in those regions. Parts assigned to *virtual* networks are shipped by suppliers to all three RDC-s.

1.3 Research Questions

In designing an integrated supply chain, a decision maker needs to take into consideration both inventory costs and distribution costs when the number and location of the DC-s are determined (Shen, 2007). Some of the initial design choices made with respect to the SPDN configuration are being questioned due to the dynamic environment in which the SPS department operates. Both the geographical location and the rate of demand for service parts have been subject to change. In addition, inventory and transportation rates may have changed over time affecting the optimal SPDN design to perform its objective.

The current SPDN design of each region consists of two echelons. The first echelon contains a single RDC. The second echelon contains multiple LDC-s and multiple FSL-s. For the region EMEA, the RDC is used primarily; approximately 95% of the total demand in EMEA is fulfilled by the RDC. The FSL-s are mainly used to shorten lead times for a very limited number of service parts. The SPS department wants to investigate if there is an alternative SPDN design with lower total logistic costs. There is a special interest around the effect of applying a SPDN in which stock is installed closer to the customer. By looking into an alternative SPDN design, the SPS department gains insight into the extent to which the current SPDN of the region EMEA is well designed in terms of the number and location of the DC-s to perform its objective.

Based on a review of the literature Borst (2016), it has been concluded that designing a supply chain requires decisions on three traditional hierarchical levels: strategical, tactical and operational. Important decisions at the strategic level for a spare parts supply chain are the number and geographical location of stock points and the allocation of customer demands to these stock points. Research on spare parts management is mostly focused on the tactical and operational level, such as inventory control, assortment management and demand forecasting. The spare parts inventory models, treat the number and location of the stocking points and corresponding assignment of customers, as a given.

Based on this literature review, the conclusion can be drawn that research on decisions at the strategical level for a spare parts supply chain is scarce, especially on the integration of strategic decisions with tactical and operational decisions such as location-inventory models that specifically address spare parts. Nevertheless, the spare parts inventory models offered by literature give a methodological foundation for evaluating and designing spare parts supply chains. Based on the interest of the SPS department in looking into an alternative Service Parts Distribution Network configuration, we formulated the following research questions:

1. *What is the cost structure of the current Service Parts Distribution Network?*

2. *What is - based on demand patterns and cost parameters - an alternative and potentially better Service Parts Distribution Network configuration compared to the current Service Parts Distribution Network configuration in terms of total logistics costs?*

3. *How can a spare parts inventory model offered by literature be extended to a model in which both transportation times and transportation costs from DC-s to the geographical locations of demand is incorporated, to evaluate different Service Parts Distribution Network configurations?*

4. *What is the performance of the current and the alternative Service Parts Distribution Network configuration in terms of total logistics costs?*

5. *What is the influence of different cost parameters on the optimal Service Parts Distribution Network configuration?*

1.4 Scope

The scope of the Master Thesis Project is described in terms of Business Entities involved (§1.3.1), service parts involved (§1.3.2) and geographical area (§1.3.3).

1.4.1 Business Entities Involved

The SPS department consists of 8 different teams. The teams that are involved in this project are the Customer Demand & Fulfillment team and the Strategic Planning & Supply team. Customer Demand & Fulfillment is mainly concerned with fulfilling customer demand by taking care of warehousing and transportation. Strategic Planning & Supply takes care of the inventory planning and makes sure that the right target stock levels are set at each DC.

1.4.2 Geographical Area

This project includes all DC-s and customers located in the following 18 countries: Austria, Belgium, Switzerland, Germany, Denmark, Spain, Finland, France, United Kingdom, Greece, Ireland, Israel, Italy, Luxembourg, The Netherlands, Norway, Portugal and Sweden.

1.4.3 Service parts involved

In this project we focus on all Stock Keeping Units (SKU-s) that:

- need to be delivered on the Next Business Day;
- need to be delivered to customers located in the afore mentioned geographical scope;
- are stocked at at least one of the DC-s in the afore mentioned geographical scope.

Due to time limitations a subset of SKU-s representing the total set of SKU-s is used to compare SPDN configurations.

1.5 Outline Report

The remaining content of this report is structured in the following chapters: In chapter 2, the current SPDN is explained. In chapter 3, a reconfiguration of the current SPDN is described. The Inventory-Transportation model to compare different SPDN configuration is described in chapter 4. The Inventory-Transportation model is used to compare the current SPDN and the alternative SPDN configuration by means of two case studies, the case studies are described in chapter 5. Finally, the conclusions and recommendations for Philips are given in chapter 6.

Chapter 2

Current Service Parts Distribution Network

This chapter describes the current Service Parts Distribution Network (SPDN) operated by the SPS department. In §2.1, the configuration (number and location of DC-s) of the current SPDN is explained. The cost structure of the SPDN is described in §2.2. In §2.3, the analysis of the demand rates is described, followed by a description of the analysis of transportation rates in §2.4. Finally, in §2.5 a conclusion is given based on the analyses.

2.1 Configuration

The SPS department currently uses a two-echelon SPDN with one RDC and four LDC-s to fulfill demand that needs to be delivered NBD in our geographical scope. The RDC in the first echelon is located in Roermond (NL). The four LDC-s in the second echelon are located in Coventry (GB), Paris (FR), Madrid (ES) and Milan (IT). See Table 2.1 for an overview of the relative quantity and number of order lines shipped from each DC in 2015.

Table 2.1: Quantity and number of order lines shipped per DC

DC	Order lines	Quantity
LDC Coventry	0.7 %	0.9 %
LDC Paris	1.0 %	1.2 %
LDC Madrid	0.7 %	1.0 %
LDC Milan	0.4 %	0.5 %
RDC Roermond	97.2 %	96.4 %

As can be seen from Table 2.1, a large fraction of demand that needs to be delivered NBD is delivered from the RDC in Roermond. Approximately 2.8% of the total number of order lines in 2015 is shipped from the LDC-s and the remaining fraction is shipped from Roermond. This implies that nearly all demand is delivered from one central location in the first echelon.

2.2 Cost Structure

There are three main cost items associated with the current SPDN: warehousing, transportation and customs. The cost structure for warehousing is discussed in §2.2.1, for transportation in §2.2.2

and for customs in §2.2.1.

2.2.1 Warehousing

As described in chapter 1, warehousing is globally outsourced to UPS. Warehousing includes inbound handling, outbound handling and storage. Both inbound and outbound handling cost is charged per order line. An order line specifies a quantity of a single particular Stock Keeping Unit (SKU) for an order. Thus, inbound and outbound handling costs are linear in the amount of parts shipped. The SPS department has three different types of costs with regard to holding stock; the physical storage of a part in a DC of UPS, the investment of capital to buy a part and the costs associated with the potential risk of a part becoming obsolete. Storage is charged based on the amount of space that the installed stock requires in a DC. Capital costs and obsolescence costs are both dependent on the value of a part. Currently, the SPS department assumes that the holding costs for an SKU constitute 20% of a part's value. Although storage costs are dependent on the volume of a part and not on the value of a part, assuming 20% may be justified since storage costs are a relative small component of total holding costs (approximately 8%). The holding cost rate of 20% is based on a Weighted Average Costs of Capital (WACC) of 9% and a general obsolescence probability of 10%.

2.2.2 Transportation

Transportation is outsourced as well, but to multiple different carriers such as UPS, DHL, TNT and FedEX. Transportation includes inbound transportation, in-network transportation and outbound transportation. Inbound transportation includes all shipments from a supplier to a DC. In-network transportation includes shipments from a DC to another DC, e.g., replenishment shipments from the RDC to an LDC or FSL. Outbound transportation includes all shipments from a DC to a customer. For all three types of transportation, a fixed fee per shipment is charged. This fixed fee is dependent on the used carrier, the required service level, the lane over which a part needs to be shipped and the Chargeable Weight (CW) of the packaging in which the part is shipped. The choice of carrier often depends on the lane which is required. Each carrier has its own transportation network, one more cost-effective in the one region while the other more cost-effective in another region. The required service level determines the speed at which a shipment is carried out, for a parcel network typically ranging from early Next Business Day (NBD) to two days. The lane is formed by the origin country and the destination country. The Chargeable Weight (CW) of a shipment is based on the volume and weight of the package. The CW determines to which weight class a package is assigned. Let l denote the length (cm) of a package, w denote the width (cm) of a package, h denote the height (cm) of a package and aw denote the actual weight (kg) of a package. Then, the CW for an Express shipment of UPS equals $CW = \max\left(\frac{l \cdot w \cdot h}{6000}, aw\right)$. Since inbound and in-network transportation often requires a lower service level (speed), transportation rates for these types of transportation are significantly lower than outbound transportation for which a relative high service level is required.

In the current practice of transportation in our geographical scope, outbound shipments are mainly carried out using Express service of UPS. Approximately 77% of the total number of outbound shipments are shipped by UPS using mostly service level Express. Express shipments are delivered Next Business Day. In-network shipments are carried out using a low service level (5-7 days), mostly using UPS. With regard to shipments from suppliers to DC (inbound transportation), two different types of cases can be distinguished. Shipments from internal suppliers to a DC and shipments from external suppliers to a DC. Shipments from internal suppliers are arranged by the BIU itself, the costs are accounted for by the SPS department. Shipments from external suppliers to a DC are arranged by the SPS department. These types of shipments are carried out using a low service level, mostly using TNT.

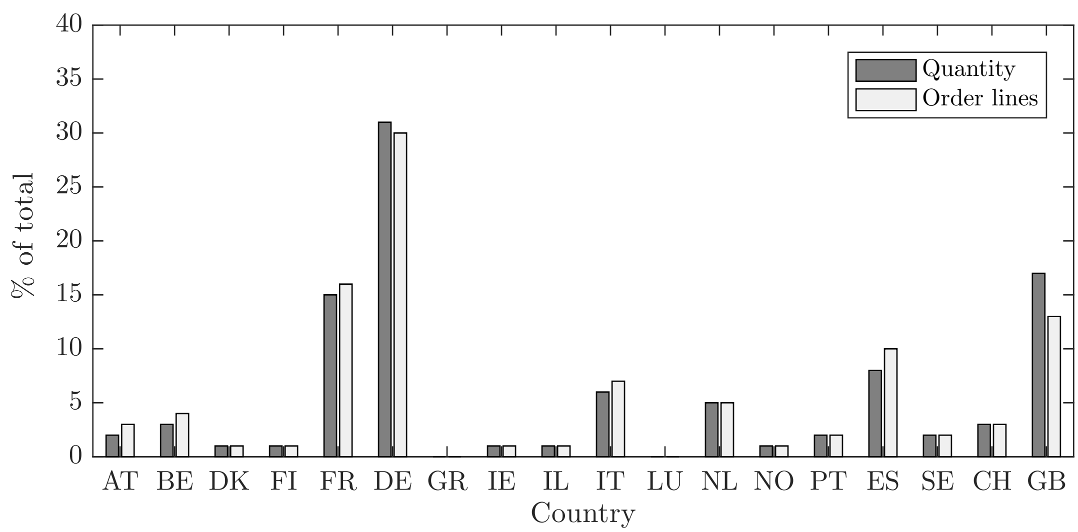
2.2.3 Customs

Custom clearance is charged on a fixed fee per clearance. This fee may depend on several factors, typically on the value of a package and the country *from* which one imports or *to* which one exports. For the region Europe the costs associated with customs are negligible. In the remainder of this study we will ignore costs for custom clearance.

2.3 Analysis of Demand Rates

As mentioned in §1.4, this Master Thesis Project is scoped on demand that need to be delivered Next Business Day for all types of service parts in our geographical scope. See Figure 2.1 for an overview of the demand rates per country for the year 2015. See Appendix A for an overview of the country codes and corresponding country names. As can be seen in Figure 2.1, there is a relatively

Figure 2.1: Demand Rates



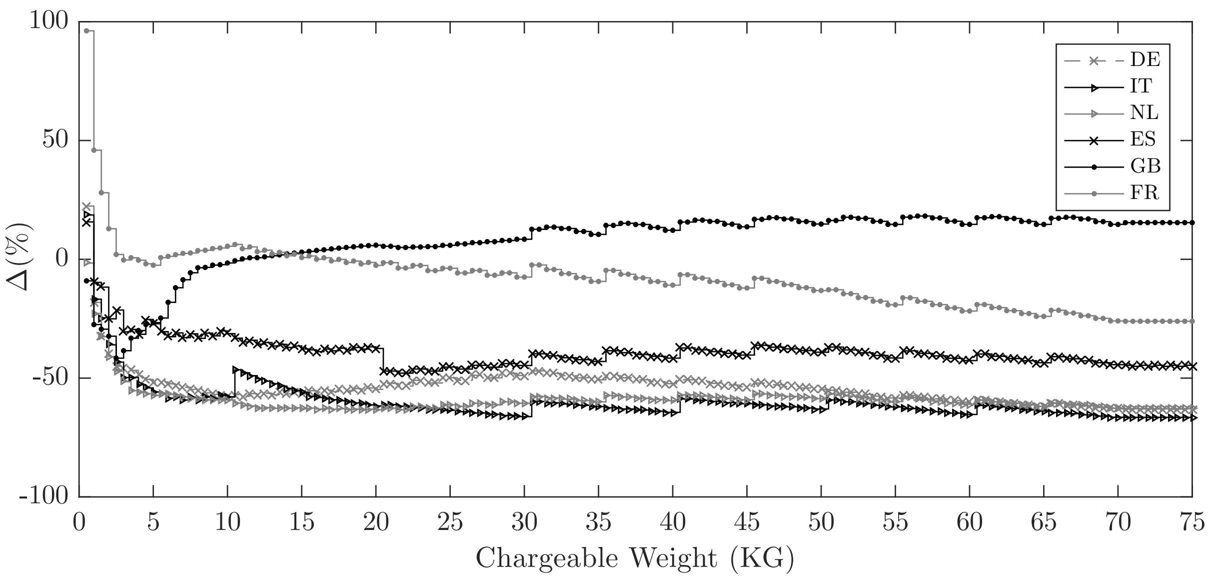
large difference between the demand rates per country. Countries FR, DE, IT, NL, ES and GB have a relative large demand compared to the other countries, combined they represent 82% of the total demand quantity. Especially DE has a relative large demand, 31% of total demand quantity. The customer order quantity was equal to one for 87% of all orders in 2015 in our geographical scope.

We are also interested in the extent to which the set of requested SKU-s is similar for each of the 18 countries. We looked at the number of different SKU-s requested by a country relative to the total number of different SKU-s requested by all 18 countries. We found that the relative number of different SKU-s requested per country ranges from 0.5% for GR to 55% for DE, approximately proportional to the demand rate of a country. We also looked at the number of countries that request a particular SKU. Roughly 42% of the SKU-s are requested from one country, 18% from two countries, 11% from three countries and 29% in four or more countries. See Appendix B for an overview of demand commonality between countries.

2.4 Analysis of Outbound Transportation Rates

In this section we will analyze outbound transportation rates for service level Express. As mentioned before, transportation is outsourced to multiple different carriers such as UPS, DHL, TNT and FedEX. We focus our analysis on UPS transportation rates since approximately 77% of outbound transportation in our geographical scope is carried out by UPS. UPS offers basically two types of transportation for service level Express, *domestic* and *cross-border*. Domestic transportation includes shipments within a country. Domestic transportation is only possible in a subset of the set of 18 countries in our geographical scope. Cross-border transportation includes shipments from one country to another country. Both domestic and cross-border transportation have a transportation time of one day (Next Business Day delivery) for all countries in the geographical scope. We compared the domestic rates and Cross-border rates for the six countries that have the largest demand. We compare the rates for different values of CW. See Figure 2.2 for an overview of the relative cost difference between a domestic shipment and the lowest cross-border rate for each CW for the six countries that have the highest demand rates. The lowest cross-border rate for a shipment to a particular country is determined by comparing the rates for the 18 different lanes that can be formed when fixing the destination country and varying the origin country. As can

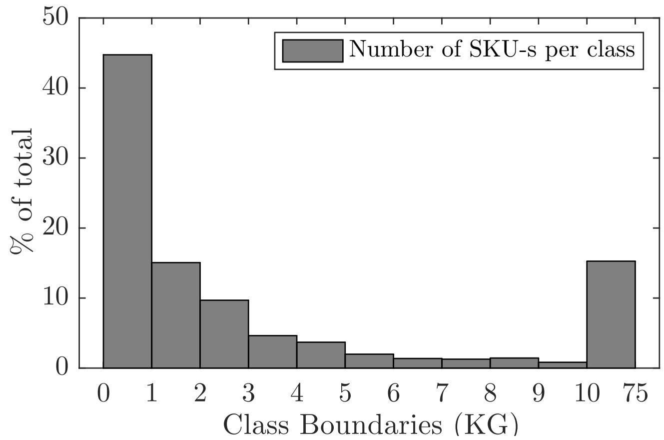
Figure 2.2: Domestic rate compared to lowest cross-border rate



be seen from Figure 2.2, domestic rates for the countries DE, IT, NL and ES are for each value of CW significantly lower than the lowest cross border rate. Over the complete CW interval on average -54% for DE, -60% for IT, -59% for NL and -39% for ES. GB and FR do not have lower domestic rates on the whole CW interval. The domestic rates for GB are lower for $CW < 11$ and are higher as soon as $CW \geq 11$. By contrast, the domestic rates for FR are higher for $CW < 17$ and are lower as soon as $CW \geq 17$. Since the CW influences the transportation rate of a shipment in general and in particular whether domestic rates of cross-border rates are lower, we looked at the distribution of the CW for all SKU-s in our scope. See Figure 2.3 for an overview of the relative number of SKU-s per CW class. As can be seen from Figure 2.3, a large fraction of SKU-s has a CW between 0 and 1 kg. Roughly 85% of the SKU-s has a CW between 0 and 10 kg. This implies for example that using domestic rates in FR will not be very beneficial.

When looking solely at cross-border transportation rates, it seems that the *origin* country

Figure 2.3: Distribution of Chargeable Weight (CW)



influences the transportation rate significantly more than the *destination* country of a particular lane. It turns out that in each of the cases considered, either NL, DE or BE have the lowest transportation rate to ship from, after looking into the transportation rates for all possible lane and CW combinations. The origin country with the lowest transportation rate for a specific destination country may vary in CW. For example, for some values of CW, it is cheaper to ship to ES from NL and for some values of CW it is cheaper to ship to ES from DE. See Figure C.1 in Appendix C. The same holds for shipments to FR. See Figure D.2 in Appendix C. This implies that when assigning demand to DC-s not only the destination country of a requested SKU is important but the Chargeable weight of an SKU as well.

2.5 Conclusion

From the analysis of demand rates as described in §2.3, we learn that there are relatively large differences in the demand rates per country. Furthermore, we observe demand commonality across the countries such that sharing of stock may be possible. From the analysis of the outbound transportation rates as described in §2.4, we learn that for DE, IT, NL, ES and GB, domestic transportation rates are significantly lower than the lowest cross-border rate. With respect to cross border transportation rates, we learn that the origin country influences the transportation rate significantly more that the destination country. In addition, we learn that transportation costs are not linear in the transportation distance. These insights are used for the reconfiguration of the current SPDN.

Chapter 3

Reconfiguration of Service Parts Distribution Network

This chapter presents a reconfiguration of the current SPDN. This reconfiguration is based on insights obtained by analyzing the demand rates and transportation rates. The alternative SPDN configuration is described in §3.1. In §3.2, the assignment of demand to DC-s in the alternative SPDN configuration is explained.

3.1 Alternative Configuration

As described in chapter 2, warehousing is outsourced to UPS. Hence, inventory costs are completely linear in the amount of stock that is installed in the DC-s. The SPS department has three different types of costs with regard to holding stock; the physical storage of a part in a DC, the investment of capital to buy a part and the costs associated with the potential risk of a part becoming obsolete. Both the capital costs and obsolescence costs per part will not be affected when reconfiguring the SPDN, i.e., changing the number and location of DC-s. The storage costs, however, may be affected. The inbound, outbound and storage capacity of each DC in a network of relatively smaller DC-s will be less compared to a single relatively large DC. This may lead to a decrease in economies of scale whereupon UPS may charge Philips higher storage costs. However, storage costs is a relative small component compared to total holding costs (approximately 8%). Capital costs and obsolescence costs combined represent 92% of the total holding cost, therefore holding costs is strongly dependent on the value of a part. For this reason, we assume that any change in the configuration of the current SPDN will not lead to a change in holding costs.

In the reconfiguration of the current SPDN network, we started with zero DC-s and subsequently considered installing a DC in the six countries that have the largest demand; FR, DE, IT, NL, ES and GB. Next, based on the analysis of domestic and cross-border transportation rates we determined in which of these countries it is beneficial to install a DC in terms of transportation costs. Since the domestic rates of FR are only lower when $CW \geq 17$ and approximately 90% of SKU-s has $CW < 17$, it seems that installing a DC in FR is not beneficial. For DE, IT, NL, ES and GB it is beneficial for the transportation costs to install a DC since demand for those countries may be fulfilled with domestic shipments. Domestic shipments are, dependent on the country, 39% to 60% percent lower compared to the lowest cross border rate. For this reason, we reconfigure the current SPDN to a single-echelon SPDN with 5 DC-s. See Table 3.1 for the locations of the DC-s in the alternative SPDN. The location of a DC within a country is not specified since the location of a DC within a country does not influence the transportation costs nor the inventory costs in this study. By introducing a network configuration of multiple DC-s, sharing of stock across

Table 3.1: Alternative SPDN configuration

DC	Country
1	Germany (DE)
2	Italy (IT)
3	The Netherlands (NL)
4	Spain (ES)
5	Great Brittain (GB)

the DC-s becomes possible. In this way, the same level of risk pooling may be obtained as when using a network configuration with one single large DC such as the current SPDN configuration (Paterson et al., 2011). Risk pooling is the reduction of demand variability by aggregating demands from multiple stock locations. Eppen (1979) showed that significant inventory-cost savings can be obtained by grouping stock locations, and thus exploiting risk pooling effects. Sharing of stock, however, may lead to increased transportation costs since it is likely that performing a lateral transshipment requires the use of relative high cost transportation lanes. It is likely that the inbound transportation costs will increase due to a less consolidated transportation flow from the supplier to the DC-s when moving from the current SPDN configuration to the alternative SPDN configuration. In addition, in the alternative SPDN configuration parts need to be shipped from the supplier to countries for which it is likely that the in-country transportation network will be less cost effective compared to NL. However, due to a lack of information about inbound transportation costs, we omit inbound transportation costs in this research. Nevertheless, we will perform a sensitivity analysis on the replenishment lead times to partly determine the effect of inbound transportation.

3.2 Demand Assignment

The assignment of demand to the DC-s in the alternative SPDN configuration is based on the outbound transportation rates. Demand for a particular SKU is assigned to the DC that can deliver the SKU with the lowest transportation costs. In chapter 4, a mathematical formulation of this assignment policy is provided. By using this assignment policy, demand of the countries DE, IT, NL, ES and GB will be assigned to the corresponding DC-s in those countries. This will hold for all SKU-s and all Chargeable Weight's except for a small fraction of demand requested from GB since domestic transportation rates in GB are only lower when $CW < 11$. Thus, all demand for GB is assigned to DC 5 (GB) except for demand for SKU-s with $CW \geq 11$. The remaining demand requested from GB and the other 15 countries where no DC is installed, is assigned to the DC that can deliver the part with the lowest transportation costs. The transportation rates are dependent on the country where an SKU needs to be shipped and the CW of an SKU. In most of the cases this will be either NL or DE.

Chapter 4

Inventory-Transportation Model

This chapter presents an Inventory-Transportation model that is used to compare the current SPDN configuration with the alternative SPDN configuration. A brief introduction to spare parts inventory models with lateral transshipments is provided in §4.1. In §4.2, a description of the inventory-transportation model is provided followed by the assumptions in §4.3. The evaluation and optimization of the model is discussed in §4.4 and §4.5.

4.1 Introduction

We need to model a multi-item, multi-location inventory system that allows for sharing of stock between DC-s in order to compare the current SPDN configuration with the alternative SPDN configuration. In the course of time, a considerable amount of spare parts management research has been dedicated to spare parts inventory models with lateral transshipments. Lateral transshipments are stock movements between locations of the same echelon (Paterson et al., 2011).

Wong et al. (2006) were one of the first to study a multi-item, multi-location inventory model with lateral transshipments and aggregate mean waiting time constraints. Their goal is to minimize total costs of inventory holding, lateral transshipments and emergency shipments subject to a target level for the average waiting time at all locations. Lateral transshipments and emergency shipments act as two additional transportation modes that are available in the inventory system. When a part fails, it is removed, sent to repair and immediately replaced by a Ready-For-Use item at the local warehouse. If a local warehouse is out of stock, a lateral transshipment is used to deliver the part from another local warehouse. Wong et al. (2006) use a so-called closest neighbor sourcing rule when selecting the location that acts as the source of a lateral transshipment. They show that the closest neighbor sourcing rule is preferable to the random sourcing rule used by Axsäter (1990) and Patrik Alfredsson (1999). Wong et al. (2006) assume complete pooling. If none of the local warehouses have stock on hand, an emergency shipment takes place from an external supplier.

Kranenburg and Van Houtum (2009) study a similar inventory system with a single-echelon structure that allows for lateral transshipments between local warehouses. They distinguish two types of local warehouses; main and regular local warehouses. Main local warehouses can both request and perform a lateral transshipment, regular local warehouses can only request a lateral transshipment. This distinction leads to a partial pooling structure. If a demand occurs, the local warehouse delivers the item immediately when it has stock on hand. If a local warehouse does not have stock on hand, it tries to deliver the part through a lateral transshipment from a main local warehouse. Each local warehouse is assigned to one main. Each main checks the other mains in a pre-specified order. If none of the main local warehouses have stock on hand, the central warehouse sends an emergency shipment. Their model assumes that the central warehouse has infinite supply of items and can always deliver the requested parts. The aggregate mean waiting time is used as a service measure.

The option to predefine the order in which a main local warehouse submits a request for a lateral transshipments at another main local warehouse, makes the model of Kranenburg and Van Houtum (2009) suitable to model the alternative SPDN configuration since transportation costs are not linear in the transportation distance. A closest neighbor source rule will not be optimal. Moreover, the model of Kranenburg and Van Houtum (2009) allows for multiple interpretations with respect to transportation times and transportation costs.

This remainder of this chapter describes an Inventory-Transportation model based on the the model of Kranenburg and Van Houtum (2009). We use this model to determine the inventory and transportation costs for a given SPDN configuration.

4.2 Model Description

Let I denote the (non-empty) set of SKU-s and J the (non-empty) set of DC-s. We distinguish two types of DC-s: main DC-s and regular DC-s. Main DC-s have the ability to perform a lateral transshipment, regular DC-s do not. The set of main DC-s is denoted by $K(\subseteq J)$. Let L denote a set of countries from which a request for a service part is submitted. Each country $l \in L$ is assigned to exactly one DC $j \in J$ (either a main or a regular DC). The demand rate for each SKU i for each country $l \in L$ is assumed to follow a Poisson process with a constant rate $m_{i,l}$. Let $Q_{i,j}(\subseteq L)$ denote the set of countries for which demand of SKU $i \in I$ is assigned to DC $j \in J$. Demand for SKU $i \in I$ from country $l \in L$ is assigned to DC $j \in J$ that can ship the part with the lowest transportation costs. Let $C^{trp}_{i,j}$ denote the transportation cost for a shipment of SKU i from DC j to country l, then $Q_{i,j} = \{l \in L | C^{trp}_{i,j,l} = \min\{C^{trp}_{i,1,l}, C^{trp}_{i,2,l}, ..., C^{trp}_{i,5,l}\}\}$. The total demand rate for SKU $i \in I$ at DC $j \in J$ is denoted by $M_{i,j}$, i.e., $M_{i,j} \equiv \sum_{l \in Q_{i,j}} m_{i,l}$. Also, let M_i denote the total demand rate for SKU $i \in I$, i.e., $M_i = \sum_{j \in J} M_{i,j}$. In addition, let M denote the total demand rate for all SKU-s $i \in I$ at all DC-s $j \in J$, i.e., $M \equiv \sum_{i \in I} \sum_{j \in J} M_{i,j}$.

When a part of SKU i is requested at DC j it is shipped directly to the customer when this DC has stock on hand. The mean transportation time for a direct shipment of SKU i from DC j to an arbitrary country assigned to DC j is denoted by $t^{dir}_{i,j}$. Different from Kranenburg and Van Houtum (2009), we calculate a mean transportation cost for a direct shipment since multiple countries may be assigned to a DC. Let $C^{dir}_{i,j}$ denote the mean transportation cost for a direct shipment of SKU i from DC j to an arbitrary country assigned to DC j, then

$$C^{dir}_{i,j} = \sum_{l \in Q_{i,j}} \frac{m_{i,l}}{\sum_{x \in Q_{i,j}} m_{i,x}} C^{trp}_{i,j,l}. \tag{4.2.1}$$

When this DC has no stock on hand, it submits a request to ship the part from a (other) main DC via a lateral transshipment. The mean transportation time for a lateral transshipment of SKU i from main DC k to an arbitrary country assigned to DC j is denoted by $t^{lat}_{i,j,k}$. Let $C^{lat}_{i,j,k}$ denote the mean transportation cost for a lateral transshipment of SKU i from DC k to an arbitrary country assigned to DC j, then

$$C^{lat}_{i,j,k} = \sum_{l \in Q_{i,j}} \frac{m_{i,l}}{\sum_{x \in Q_{i,j}} m_{i,x}} C^{trp}_{i,k,l}. \tag{4.2.2}$$

Each regular DC $j \in J \backslash K$ is assigned to one main DC $k \in K$. Let k_j denote main DC $k \in K$ to which regular DC $j \in J \backslash K$ is assigned. Each main DC submits a request for a lateral transshipment at the other main DC-s in a pre-specified order, the first main DC that has stock on hand delivers the part. Let vector $\sigma(k) \equiv \big(\sigma_1(k), ..., \sigma_{|K|-1}(k)\big)$ define the permutation of main DC-s $K \setminus \{k\}$ that represents this pre-specified order. We determine this pre-specified order in such a way that the transportation costs are minimized. Let $\Psi_{k,j}$ denote the mean transportation cost for a lateral transshipment from DC j to an arbitrary country assigned to DC k, i.e., $\Psi_{k,j} = \frac{\sum_{i \in I} C^{lat}_{i,k,j}}{|I|}$. Then, the pre-specified order that will lead to the lowest possible transportation costs associated with a lateral transshipment is given by

$$\begin{aligned}\sigma(k) = \{j \in K | \Psi_{k,j} = \min_{j \in K \setminus \{k\}}(\Psi_{k,j})\}, \{j \in K | \Psi_{k,j} = \min_{j \in K \setminus \{k, \sigma_1(k)\}}(\Psi_{k,j})\}, \{j \in K | \Psi_{k,j} = \min_{j \in K \setminus \{k, \sigma_1(k), \sigma_2(k)\}}(\Psi_{k,j})\}, \\ \{j \in K | \Psi_{k,j} = \min_{j \in K \setminus \{k, \sigma_1(k), \sigma_2(k), \sigma(3)\}}(\Psi_{k,j})\}, \ \dots \ , \{j \in K | \Psi_{k,j} = \min_{j \in K \setminus \{k, \sigma_1(k), \sigma_2(k), ..., \sigma(|K|-1)\}}(\Psi_{k,j})\} \quad (4.2.3)\end{aligned}$$

It is also possible to define a different pre-specified order for each SKU, i.e., $\sigma(i,k)$. Note that $\sigma(i,k)$ may be determined by using Equation (4.2.3) with $\Psi = C^{lat}_{i,k,j}$. In chapter 5, we determine the cost savings if a different pre-specified order for each SKU is used. In the remainder of this report, however, we will use the same pre-specified order for all SKU-s. Let $K(k, \tilde{k})$ ($\subset K$) denote the subset of main DC-s that receive a request for a lateral transshipment earlier than main $\tilde{k}$ according to the pre-specified order for main DC k. If none of the DC-s can deliver the part, an emergency shipment from its corresponding external supplier takes place. An infinite stock of SKU-s is assumed at the external supplier. This implies that the transportation costs are independent on the SPDN configuration since these parts do not pass any DC. The mean transportation time for an emergency shipment of SKU i from its corresponding external supplier to an arbitrary country assigned to DC j is denoted by $t^{em}_{i,j}$. Let $C^{em}_{i,j}$ denote the mean transportation cost for an emergency shipment of SKU i from its corresponding external supplier to an arbitrary country assigned to DC j. Finally, let C^h_i denote the costs for holding one unit of SKU i in stock for one time unit. We assume that the inventory holding costs are the same for all DC-s $j \in J$ and are incurred for parts in replenishment as well.

Remark Note that we relax the assumption of Kranenburg and Van Houtum (2009) that transportation costs are mainly determined by transportation distances and therefore the same for all SKU-s. From §2.4, we learned that the CW of an SKU influences the transportation rate. As such, transportation costs for direct shipments, lateral transshipments and emergency shipments are SKU dependent. In addition, we interpret $C^{lat}_{i,j,k}$ and $C^{em}_{i,j}$ as the costs to perform a lateral or emergency shipment instead of the additional costs (additional to $C^{dir}_{i,j}$) to perform a lateral or emergency shipment.

For each SKU at all DC-s, stock is controlled using a basestock policy. Let $S_{i,j}$ denote the basestock level for SKU i at DC j. Furthermore, let vector $\mathbf{S}_i \equiv (S_{i,1}, ..., S_{i,|J|})$ $i \in I$ denote the basestock levels for SKU i at all DC-s. Finally, let $\mathbf{S}$ denote a $|I| \times |J|$ matrix with all basestock levels $S_{i,j}$ describing the full system policy, i.e.

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

In evaluating this model‘, we are interested in three types of fractions regarding the fulfillment of demand for SKU $i \in I$ at DC $j \in J$;

- $\beta_{i,j}(\mathbf{S}_i)$, the fraction of demand for SKU i at DC j that is delivered from the stock at DC j itself, also referred to as the *fill rate*;
- $\alpha_{i,j,k}(\mathbf{S}_i)$, $k \in K$, $k \neq j$, the fraction of demand for SKU i at DC j that is delivered from the stock at DC k by means of a lateral transshipment;
- $\theta_{i,j}(\mathbf{S}_i)$, the fraction of the demand for SKU i at DC $j \in J$ that is delivered from the external supplier.

In addition, let $A_{i,j}$ denote the total fraction of demand for SKU i at DC $j \in J$ that is delivered by using a lateral transshipment, i.e., $A_{i,j} = \sum_{k \in K, k \neq j} \alpha_{i,j,k}(S_i)$. Note that for SKU $i \in I$ at each DC $j \in J$ the following relation holds

$$\beta_{i,j}(\mathbf{S}_i) + \alpha_{i,j,k}(\mathbf{S}_i) + \theta_{i,j}(\mathbf{S}_i) = 1. \tag{4.2.4}$$

Contrary to Kranenburg and Van Houtum (2009), we are not interested in the mean waiting time for an arbitrary request but in the fraction of demand that is delivered NBD. Let $NBD_{i,j}(\mathbf{S}_i)$ denote the fraction of demand for SKU i at local warehouse j that is delivered NBD given $\mathbf{S}_i$. In addition, let $N\hat{B}D_j(\mathbf{S})$ denote the fraction of the aggregated demand at local warehouse j that is delivered NBD given $\mathbf{S}$. We know from chapter 2 that the transportation times for all direct shipments and lateral transshipments in our geographical scope are one business day, so $t^{dir}_{i,j} = 1$, $t^{lat}_{i,j,k} = 1 \; \forall i \in I, j \in J$. If we assume that transportation times are deterministic, we have that

$$\begin{aligned} NBD_{i,j}(\mathbf{S}_i) &= \beta_{i,j}(\mathbf{S}_i) + A_{i,j}(\mathbf{S}_i) \\ &= 1 - \theta_{i,j}(\mathbf{S}_i). \end{aligned} \tag{4.2.5}$$

Thus, the fraction of demand delivered by means of an emergency shipment is not delivered NBD and the remaining fraction is delivered NBD. The total inventory costs for SKU i per unit of time equals

$$\sum_{j \in J} C^h_i S_{i,j}. \tag{4.2.6}$$

The total transportation costs for SKU $i \in I$ per unit of time equals

$$\sum_{j \in J} M_{i,j} C^{dir}_{i,j} \beta_{i,j}(\mathbf{S}_i) + \left(\sum_{k \in K} M_{i,j} C^{lat}_{i,j,k} \alpha_{i,j,k}(\mathbf{S}_i) \right) + M_{i,j} C^{em}_{i,j} \theta_{i,j}(\mathbf{S}_i). \tag{4.2.7}$$

Note that, different from Kranenburg and Van Houtum (2009), we add the costs of direct shipments to the total transportation costs. The transportation costs for direct shipments depend on the SPDN configuration and are therefore not sunk costs. The expected total costs per unit of time for SKU $i \in I$ equals

$$C_i(\mathbf{S}_i) = \sum_{j \in J} C^h_i S_{i,j} + M_{i,j} C^{dir}_{i,j} \beta_{i,j}(\mathbf{S}_i) + \left(\sum_{k \in K} M_{i,j} C^{lat}_{i,j,k} \alpha_{i,j,k}(\mathbf{S}_i) \right) + M_{i,j} C^{em}_{i,j} \theta_{i,j}(\mathbf{S}_i). \tag{4.2.8}$$

The objective of Kranenburg and Van Houtum (2009) is to minimize the expected total costs for all SKU-s, under the condition that the expected mean waiting time for an arbitrary request submitted at DC $j \in J$ does not exceed a target aggregate mean waiting time $\hat{W}^{obj}$. The mean waiting time for a request of SKU i at DC j given $\mathbf{S}_i$ denoted by $W_{i,j}(\mathbf{S}_i)$ equals

$$W_{i,j}(\mathbf{S}_i) = t^{dir}_{i,j} \beta_{i,j}(\mathbf{S}_i) + \sum_{k \in K, k \neq j} t^{lat}_{i,j} \alpha_{i,j,k}(\mathbf{S}_i) + t^{em}_{i,j} \theta_{i,j}(\mathbf{S}_i). \tag{4.2.9}$$

For DC $j \in J$, the aggregate mean waiting time equals

$$\hat{W}_j(\mathbf{S}) = \sum_{i \in I} \frac{M_i}{M} W_{i,j}(\mathbf{S}_i). \tag{4.2.10}$$

Let (P) be the problem for which Kranenburg and Van Houtum (2009) want to find a solution, then (P) is mathematically formulated as follows:

$$\begin{aligned} \text{(P)} \quad \min \ & \sum_{i \in I} C_i(\mathbf{S}_i) \\ \text{s.t. } & \hat{W}_j(\mathbf{S}) \leq \hat{W}_j^{obj}, \ j \in J, \\ & \mathbf{S} \in \mathscr{S}, \end{aligned} \tag{4.2.11}$$

with $\mathscr{S} = \{\mathbf{S} = (S_{i,j})_{i \in I, j \in J} | S_{i,j} \in \mathbb{N}_0, \forall i \in I \text{ and } j \in J\}$. Contrary to Kranenburg and Van Houtum (2009), our objective is to minimize the expected total costs for all SKU-s, under the condition that the fraction of the aggregated demand at local warehouse $j \in J$ that is delivered NBD is at least $N\hat{B}D^{obj}$. It is easy to show that our constraint can be fitted into the constraint of Problem (P) as introduced by Kranenburg and Van Houtum (2009). If we set $t_{i,j}^{dir} = 0$, $t_{i,j,k}^{lat} = 0$ and $t_{i,j}^{em} = 1$, then Equation (4.2.9) becomes

$$\begin{aligned} W_{i,j}(\mathbf{S}_i) &= \theta_{i,j}(\mathbf{S}_i) \\ &= 1 - NBD_{i,j}(\mathbf{S}_i). \end{aligned} \tag{4.2.12}$$

Thus, to make sure that $N\hat{B}D_j \geq N\hat{B}D^{obj}$ $\forall j \in J$ we need to have that $\hat{W}_j(\mathbf{S}_i) \leq 1 - N\hat{B}D^{obj}$ $\forall j \in J$. Hence, Problem (P) becomes

$$\begin{aligned} \text{(P)} \quad \min \ & \sum_{i \in I} C_i(\mathbf{S}_i) \\ \text{s.t. } & \hat{W}_j(\mathbf{S}) \leq 1 - N\hat{B}D_j^{obj}, \ j \in J, \\ & \mathbf{S} \in \mathscr{S}, \end{aligned} \tag{4.2.13}$$

with $\mathscr{S} = \{\mathbf{S} = (S_{i,j})_{i \in I, j \in J} | S_{i,j} \in \mathbb{N}_0, \forall i \in I \text{ and } j \in J\}$. A summary of the introduced notation is provided in Table 4.1.

4.3 Assumptions

The model described in this chapter, contains the following critical assumptions:

1. **Demands for the different SKU-s occur according to independent Poisson processes with a constant demand rate**

   This is a common assumption in the literature on spare parts inventory models. This assumption is often justified as lifetimes of parts are exponentially distributed. When the lifetimes are non-exponential but the installed base is large enough such that time between two consecutive failures for the complete set of technical systems is close to exponentially distributed, this assumption is justified as well (Wong et al., 2006). In addition, Hupys (2015) used a generic χ^2 test to test if demand data follow a Poisson distribution for five randomly selected SKU-s out of complete set of SKU-s of the SPS department. It turns out that for five out of the five randomly selected SKU-s the hypothesis that demand data follow a Poisson distribution cannot be rejected.

Table 4.1: Summary of notation

Notation	Description
i	Index of SKU $i \in I$
I	Set of SKU-s
j	Index of DC $j \in J$
J	Set of DC-s
l	Index of country $l \in L$
L	Set of countries
$Q_{i,j}$	Set of countries for which demand of SKU i is assigned to DC j, $Q_{i,j} \subseteq L$
$t_{i,j}^{dir}$	Mean transportation time for a direct shipment of SKU $i \in I$ from DC j to an arbitrary country assigned to DC j
$t_{i,j,k}^{lat}$	Mean transportation time for a lateral transshipment of SKU i from DC k to an arbitrary country assigned to DC j
$t_{i,j}^{em}$	Mean transportation time for an emergency shipment of SKU i from its corresponding external supplier to an arbitrary country assigned to DC j
$t_{i,j}^{repl}$	Mean replenishment lead time of SKU i at DC j
$C_{i,j}^{dir}$	Mean transportation cost for a direct shipment of SKU i from DC j to an arbitrary country assigned to DC j
$C_{i,j,k}^{lat}$	Mean transportation cost for a lateral transshipment of SKU i from DC k to an arbitrary country assigned to DC j
$C_{i,j}^{em}$	Mean transportation cost for an emergency shipment of SKU i from its associated external supplier to an arbitrary country assigned to DC j
$C_{i,j,l}^{trp}$	Transportation costs for a shipment of SKU i from DC j to country l
C_i^h	Cost for holding one unit of SKU i in stock for one time unit
$m_{i,l}$	Constant demand rate for SKU i from country l
$M_{i,j}$	Total demand rate for SKU i at DC j
M_i	Total demand rate for SKU i
M	Total demand rate for all SKU-s i at all DC-s j
$S_{i,j}$	Basestock level for SKU i at DC j
$\mathbf{S}_i$	Vector of basestock levels for SKU i, i.e., $S_i \equiv (S_{i,1}, S_{i,2}, ..., S_{i,\lvert J \rvert})$
$\mathbf{S}$	Matrix of all basestock levels
$\beta_{i,j}(\mathbf{S}_i)$	Fraction of the demand for SKU i at DC j that is delivered from the stock at DC j itself, also called the *fill rate*
$\alpha_{i,j,k}(\mathbf{S}_i)$	Fraction of the demand for SKU i at DC j that is delivered from the stock at DC k
$A_{i,j}$	Fraction of demand for SKU i at DC $j \in J$ that is delivered via a lateral transshipment
$\theta_{i,j}(\mathbf{S}_i)$	Fraction of the demand for SKU i at DC j that is delivered from the external supplier
$NBD_{i,j}(\mathbf{S}_i)$	Fraction of demand for SKU i at local warehouse j that is delivered NBD given $\mathbf{S}_i$
$N\hat{B}D_j(\mathbf{S})$	Fraction of the aggregated demand at local warehouse j that is delivered NBD given $\mathbf{S}$

2. **The external supplier of each SKU has infinite stock**

   There is no information on the availability of stock at the external suppliers. This assumption ensures that the mean replenishment lead times are constant. In §5.5, we will perform a sensitivity analysis on the mean replenishment lead times.

3. **The stock in all DC-s is controlled by a basestock policy**

   Approximately 55% of all SKU-s have an Reorder Quantity equal to 1. In performing our case-studies we will select only SKU-s that have ROQ=1 such that this assumption is justified.

4. **Outbound transportation times are deterministic**

   Outbound transportation is done using service level Express from UPS. UPS promises Next Business Day delivery for this service level.

4.4 Evaluation

The model described in §4.2 can be evaluated both exactly and approximately. The exact evaluation requires the additional assumption that the replenishment lead times are exponentially distributed. In both types of evaluations the evaluation can be done for each SKU i separately.

In the exact method, a Markov Process description is used in which the states are described by the on hand stock at all DC-s. Since this gives a $|J|$-dimensional state space, the exact numerical evaluation is only applicable for a limited number of DC-s due to exponentially increasing computation times in $|J|$. Since we are interested in evaluating a real-life instance, we are using the approximate method.

In the approximate method, we use the loss probability in the Erlang loss model ($M|G|c|c$ queue). Let $L(c, \rho)$ denote the loss probability in which $c \in N_0$ represent the number of servers and $\rho > 0$ the offered traffic load, then

$$L(c, \rho) = \frac{\rho^c/c!}{\sum_{x=0}^{c} \rho^x/x!}, \tag{4.4.1}$$

with $L(0, \rho) = 1$, $\rho > 0$ by convention. Key in our approximate evaluation of this model is that a) the network of different DC-s is decoupled into individual DC-s and b) the extra demand processes in main DC-s (due to requests for lateral transshipments) are assumed to be Poisson processes. The formal evaluation procedure is described in Algorithm A and B.

Table 4.2: Algorithm A

Algorithm A	
Step 1	For all regular DC-s $j \in J \backslash K$, $\beta_{i,j}(\mathbf{S}_i) \equiv 1 - L(S_{i,j}, M_{i,j} t_{i,j}^{repl})$.
Step 2	For all main DC-s $k \in K$, $\tilde{M}_{i,k} \equiv M_{i,k} + \sum_{j \in J \mid k_j = k} (1 - \beta_{i,j}(\mathbf{S}_i)) M_{i,j}$.
Step 3	For all main DC-s $k \in K$, compute, $\beta_{i,k}(\mathbf{S}_i)$, $\alpha_{i,k,\tilde{k}}(\mathbf{S}_i)$, $\tilde{k} \in K, \tilde{k} \neq k$ and $\theta_{i,k}(\mathbf{S}_i)$ using Algorithm B.
Step 4	For all regular DC-s $j \in J \backslash K$, if $K = \emptyset$, then $\theta_{i,j}(\mathbf{S}_i) \equiv 1 - \beta_{i,j}(\mathbf{S}_i)$, else, $$\alpha_{i,j,k}(\mathbf{S}_i)\} \equiv \begin{cases} (1 - \beta_{i,j}(\mathbf{S}_i))\beta_{i,k_j}(\mathbf{S}_i), & \text{for } k = k_j, \\ (1 - \beta_{i,j}(\mathbf{S}_i))\alpha_{i,k_j,k}(\mathbf{S}_i), & \text{for } k \in K, k \neq k_j, \end{cases}$$ and $\theta_{i,j}(\mathbf{S}_i) \equiv (1 - \beta_{i,k}(\mathbf{S}_i))\theta_{i,k_j}((\mathbf{S}_i))$.

Table 4.3: Algorithm B

Algorithm B	
Step 1	For all mains DC-s $k \in K$, $\theta_{i,j}(\mathbf{S}_i) \equiv L(\sum_{k\in K} S_{i,j}, \sum_{k\in K} \tilde{M}_{i,j} t_{i,j}^{repl})$.
Step 2	For all mains DC-s $k \in K$, $\beta_{i,j}(\mathbf{S}_i) \equiv 1 - L(\sum_{k\in K} S_{i,j}, \sum_{k\in K} \tilde{M}_{i,j} t_{i,j}^{repl})$ and $A_{i,k}(\mathbf{S}_i) \equiv 1 - (\beta_{i,j}(\mathbf{S}_i) + \theta_{i,j}(\mathbf{S}_i))$.
Step 3	For one main DC $k \in K$:
Step 3.1	If $S_{i,\ell} > 0$ for at least one $\ell \in K\backslash\{\tilde{k}\}$, then, $$\tilde{M}_{i,\tilde{k},k} \equiv \frac{A_{i,\tilde{k}}(\mathbf{S}_i))\tilde{M}_{i,\tilde{k}}}{1 - \prod_{\ell\in K,\ell\neq\tilde{k}}(1-\beta_{i,\ell}(\mathbf{S}_i))} \prod_{\ell\in K(\tilde{k},k)} (1-\beta_{i,\ell}(\mathbf{S}_i)),$$ else $\tilde{M}_{i,\tilde{k},k} \equiv 0$ with product term $\prod_{\ell\in K(\tilde{k},k)}(1-\beta_{i,\ell}(\mathbf{S}_i))$ defined as 1 if $K(\tilde{k},k) = \emptyset$, and $\hat{M}_{i,k} \equiv \tilde{M}_{i,k} + \sum_{\tilde{k}\in K,\tilde{k}\neq k} \hat{M}_{i,\tilde{k},k}$.
Step 3.2	$\beta_{i,k}(\mathbf{S}_i) \equiv 1 - L(S_{i,k}, \hat{M}_{i,k} t_{i,k}^{repl})$ and $A_{i,k}(\mathbf{S}_i) \equiv 1 - (\beta_{i,k}(\mathbf{S}_i)) + \theta_{i,k}(\mathbf{S}_i)))$.
Step 4	Repeat Step 3 for all other main DC-s $j \in J$.
Step 5	Repeat Step 3 and Step 4 while $\hat{M}_{i,k}$ does not change more than ϵ for each main DC $k \in K$ with ϵ small.
Step 6	For all main DC-s $k \in K$, $\alpha_{i,j,k}(\mathbf{S}_i) \equiv \beta_{i,k}(\mathbf{S}_i)\hat{M}_{i,k,\tilde{k}}/\tilde{M}_{i,k}$, $\tilde{k} \in K$, $\tilde{k} \neq k$.

4.5 Optimization

In order to find a feasible solution for problem (P), we make use of the optimization procedure of Kranenburg and Van Houtum (2009). They use a greedy algorithm that increases inventory for all SKUs $i \in I$ in all DC-s $j \in J$ in three steps. In the first step all basestock levels are set equal to zero, i.e., $S_{i,j} \equiv 0$ $i \in I$, $j \in J$. In the second step, basestock levels $S_{i,j}$ are increased if and as long as total costs are decreasing. This step is executed for each SKU $i \in I$ separately. In each iteration, the basestock level that leads to the largest cost decrease is increased by one. The change in total costs by increasing $S_{i,j}$ $i \in I$, $j \in J$ by 1 equals

$$\Delta_j C_i(\mathbf{S}_i) = C_i(\mathbf{S}_i + \mathbf{e}_j) - C_i(\mathbf{S}_i) \tag{4.5.1}$$

where $\mathbf{e}_j$ is the j-th unit vector with dimension $|J|$. In the third and final step, basestock levels are further increased if after the second step still no feasible solution is obtained. In a iterative fashion, the basestock level $S_{i,j}$ $i \in I$, $j \in J$ that gives the largest decrease in distance to set of feasible solutions per unit of increase in cost, is increased by 1. Let $\mathscr{S}^{feas}(\subseteq \mathscr{S})$ denote the subset of feasible solutions, i.e., $\mathscr{S}^{feas} \equiv \{\mathbf{S} \in \mathscr{S} | \tilde{W}_j(\mathbf{S}) \leq (1 - N\tilde{B}D_j^{obj}) \ \forall\ i \in I, j \in J\}$. Let $d(\mathbf{S})$ denote the distance to set $\mathscr{S}^{feas}$ given solution $\mathbf{S} \in \mathscr{S}$, then

$$d(\mathbf{S}) \equiv \sum_{j\in J} \left(\sum_{i\in I} \frac{M_i}{M} W_{i,j}(\mathbf{S}_i) - (1 - N\tilde{B}D_j^{obj}) \right)^+ \tag{4.5.2}$$

in which $x^+ \equiv \max\{0, x\}$ for all $x \in \mathbb{R}$. Note that $W_{i,j}(\mathbf{S}_i)$ is given by Equation (4.2.12). Subsequently, let $\Delta_{i,j} d(\mathbf{S})$ denote the decrease in distance when increasing basestock level $S_{i,j}$, $i \in I$,

$j \in J$ by one, then

$$\Delta_{i,j} d(\mathbf{S}) = \sum_{j \in J} \left[\left(\sum_{i' \in I \setminus \{i\}} \frac{M_{i'}}{M} W_{i',j'}(\mathbf{S}_{i'}) + \frac{M_i}{M} W_{i,j'}(\mathbf{S}_i + \mathbf{e}_j) - (1 - N\tilde{B}D_j^{obj}) \right)^+ - \left(\sum_{i' \in I} \frac{M_{i'}}{M} W_{i',j'}(\mathbf{S}_{i'}) + \mathbf{e}_j) - (1 - N\tilde{B}D_j^{obj}) \right)^+ \right]. \quad (4.5.3)$$

Finally, let $\Gamma_{i,j}$ denote the decrease in distance to $\mathscr{S}^{feas}$ per unit of increase in total costs, then

$$\Gamma_{i,j} = \frac{-\Delta_{i,j} d(\mathbf{S})}{\Delta_{i,j} C(\mathbf{S})}. \quad (4.5.4)$$

In each iteration of step 3, basestock level $S_{i,j}$, $i \in I$, $j \in J$ with the highest corresponding ratio $\Gamma_{i,j}$ is increased by one, in this way we obtain the "biggest bang for the buck". The formal optimization procedure is described in Algorithm C. Algorithms A, B and C are implemented in MATLAB.

Table 4.4: Algorithm C

Algorithm C	
Step 1	Set $S_{i,j} \equiv 0$, $i \in I, j \in J$.
Step 2	For each SKU $i \in I$:
Step 2.1	Calculate $\Delta_j C_i(\mathbf{S}_i), \jmath \in J$;
Step 2.1	While $\min_{j \in J}\{\Delta_j C_i(\mathbf{S}_i)\} \leq 0$:
(a)	Determine j' such that $\Delta_{j'} C_i(\mathbf{S}_i) \leq \Delta_j C_i(\mathbf{S}_i)$, $j \in J$;
(b)	Set $S_{i,j'} \equiv S_{i,j'} + 1$;
(c)	Calculate $\Delta_j C_i(\mathbf{S}_i)$, $j \in J$.
Step 3	
Step 3.1	Calculate $\Delta_{i,j} C(\mathbf{S})$, $\Delta_{i,j} d(\mathbf{S})$ and $\Gamma_{i,j}$, $i \in I$, $j \in J$.
Step 3.2	While $d(\mathbf{S}) > 0$:
(a)	Determine i' and j' such that $\Gamma_{i',j'} \geq \Gamma_{i,j}$, $i \in I$, $j \in J$;
(b)	Set $S_{i',j'} \equiv S_{i',j'} + 1$;
(c)	Calculate $\Delta_{i,j} C(\mathbf{S})$, $\Delta_{i,j} d(\mathbf{S})$ and $\Gamma_{i,j}$, $i \in I$, $j \in J$.

Chapter 5

Case Studies

This chapter addresses two case studies. Case study 1 concerns the analysis of the current SPDN configuration as described in chapter 2. Case study 2 concerns the analysis of the alternative SPDN configuration such as described in chapter 3. In §5.1, an introduction to the case studies is given. In §5.2, case study 1 is discussed, followed by case study in §5.3. In §5.4, a comparison of the case studies is given. Finally, in §5.5, the influence of input parameters on the cost difference between the current SPDN configuration and the alternative SPDN configuration is discussed.

5.1 Introduction

The SPS department of Philips intends to deliver at least 95% of submitted demand at each DC Next Business Day against minimal total costs. Hence, the target of the SPS department can be expressed as $N\hat{B}D_j^{obj} = 0.95 \; \forall j \in J$. In both case studies the goal is to find a solution for Problem (P), in case study 1 for the current network configuration and in case study 2 for the alternative network configuration. We performed the case studies with a subset of the complete set of SKU-s in order to maintain acceptable computation times for Problem (P) . The complete set of SKU-s is filtered such that it only contains SKU-s that have a Customer Order Quantity (COQ) strictly equal to one (Assumption 1) and a Reorder Quantity (ROQ) equal to one (Assumption 3). We used Proportionate Stratified Random Sampling for selecting the subset of SKU-s. We used the different part segments (CCP, HCFM, LCFM, etc.) as strata. A subset size of 500 SKU-s showed to be sufficiently large to represent the complete set. The case studies and sensitivity analysis such as described in this chapter are performed with the same subset of 500 SKU-s. See Appendix D for an overview of the strata, the relative number of SKU-s belonging to each stratum and the sample size per stratum.

5.2 Case study 1: Current Configuration

We determine the performance of the current SPDN configuration in this case study. As described in chapter 2, 96.4% of the parts are being delivered from the RDC in Roermond, the Netherlands. The remaining 3.6% of the parts are being delivered from LDC-s in a lower echelon. We decide to ignore the LDC-s in the lower echelon and model the current SPDN configuration with only RDC Roermond since such a large part of total demand is being delivered from the RDC in Roermond. In our model, demand submitted at LDC-s is assigned to the RDC in Roermond as well. The parameter settings for case study 1 are discussed in §5.2.1. The results of case study 1 are provided in §5.2.2.

5.2.1 Parameter Settings

We drop index j for all input parameters in this case study since we only have one DC in this network configuration. The values for m_i are based on the demand rates from 2015. The values for t_i^{repl} are supplied by the Strategic Planning & Supply team of the SPS department. The values for C^{trp} are based on the transportation rates of UPS for service level Express. Parameter C_i^{dir} is based on the Equation (4.2.1). We assume that the costs for an emergency shipment are five times the cost of a direct shipment, i.e., $C_i^{em} = 5 \cdot C_i^{dir}$ since there is a lack of transparency in the costs of an emergency shipment at the SPS department. In §5.5, we will perform a sensitivity analysis on this parameter. As mentioned before, holding costs constitute 20% of the value of a particular SKU. Let p_i denote the value (EUR) of SKU $i \in I$, then the holding costs for SKU $i \in I$ per unit of time equals $C_i^h = 0.2p_i$. The values for p_i are supplied by the Strategic Planning & Supply team of the SPS department.

5.2.2 Results

With respect to the current SPDN configuration, we are interested in the inventory costs, the transportation costs and the total costs of the current SPDN. In addition, we want to know the fraction of domestic shipments, which equals $\sum_{i \in I} \left(\frac{M_{i,12}}{M}\beta_i\right)$. Note that $l = 12$ represents country NL. An overview of the results of case study 1 is shown in Table 5.1.

Table 5.1: Results of Case Study 1

Measure	**Result**
Total demand (# of parts per year)	4638
Fraction of total demand assigned to DC (NL)	1
Expected fraction of Inventory Costs	74.3%
Expected fraction of Transportation Costs	25.7%
Fraction of total demand shipped domestically	8.2%
Total Stock (# of parts)	2076

5.3 Case study 2: Alternative Configuration

In this case study we determine the performance of the alternative SPDN configuration such as described in chapter 3. There are multiple DC-s in the alternative network configuration, therefore we need to make an additional decision on the assignment of demand to the different DC-s. Also, stock may be shared between DC-s since the SPDN configuration now contains multiple DC-s. The parameter settings for case study 2 are discussed in §5.3.1. The results of case study 2 are provided in §5.3.2.

5.3.1 Parameter Settings

The five DC-s in this case study are all main DC-s ($|J| = |K| = 5$), meaning that every DC has the ability to perform a lateral transshipment. We used the same values for C_i^h as in case study 1. The values for C^{trp} are based on the transportation rates of UPS for service level Express. Parameter $C_{i,j}^{dir}$ is determined by using Equation (4.2.1). When a DC is out of stock, it submits a request for a lateral transshipment according to a pre-specified order $\sigma(k) \equiv \big(\sigma_1(k), ..., \sigma_{|K|-1}(k)\big)$. By using Equation (4.2.3) we obtain $\sigma(1) = (3, 2, 5, 4)$, $\sigma(2) = (1, 3, 5, 4)$, $\sigma(3) = (1, 5, 2, 4)$, $\sigma(4) = (1, 3, 5, 4)$

and $\sigma(5) = (1, 3, 2, 4)$. Parameter $C^{lat}_{i,j,k}$ is determined by using Equation (4.2.2). We used the same value for C^{em}_i as in case study 1. With respect to the replenishment lead time of an SKU, we assume that the replenishment lead time will not change when moving from the current SPDN configuration to the alternative SPDN configuration. Hence, $t^{repl}_{i,j} = t^{repl}_i$ with the values of t^{repl}_i equal to the values in case study 1. This assumption may be justified since transportation time is often a relatively small component of the total replenishment lead time. In §5.5, we will perform a sensitivity analysis on $t^{repl}_{i,j}$ to determine the effect of an increased replenishment lead time.

5.3.2 Results

We are interested in the inventory costs, the transportation costs and the total costs of the alternative SPDN configuration. In addition, we want to know the fraction of total demand assigned to each DC and the fraction of domestic shipments. The percentage of parts delivered domestically equals $\sum_{i \in I} \big(m_{i,6}\beta_{i,1} + m_{i,2}\beta_{i,2} + m_{i,12}\beta_{i,3} + m_{i,4}\beta_{i,4} + m_{i,5}\beta_{i,5}\big)/M$. Note that $l = 6$ represent country DE, $l = 2$ represent country IT, $l = 12$ represent country NL, $l = 4$ represent country ES and $l = 5$ represent country GB. An overview of the results of case study 2 is shown in Table 5.2.

Table 5.2: Results of Case Study 2

Measure	**Result**
Total demand (# of parts per year)	4638
Fraction of total demand assigned to:	
- DC 1 (DE)	36.6%
- DC 2 (IT)	6.6%
- DC 3 (NL)	37.9%
- DC 4 (ES)	10,0%
- DC 5 (GB)	8.9%
Total stock (# of parts)	2092
Fraction of total stock installed in:	
- DC 1 (DE)	39.7%
- DC 2 (IT)	4.3%
- DC 3 (NL)	39.1%
- DC 4 (ES)	6.0%
- DC 5 (GB)	10.9%
Expected fraction of:	
- Inventory Costs	76.4%
- Transportation Costs	23.6%
- Total demand shipped laterally	13.8%
- Total demand shipped domestically	44.5%

5.4 Comparison

In comparing the current SPDN configuration with the alternative SPDN configuration we are mainly interested in the difference in total logistics costs. This relative cost difference is determined as follows:

$$\text{Cost difference} = \frac{\text{Total Costs of alternative SPDN} - \text{Total Costs of current SPDN}}{\text{Total Costs of current SPDN}} \times 100\% \tag{5.4.1}$$

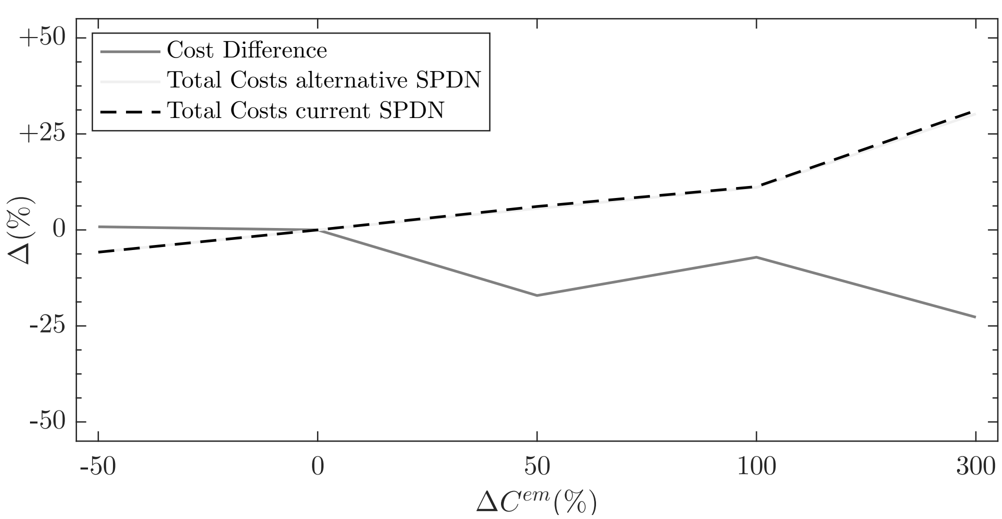
The cost difference between the current SPDN and alternative SPDN for the subset of 500 SKU-s equals -2,9%. Note that the cost difference does not take into account the change in inbound transportation costs. As mentioned in §5.2, it is likely that the inbound transportation costs will increase when moving from the current SPDN to the alternative SPDN.

We see that the fraction of domestic shipments is approximately proportional to the demand of the countries where a DC is installed when looking at the fraction of total demand shipped domestically. For the subset of 500 SKU-s, this was 8.2% for the current SPDN, proportional to the total demand in NL and for the alternative SPDN 44,5%, proportional to the combined demand of DE, IT, NL, ES and GB. Inventory holding costs dominate in both SPDN configurations. Complete pooling between DC-s seems suitable since holding costs are large compared to transportation costs. Transportation costs are lower for the alternative SPDN configuration due to the lower transportation rates associated with domestic shipments. The expected fraction of total demand fulfilled by means of a lateral transshipment is 13.8%. Finally, the total stock in the alternative SPDN (2043 parts) is slightly larger than the current SPDN (2038), probably due to the incentive to install more stock such that domestic transportation can be used.

5.5 Sensitivity Analysis

In this section we vary values for some of the input parameters (while keeping the other input parameters constant) to determine the effect of these input parameters on different measures. For the parameters $C^{trp}_{i,j,l}$, $C^{hold}_{i,j}$ and $C^{em}_{i,j}$, a sensitivity analysis is performed. For each of the three parameters, we changed the parameter for each SKU $i \in I$ at each DC $j \in J$ with a fixed percentage. For this reason, we omit index i and j in the remainder of the section. We determine the sensitivity of three different measures: the cost difference (Equation 5.4.1), the total costs of the alternative SPDN and the total costs of the current SPDN. We performed the sensitivity analysis with the same 500 SKU-s that are used to determine the cost difference between the current SPDN and alternative SPDN. As mentioned before, there is a lack of information to determine C^{em} correctly. For this reason we test the sensitivity for this parameters for a wide range of values, ranging from -50% to $+300\%$. See Figure 5.1 for the results of the sensitivity analysis. As can be seen from Figure 5.1,

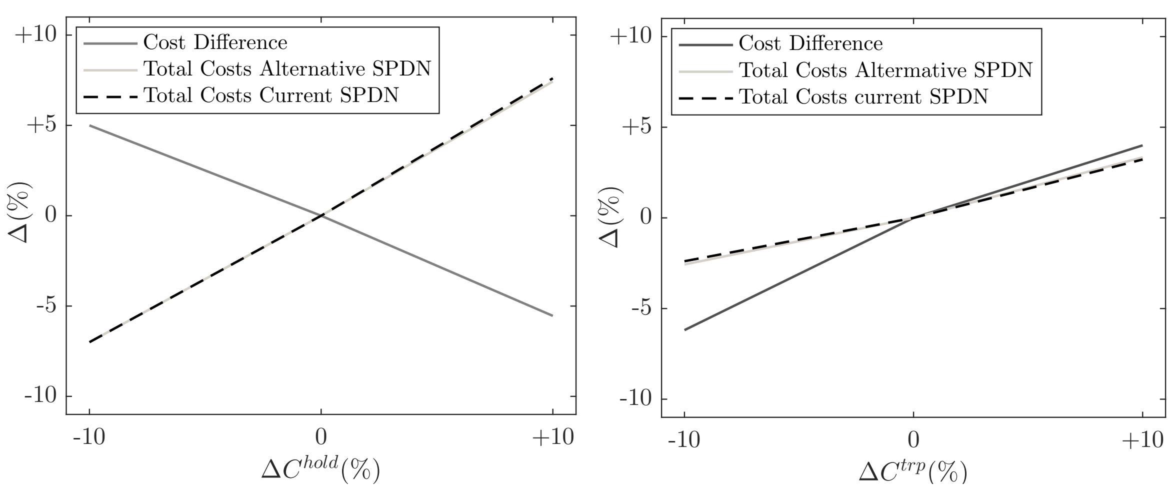
Figure 5.1: Sensitivity for C^{em}



the sensitivity of the cost difference between the current SPDN and alternative SPDN for C^{em} is moderate. For an increase of 300% from $C^{em} = 5C^{dir}$ to $C^{em} = 20C^{dir}$ the cost difference changes from -2,9% to -2,2%. Note that the change in cost difference is larger for a 50% increase in C^{em} than an increase of 100% in C^{em}. The sensitivity of the total costs of both the current SPDN and alternative SPDN is moderate. A 50% change in C^{em} leads to approximately 6% change in total costs for both configurations.

See Figure 5.2 (a) for the sensitivity for holding costs, C^{hold}. As can be seen from Figure 5.2 (a), the cost difference between the current SPDN and the alternative SPDN decreases approximately 5% when holding costs increases and vice versa. The total costs of both the current SPDN and the alternative SPDN show a similar sensitivity. When holding costs are increased by 10%, the total costs for both SPDN configurations increase 8% and similarly when holding costs are decreased by 10% the total costs decrease with 7%. See Figure 5.2 (b) for the sensitivity for the transportation costs, C^{trp}. As can be seen from Figure 5.2 (a), the cost difference between the current SPDN and the alternative SPDN decreases when transportation decrease and increases when the transportation costs increase. As soon as transportation costs increase, the alternative SPDN will become more attractive due to the use of domestic shipments and its associated lower transportation costs. A change in the holding costs leads to a small change in the cost difference, a 10% decrease leads to a cost difference of -3.0% and a 10% increase to a cost difference of -2.7%. In our case studies,

Figure 5.2: Sensitivity for C^{hold} and C^{trp}



(a) Sensitivity for C^{hold}

(b) Sensitivity for C^{trp}

we assumed that the mean replenishment lead time of an SKU does not change when moving from the current SPDN configuration to the alternative SPDN configuration. However, it may be the case that the replenishment lead time will increase due to a larger distance between the external supplier and the DC or due to a less efficient transportation network in the country where a DC is installed. We determined the total costs for the alternative SPDN when there was one day of extra transportation time ($t^{repl} + 1$) and two days of extra transportation time ($t^{repl} + 2$) in order to determine the cost difference when the replenishment lead time would increase. With one day extra transportation time for a replenishment the cost difference is -1.8%. With two days of extra transportation time for a replenishment the cost difference is -1.0%. Although the impact of an increased replenishment time appears to be high, the likelihood of an increased replenishment lead time when moving to the alternative SPDN seems small. Approximately 78.8% of total stock in the alternative SPDN is installed in either NL or DE. Both countries have low outbound transportation costs implying an efficient in-country transportation network.

In chapter 4, we mentioned that the pre-specified order in which a main checks other mains in case of a stock out may be defined per SKU, i.e., $\sigma(i,k) \equiv \big(\sigma_1(i,k),...,\sigma_{|K|-1}(i,k)\big)$, instead of one pre-specified order for all SKU-s. As mentioned, $\sigma(i,k)$ may be determined by using Equation (4.2.3) with $\Psi = C^{lat}_{i,k,j}$. It turns out that the total costs are slighty lower when using this pre-specified order per SKU. This pre-specified order per SKU gives a cost saving of -0.009718% for the subset of 500 SKU-s. This means that the difference between using one pre-specified order for all SKU-s and using a different pre-specified order for each SKU-s is relatively small.

Chapter 6

Conclusion & Recommendations

This chapter present the conclusion and recommendations. In §6.1, the conclusion is given which is based on the five research questions that are formulated. In §6.2, recommendations for Philips are given.

6.1 Conclusion

The objective of this research was to compare the current Service Part Distribution Network configuration with an alternative Service Part Distribution Network configuration. In this section we will discuss the main conclusions per research question such as described in §1.3.

Research Question 1. *What is the cost structure of the current Service Parts Distribution Network?*

The main cost components of the current SPDN are warehousing and transportation. Warehousing include inbound costs, outbound costs and storage. Both inbound and outbound costs are linear in the amount of parts shipped. Storage costs are linear in the amount of stock installed. Transportation includes inbound, outbound and in-network transportation costs. Outbound transportation costs are strongly dependent on the origin country of a shipment and the Chargeable Weight of a package.

Research Question 2. *What is - based on demand patterns and cost parameters - an alternative and potentially better Service Parts Distribution Network configuration compared to the current Service Parts Distribution Network configuration in terms of total logistics costs?*

In configuring the alternative SPDN network, we considered installing a DC in the six countries that have the largest demand; FR, DE, IT, NL, ES and GB. We determined in which of these countries it is beneficial to install a DC in terms of the transportation costs based on the analysis of domestic and cross-border transportation rates. It seems that installing a DC in FR is not beneficial since the domestic rates of FR are only lower when $CW \geq 17$ and approximately 90% of SKU-s has $CW < 17$. For DE, IT, NL, ES and GB it is beneficial for the transportation costs to install a DC since demand for those countries may be fulfilled with domestic shipments. Domestic shipments are, dependent on the country, 39% to 60% percent lower compared to the lowest cross border rate. Based on these insights, we introduced an alternative SPDN configuration with 5 DC-s located in DE, IT, NL, ES and GB. Each of these DC-s share their stock with another when a DC faces a stock out. In this way, the same level of risk pooling may be obtained as when using a network configuration with one single large DC such as the current SPDN configuration. The assignment of demand to the DC-s in the alternative SPDN configuration is based on the outbound transportation rates.

Research Question 3. *How can a spare parts inventory model offered by literature be extended to a model in which both transportation times and transportation costs from DC-s to the geographical locations of demand is incorporated, to evaluate different Service Parts Distribution Network configurations?*

We used the model of Kranenburg and Van Houtum (2009) to determine the inventory and transportation costs for a given SPDN configuration. We made some adjustments to their model and changed the interpretation of some of the parameters. First, we added parameter $t^{dir}_{i,j}$ and interpreted $t^{dir}_{i,j}$, $t^{lat}_{i,j,k}$ and $t^{em}_{i,j}$ as the transportation times to a customer instead of to another DC. Second, we relaxed the assumption that costs for lateral transshipments and emergency shipments are mainly determined by the transportation distances and therefore the same for all SKU-s. From §5.4 we learned that the CW of an SKU influences the transportation rate. As such, costs for lateral transshipments and emergency shipments are SKU-dependent. Third, we added the term $C^{dir}_{i,j}\beta_{i,j}(\mathbf{S}_i)$ to the cost function $C_i(S_i)$ and interpreted $C^{lat}_{i,j,k}$ and $C^{em}_{i,j}$ as the costs to perform a lateral or emergency shipment instead of the additional costs to perform a lateral or emergency shipment. Finally, we introduced a way to fit the constraint of the SPS department (fraction of NBD deliveries should be at least 0.95) into the constraint of the original minimization problem presented by Kranenburg and Van Houtum (2009).

Research Question 4. *What is the performance of the current and the alternative Service Parts Distribution Network configuration in terms of total logistics costs?*

We determined the total logistics costs for the current and the alternative SPDN configuration by means of two case studies. We performed the case studies with a subset of 500 SKU-s of the complete set of SKU-s in order to maintain acceptable computation times. The cost difference between the current SPDN and alternative SPDN equals -2,9%. Note that the cost difference does not take into account the change in inbound transportation costs. It is likely that the inbound transportation costs will increase when moving from the current SPDN to the alternative SPDN.

Inventory holding costs dominate in both SPDN configurations. Complete pooling between DC-s in the alternative SPDN configuration seems suitable since holding costs are large compared to transportation costs. Transportation costs are lower for the alternative SPDN configuration due to the lower transportation rates associated with domestic shipments.

Research Question 5. *What is the influence of different cost parameters on the optimal Service Parts Distribution Network configuration?*

For the parameters $C^{trp}_{i,j,l}$, $C^{hold}_{i,j}$ and $C^{em}_{i,j}$, a sensitivity analysis is performed. The sensitivity of the cost difference between the current and the alternative SPDN configuration seems moderate for all three parameters. In addition to these three cost parameters, we determined the influence of one and two additional days of replenishment lead time on the costs difference between the current and the alternative SPDN configuration. With one day extra transportation time for a replenishment the cost difference is -1.8%. With two days of extra transportation time for a replenishment the cost difference is -1.0%. Although the impact of an increased replenishment time appears to be high, the likelihood of an increased replenishment lead time when moving to the alternative SPDN seems small. Approximately 78.8% of total stock in the alternative SPDN is installed in either

NL or DE, both countries have low outbound transportation costs implying an efficient in-country transportation network.

6.2 Recommendations

Based on the conclusions, the main recommendation is to determine the change in inbound transportation costs when moving from the current SPDN configuration to the alternative SPDN configuration. It is important to determine this change and how it affects the total costs of both SPDN configuration and the resulting cost difference.

In addition to this main recommendation, it is recommended to determine the change in warehousing costs when moving from the current SPDN configuration to the alternative SPDN configuration. In this research we assumed that warehousing costs such as inbound handling, outbound handling and storage does not change when the configuration of the SPDN changes. However, due to a reduction of economies of scale when introducing a network with multiple relatively smaller DC-s, UPS may charge Philips higher costs for warehousing activities. In addition, we assumed that the transportation rates do not change when changing the configuration. The configuration of the SPDN influences the transportation volumes for each lane. The transportation volumes may affect the associated transportation rates for each lane that UPS charges to Philips.

We expect that by including inbound transportation costs in the comparison of the current and alternative configuration, the cost difference will be reduced. It seems that implementing the alternative SPDN configuration from a cost perspective is not recommended since the cost difference is -2.9% and it will be further reduced by including inbound transportation costs. However, the alternative SPDN configuration may be interesting when demand requirements change in the future. The alternative SPDN configuration may be more cost effective due to the proximity of DC-s to the customers when in the future demand needs to be fulfilled more quickly, for example, Same Business Day instead of Next Business Day. Especially if transportation modes will be used that have transportation costs which are more dependent on the transportation distance.

Bibliography

Axsäter, S. (1990). Modelling Emergency Lateral Transshipments in Inventory Systems. *Management Science*, 36(11):1329–1338.

Borst, R. N. (2016). Research Models for Spare Parts Supply Chain Design. Literature review, School of Industrial Engineering, Eindhoven University of Technology.

Candas, M. F. and Kutanoglu, E. (2007). Benefits of considering inventory in service parts logistics network design problems with time-based service constraints. *IIE Transactions*, 39(2):159–176.

Driessen, M., Arts, J., van Houtum, G. J., Rustenburg, J. W., and Huisman, B. (2015). *Maintenance spare parts planning and control: a framework for control and agenda for future research*, volume 325.

Eppen, G. D. (1979). Effects of Centralization on Expected Costs in a Multi-Location Newsboy Problem. *Management Science*, 25(5):498–501.

Hupys, E. (2015). Integrated inventory and transportation mode selection at Philips Healthcare. Master Thesis, School of Industrial Engineering, Eindhoven University of Technology.

Kranenburg, A. A. and Van Houtum, G. J. (2009). A new partial pooling structure for spare parts networks. *European Journal of Operational Research*, 199(3):908–921.

Öner, K., Kiesmüller, G., and Van Houtum, G. (2010). Optimization of component reliability in the design phase of capital goods. *European Journal of Operational Research*, 205(3):615–624.

Paterson, C., Kiesmüller, G., Teunter, R., and Glazebrook, K. (2011). Inventory models with lateral transshipments: A review. *European Journal of Operational Research*, 210(2):125–136.

Patrik Alfredsson, J. V. (1999). Modeling Emergency Supply Flexibility in a Two-Echelon Inventory System. *Management Science*, 45(10):1416–1431.

Shen, Z. (2007). Integrated supply chain design models: a survey and future research directions. *Journal of Industrial and Management Optimization*, 3(1):1–27.

Wagner, S. M. and Lindemann, E. (2008). A case study-based analysis of spare parts management in the engineering industry. *Production Planning & Control*, 19(4):397–407.

Wong, H., Van Houtum, G. J., Cattrysse, D., and Van Oudheusden, D. (2006). Multi-item spare parts systems with lateral transshipments and waiting time constraints. *European Journal of Operational Research*, 171(3):1071–1093.

Appendices

Appendix A

Country Indices

See Table A.1 for the country indices and corresponding country names and country codes.

Table A.1: Country Indices

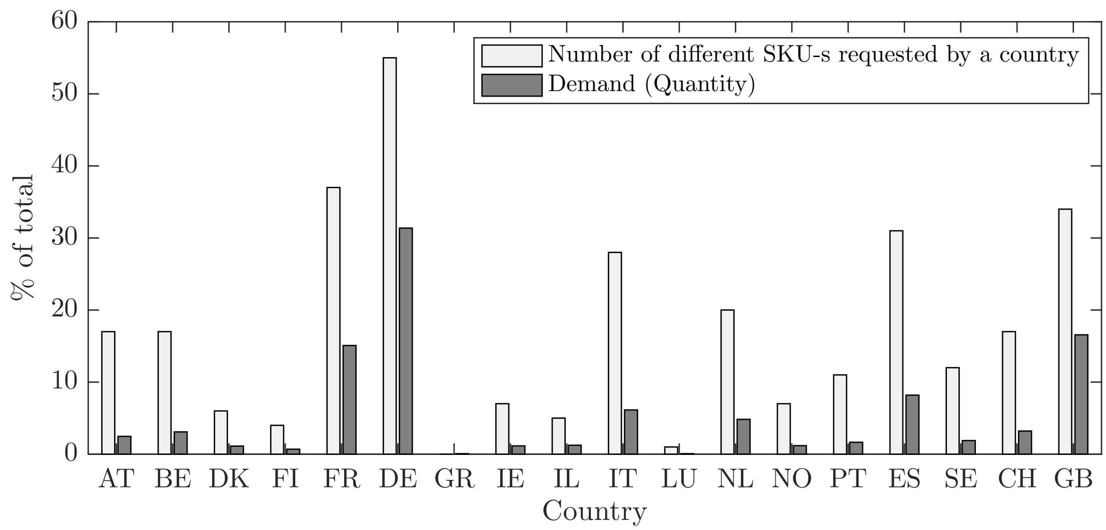
Index (j)	Country Name	Country Code
1	Austria	AT
2	Belgium	BE
3	Denmark	DK
4	Finland	FI
5	France	FR
6	Germany	DE
7	Greece	GR
8	Ireland	IE
9	Israel	IL
10	Italy	IT
11	Luxembourg	LU
12	Netherlands	NL
13	Norway	NO
14	Portugal	PT
15	Spain	ES
16	Sweden	SE
17	Switzerland	CH
18	United Kingdom	GB

Appendix B

Demand Commonality

See Figure B.1 for the number of different SKU-s requested by a country relative to the total number of different SKU-s requested by all 18 countries. As can be seen in Figure B.1, the relative

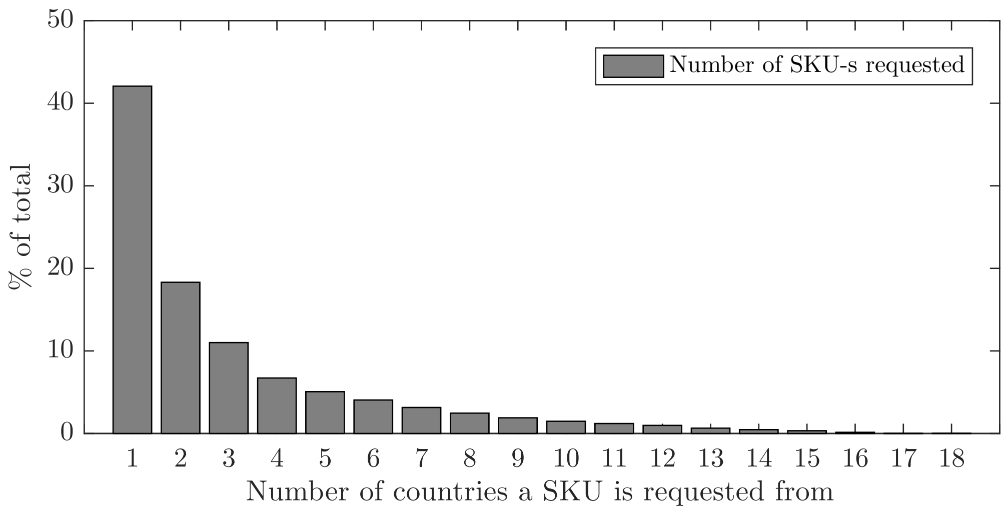
Figure B.1: Number of different SKU-s requested by a country



number of different SKU-s requested for each country, correlates with the demand rate of a country.

See Figure B.2 for the number of different countries an SKU is requested. As can be seen in Figure B.2, approximately 42% of all SKU-s is requested in one country. Roughly 83% of the SKU-s is requested in 5 countries or less.

Figure B.2: Number of different countries an SKU is requested

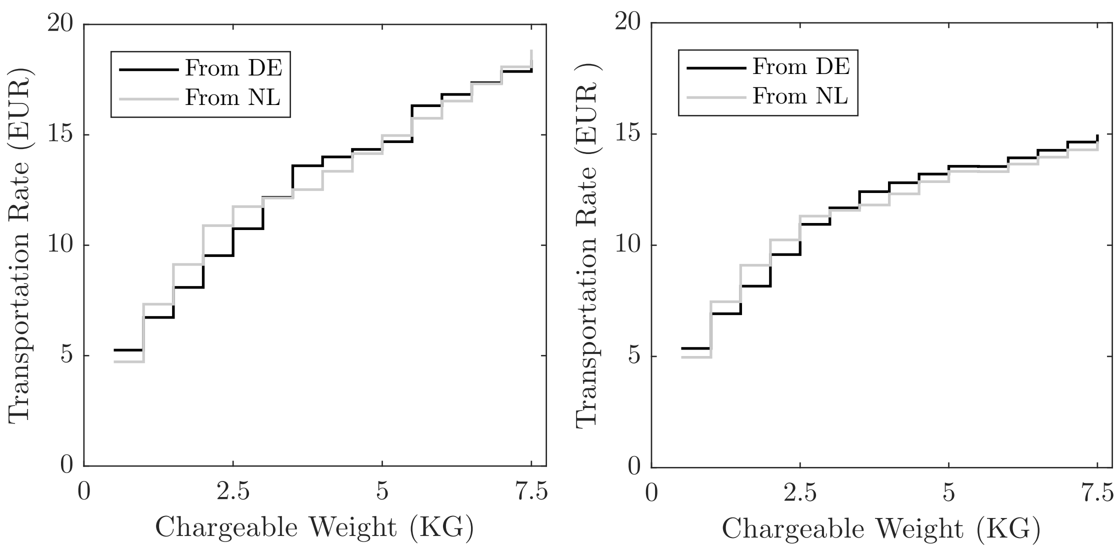


Appendix C

Cross-border Transportation Rates for shipments to ES and FR

See Figure D.1 (a) for a visualization of the cross-border transportation rates for a shipment from NL to ES and for a shipment from DE to ES for different CW-s. As can be seen from Figure D.1 (a), the origin country with the lowest transportation rate to ship to ES varies in CW. For some values of CW it is cheaper to ship to ES from NL and for some values of CW it is cheaper to ship from DE. See Figure D.2 (b) for a visualization of the cross-border transportation rates for a shipment from NL to FR and for a shipment from DE to FR for different CW-s. As can be seen in Figure D.2 (b), what holds for shipments to ES holds also for shipments to FR. We learn from this that it is important to assign demand to DC-s not only based on the country from which an SKU is requested but also the CW of an SKU that is requested.

Figure C.1: Transportation rates to ES and FR for different values of CW



(a) Shipment to Spain (ES)   (b) Shipment to France (FR)

Appendix D

Strata used in Proportionate Stratified Random Sample

See Table E.1 for an overview of 1) the number of parts requested per part segment, 2) the number of parts requested per part segment that have a Reorder Quantity (ROQ) equal to one and had Customer Order Quantities (COQ-s) in year 2015 strictly equal to one and, 3) the number of parts per part segment that are included in the subset of 500 SKU-s. Each part segment represents a stratum in the Proportionate Stratified Random Sample of 500 SKU-s.

Table D.1: Part segments and corresponding demand rates (year 2015)

Part Segment	Absolute # of parts requested	Relative # of parts requested	Absolute # of parts requested with ROQ=1 and COQ=1	Relative # of parts requested with ROQ=1 and COQ=1	Absolute # of parts in in subset	Relative # of parts in in subset
CCP	31877	16,4%	3743	11,7%	83	16,6%
EOL	3011	1,6%	1190	3,7%	8	1,6%
FCO	22066	11,4%	3293	10,3%	58	11,6%
HCFM	13100	6,8%	3441	10,8%	33	6,6%
LCFM	89283	46,1%	5659	17,7%	228	45,6%
LTB	3415	1,8%	2166	6,8%	10	2,0%
NPI	4146	2,1%	1706	5,3%	11	2,2%
SLOW	24690	12,7%	10125	31,7%	64	12,8%
TO	1542	0,8%	487	1,5%	4	0,8%
TUBES	750	0,4%	135	0,4%	1	0,2%
Total	193880	100,0%	31945	100,0%	500	100,0%