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Distribution Network Design

An Empirical Study in General Electric Healthcare Service Parts Delivery Network

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An Empirical Study in General Electric Healthcare Service Parts Delivery Network

By

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Tuba Duygu Kaynak
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List of Abbreviations

OEM	Original Equipment Manufacturer
DC	Distribution Center
CDC	Central Distribution Center
RDC	Regional Distribution Center
PuDo	Pick up Drop off
GE	General Electric
GEHC	General Electric Healthcare
TMS	Transport Management System
UFCFLP	Uncapacitated Fixed Charge Facility Location Problem

Executive Summary

A distribution network design is of importance to systematically organize the flow of products from supply points to demand points. A distribution network is not only crucial before sales but also after sales because regardless of the initial quality of product, malfunctions occur. These malfunctions need to be repaired by replacing defective parts, which are delivered through after sales distribution network and all activities, carried out from the report of the malfunction until the product is up and running, are called after sales services. The replacement parts are called service parts or spare parts and this thesis project focuses on the distribution network design for delivery of these items.

Customer surveys point out that high quality after sales services has become a criterion for selecting supplier companies. A shorter response time to failures and availability of service parts in the storage are given importance. Because after sales services became a field that companies can differentiate themselves from the competitors, practitioners have an increasing interest on establishing the optimal distribution network design to meet customer expectations while being cost-competitive.

The researchers have addressed service parts distribution with a strong focus on inventory management. However, distribution network design involves more decisions such as number of facilities, facility locations, allocation of customer demand to these facilities, and storage capacities. In addition, the managerial aspects and strategies for service parts logistics in business case studies are derived from electronic, automotive and aviation industries. Considering these, there is a knowledge gap about distribution network design for service parts in healthcare industry. This thesis project aims at filling this gap by introducing a general mathematical model for distribution network optimization based on an empirical study, conducted in General Electric Healthcare service parts delivery network. Following this, the main research question is formulated as:

How can a medical devices service parts distribution network be designed to minimize the costs while meeting the customer service level requirements?

To answer this question, firstly the decisions involved in designing a distribution network are investigated. Then, the current state-of-the-art distribution network mathematical modelling algorithms and characteristics of service parts logistics have been discovered. Following this, the problem at hand is explored in detail and resulted in an optimal distribution network design. This design is further investigated by building design alternatives. To successfully carry on these steps, the project was initiated with a literature review. Then, interviews were conducted with the practitioners for the empirical study and mathematical modelling was the method that was used to formulate the problem.

The mathematical model addressed four main distribution network design decisions, which are namely (1) the number of distribution centers, (2) the location of distribution centers, (3) the size of distribution centers, and (4) the allocation of customer demand to distribution centers. These decisions are made to minimize the total service parts delivery costs, which consists of shipment costs, facility rental costs, and penalty costs in case of late deliveries.

The geographical scope of the empirical study was limited to Europe so the challenges that come along with customs operations in shipments to and from non-European countries are avoided. Because the scope is limited to Europe, only the service parts that are currently stocked in the European central distribution center and the five European regional distribution centers are incorporated. The target in time delivery is determined as next day 9 am. Service parts shipments for preventive maintenance are excluded since these activities are planned ahead and do not require next day 9 am deliveries. Also, reverse logistics for repair activities are excluded.

In the mathematical model, it is assumed that demand is known and the demand data from 2016, which are collected from the company database, have been used. For the regional distribution centers, the candidate locations are determined based on the logistics service providers hub locations that are close to international airports since the company does not have own warehouses but rents from these service providers. Because inventory stocking decisions are out of scope of this study, it is assumed that the fill rate is 100%. Lastly, it is assumed that customers can be served from multiple facilities.

Minimizing the total costs, the model run results indicate that there should be six distribution centers in total. The central distribution center should be located in Paris and the regional distribution centers should be in Manchester, Berlin, Stuttgart, Liege, and Rome. The allocation of the customer demand to these distribution centers are shown in Figure 1.

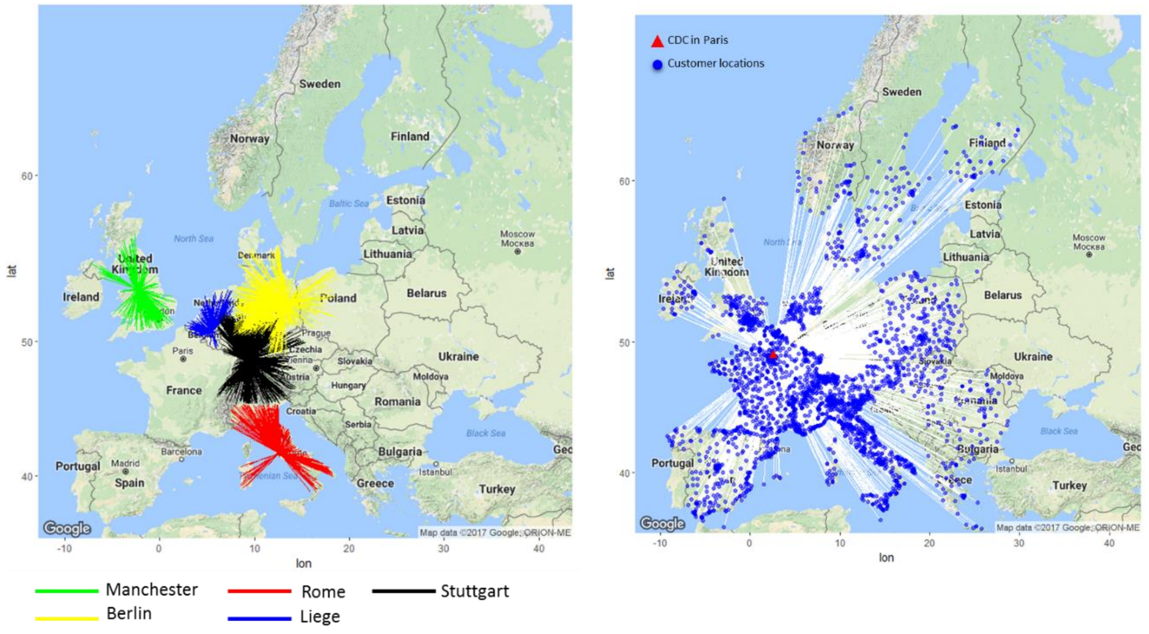


Figure 1. Customer demand allocation to the distribution centers
(Left: Demand allocation to the regional distribution centers, Right: Demand allocation to the central distribution center)

The robustness of the model results with respect to the parameters is tested by performing sensitivity analysis. This implies that possible changes in parameters during the upcoming years, such as increase in unit shipment costs due to increase/decrease in fuel costs, do not have a significant impact, which increase the confidence to trust the results.

This optimal distribution network is further examined by investigating alternative designs. To do so, a cost minimizing and a service level maximizing (by minimizing the maximum travel duration from a distribution center to a customer) mathematical model are used. This way, an improved decision-making is allowed by presenting alternative outcomes. In total, nine distribution network configurations under two main alternative designs were investigated by consulting the academic and company supervisors. These alternatives are described in Table 1 below.

Table 1. Description of the alternative designs

Alternative design	Description
1	Under cost minimization objective, late deliveries are allowed to find out the cheapest distribution network design option.
2.1	Under cost minimization objective, central distribution center is eliminated to investigate the optimal distribution center locations in case domestic supply is preferred more than the international shipments.
2.1(b)	Like in alternative design 2.1, the central distribution center is eliminated but this time, the capacity of the regional distribution centers has been increased.
2.2, *P*=8 2.2, *P*=7 2.2, *P*=6	Under service level maximization objective and without a central distribution center, the problem is solved. *P* stands for the total number of regional distribution centers so the problem has been solved for renting 8, 7, 6 distribution centers.
2.2(b), *P*=8 2.2(b), *P*=7 2.2(b), *P*=6	Like in alternative design 2.2, the objective function was service level maximization. But this time, the regional distribution centers were uncapacitated except the one in Paris. The problem has been solved for renting 8, 7, 6 distribution centers.

The results of these designs are discussed with the practitioners and as a result of these discussions, five factors to decide the optimal distribution network design have been identified. These factors are (1) in time delivery, (2) total cost, (3) domestic supply, (4) operational complexity, (5) network structure.

In time delivery means that a requested service part is delivered to the customer before next day 9 am. In fact, solving the problem with the service level maximization objective, it has been realized that it is possible to deliver even earlier to certain customers. Total cost stands for the summation of the shipment, rental, and late delivery penalty costs. Domestic supply implies that the service parts are sent to the customers from a domestic distribution center, rather than international shipments.

Operational complexity is determined based on the total number of distribution centers in the network. As the number increases, the complexity increases as well. Finally, network structure depends on whether the customers are delivered only from the regional distribution centers or both from central and regional distribution centers.

A score table is prepared, which shows the performance of each alternative distribution network design. This is presented in Table 2 below. The green colour implies a desirable outcome, while yellow and red stand for moderate and undesirable, respectively. Looking at this score table, each alternative has its own advantages and disadvantages considering the five factors. If all these five factors are taken equally important, there is no single best network design. However, the weights of the five factors can vary specific to the empirical study and as a result, depending on these weights, an optimal distribution network design could be chosen.

Table 2. Score table summarizing the performance of the alternative designs

	Total costs	**In time delivery**	**Operational complexity (Number of DCs)**	**Domestic supply (DC in top 5 countries)**	**Network structure (Is there a CDC?)**
Original model				No	Yes
Alternative design 1				Yes	Yes
Alternative design 2.1				Yes	No
Alternative design 2.1(b)				Yes	No
Alternative design 2.2, *P*=8				Yes	No
Alternative design 2.2, *P*=7				No	No
Alternative design 2.2, *P*=6				No	No
Alternative design 2.2(b), *P*=8				Yes	No
Alternative design 2.2(b), *P*=7				No	No
Alternative design 2.2(b), *P*=6				Yes	No

Because this study focuses on medical devices service parts delivery next day 9 am, the emergency level is high. Revenue gain from the maintenance service agreements are considered significant for companies and customer satisfaction is the key to maintain this revenue. Following these insights, in time delivery as well as domestic supply factors receive higher weights. Comparing costs and operational complexity factors, a more complex distribution network could be still manageable when there is a major cost saving. Comparing network structure with other factors within the scope of this study is rather tricky because the trade-offs related to a single and a multi-echelon network are usually related to the inventory management, which is out of scope of this study. Nevertheless, because this factor still affects the optimal distribution network design, the recommendations are given for both delivering only from the regional distribution centers and delivering both from regional and central distribution centers.

Based on the five factors, three alternative designs have been identified, which perform the best among the others. These are design 2.1(b), design 2.2 *P*=8, and design 2.2(b) *P*=8. Because design 2.2 *P*=8 and design 2.2(b) *P*=8 have the same objective, network structure, operational complexity, they can be easily compared and as a result, design 2.2(b) *P*=8 is preferable since the total costs is roughly XX lower. The distribution center locations of the remaining two designs, which are design 2.1(b) and design 2.2(b) *P*=8, are shown in Figure 2 below.

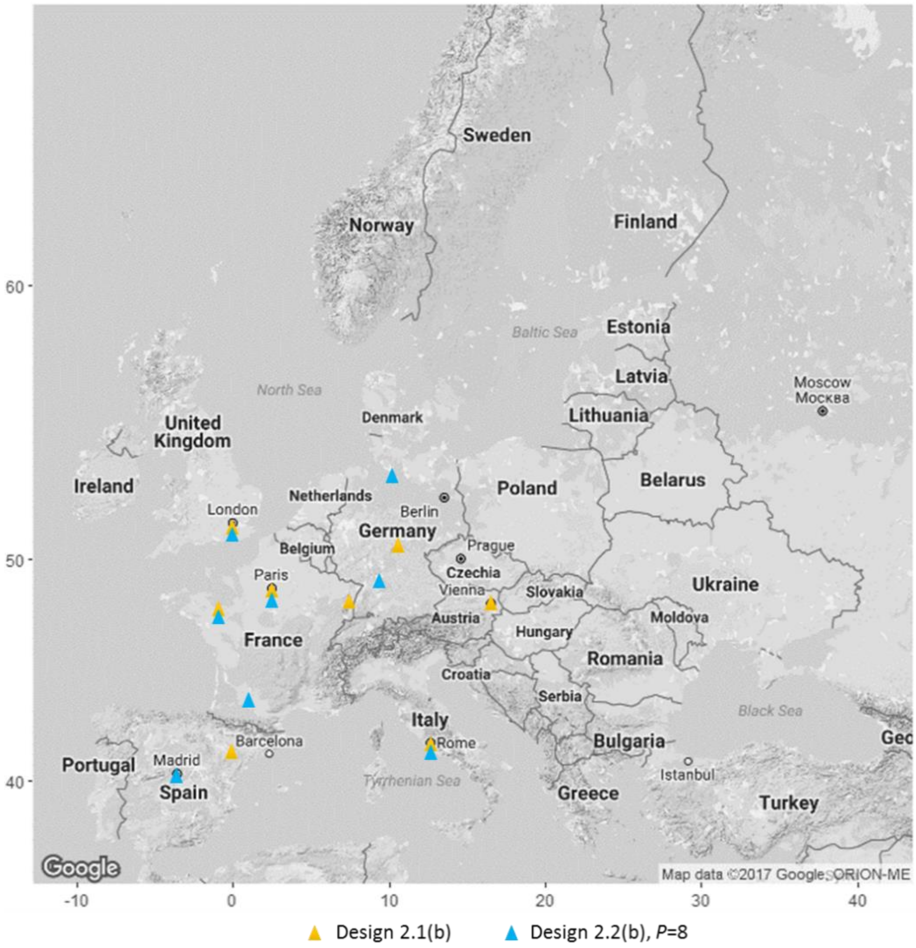


Figure 2. Distribution center locations of two alternative optimal distribution network designs

It is important to emphasize that design 2.1(b) minimizes the costs while design 2.2(b) *P*=8 maximizes the service level. Both alternative designs are able to deliver to all of the customers next day before 9 am but in design 2.2(b) *P*=8, the possibility to deliver earlier to the customers is maximized.

In both alternative designs, there is no central distribution center. Incorporating the network structure factor, if deliveries from a central distribution center, having a massive capacity, is preferred as an outcome of inventory decisions, then Paris seems to be the best location for it with the advantage of in time air deliveries to all customer locations. In this case, all the demands allocated to the regional distribution centers in France can be aggregated in Paris. With the involvement of network structure factor, in total, four alternative distribution networks can be derived from design 2.1(b) and design 2.2(b) *P*=8 as shown in the decision tree in Figure 3.

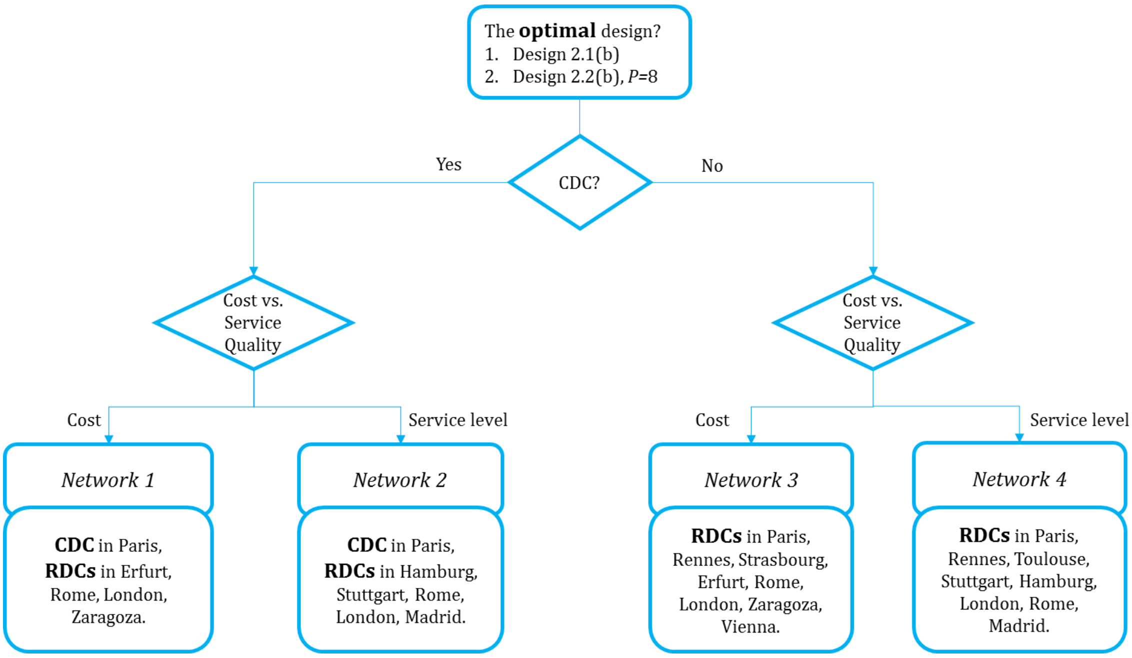
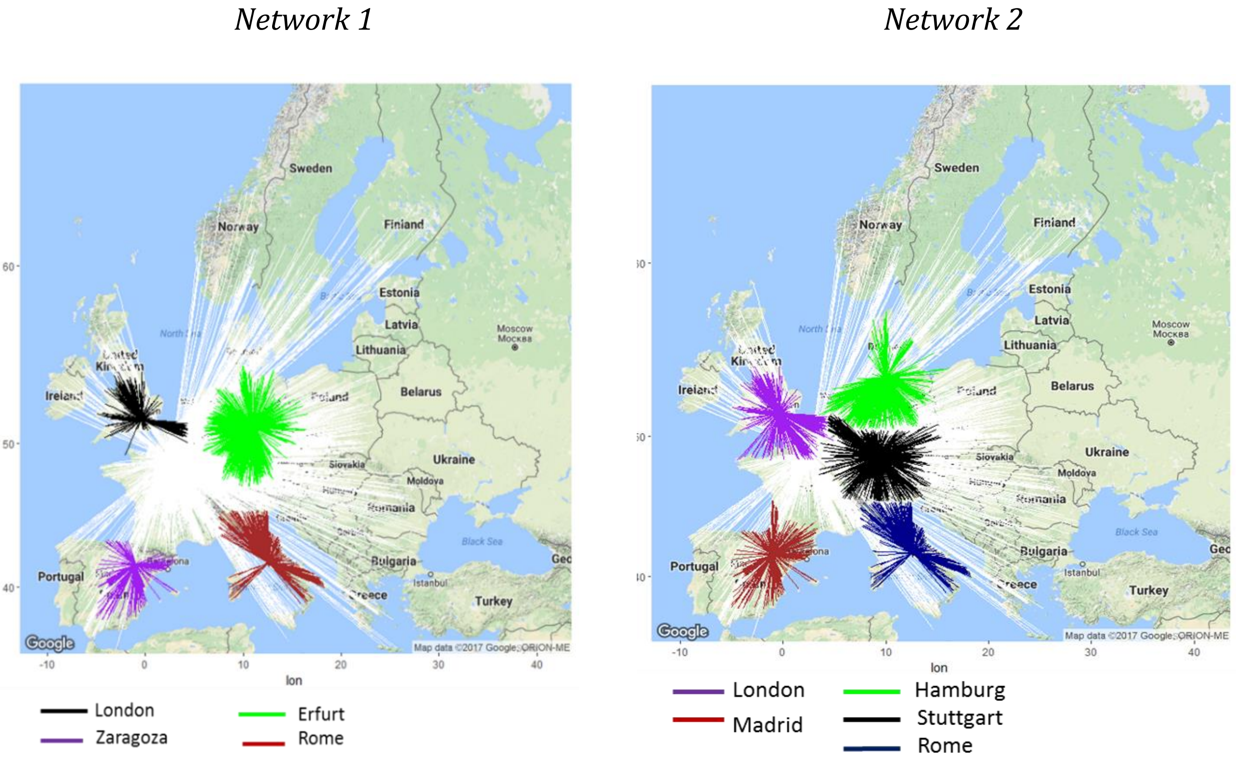
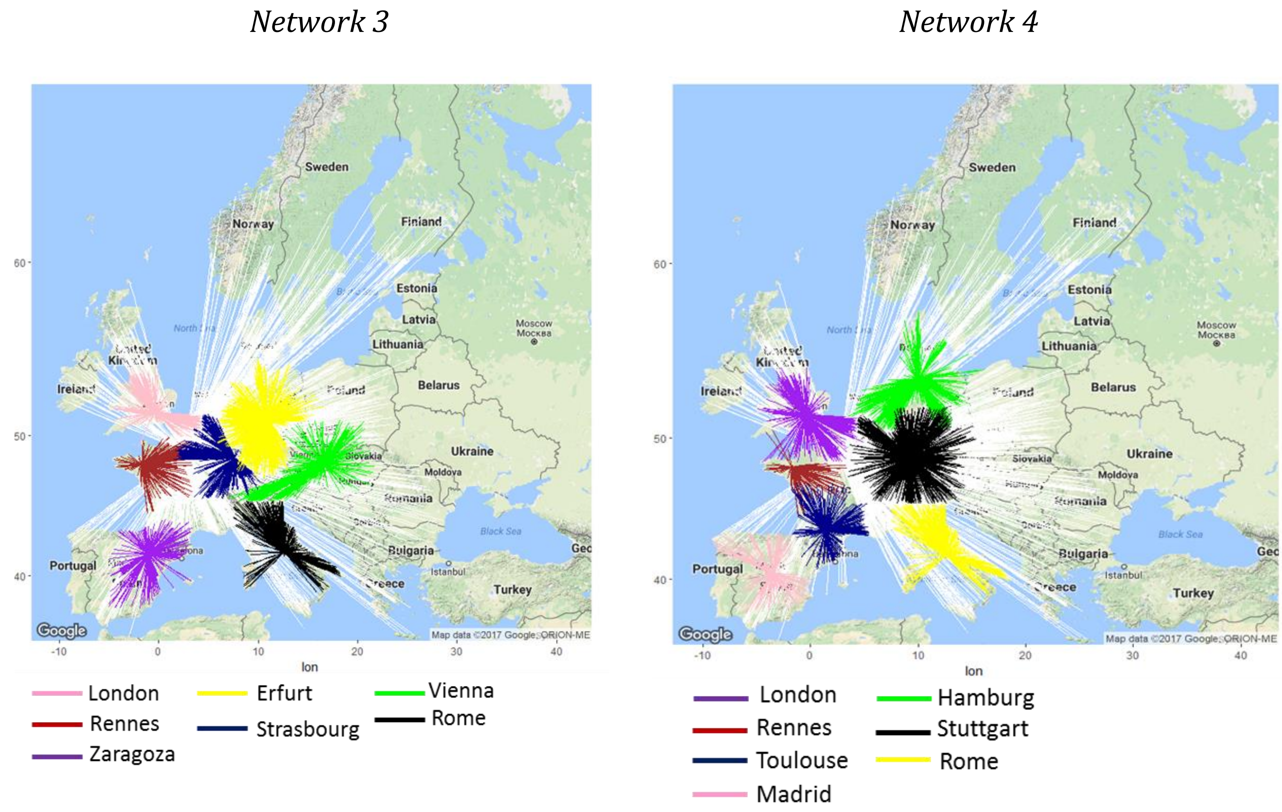


Figure 3. Decision tree to choose the optimal distribution network design

In this figure, choosing customer service level over cost implies that strategically, the company wants to strive for earlier deliveries than next day 9 am (i.e. shorter delivery time than 15 hours) to some customers to further improve its competitiveness in the market. The allocation of the customer demand to the distribution centers in these networks are shown in Figure 4.




Network 3

Network 4

Figure 4. Customer demand allocation to the distribution centers of four networks

If a CDC is desired, choosing network 1 instead of network 2 implies cost savings up to XX since there will be one less RDC. However, network 2 promises deliveries within 12-13 hours to the customers around the very east and very west parts of Germany, around Madrid in Spain, and central part of Finland and Denmark. If it is of interest to improve the service quality in these locations, choosing network 2 would be a good choice.

In case there is no CDC, there are significant cost savings up to XX because a massive CDC costs much more than an RDC. Comparison between network 3 and network 4 shows that the transportation costs in network 4 are roughly XX higher. However, network 4 enhances the customer satisfaction by delivering to more customers within 12-13 hours in the very west and very east parts of France, southern Italy, central and southern Spain, and central part of Finland and Denmark. From the perspective of sales and marketing, choosing this network could give GE Healthcare an advantage and contribute in increasing revenues in these locations.

Based on the researcher's understanding of the industry, prioritizing service level over costs is more promising in the long term. Especially, considering the healthcare initiatives regarding extending the visiting hours of hospitals to 24/7 such as in Canada (Crawley, 2017), earlier deliveries than next day 9 am (i.e. faster than 15 hours) could become a common request from the customers in the near future. Considering this, the optimal distribution network design would be network 4. This alternative is chosen because it prioritizes service level and delivers only from the regional distribution center, which increases the confidence to deliver in time.

Contents

1 Introduction

This chapter starts with the explanation of the research background, which is followed by specification of the research problem. Later, research objective and research questions are presented and research methods are discussed. This chapter is finalized by describing the research framework and thesis outline.

1.1. Research Background

Distribution network design can be described as the systematic organization of the flow of products from supply points to the demand points, which can be distribution centers or directly customers (Chopra, 2003). A distribution network design is not only crucial before sales, but also after sales because regardless of the initial quality of the product and workmanship, the product eventually fails to meet the design specifications: a malfunction occurs (Cohen & Lee, 1990). Following this, the defective part must be replaced with a new part that is delivered through the after-sales distribution network. The activities that are carried out to support customers in case of malfunctions during the lifetime of the purchased products is called “after sales service” and the replacement parts are called “service parts” or “spare parts”.

Service parts usually flow through one or more intermediate places within the distribution network where they are stored, transshipped, and consolidated until they reach to demand points. These places are called “echelons” (Tsiakis, Shah, & Pantelides, 2001). In a single-echelon system, a distribution center is the central storage between manufacturer and customer whereas in a multi-echelon system, there are multiple layers. A typical multi-echelon system consists of manufacturer, warehouses, regional distribution centers and customers. The number and location of the warehouses and regional distribution centers depend on the size of the area of distribution, customer locations, transport facilities and routes (Mohamed, Vanderbeck, & Klibi, 2016).

In case of high technology products such as medical devices, heavily automated production systems, and military systems, original equipment manufacturer (OEM) company and customers establish relations through maintenance service agreements. These agreements typically specify the duration of the support (usually in years), the service level and the time window within the service will be provided. In case of medical devices, downtime of the systems due to a part failure play an important role in the public healthcare services. Undesirable consequences such as quality reduction in healthcare and direct negative impact on patients due to delays in diagnostic imaging could occur. Hence fast and correct supply of service parts is essential (Kutanoglu & Lohiya, 2008).

Customer surveys point out that high-quality after sales service has become a criterion for selecting supplier companies, i.e. maintenance service providers, of high technology products. Customers prefer the suppliers with shorter response time to failures and available service parts in storage. In this regard, supplier companies differentiate themselves from their competitors by striving for a better after sales service (Candas & Kutanoglu, 2007). At the same time, it is important to take the costs of providing these services into account to be able to remain competitive in the market. Therefore, a well-established distribution network design is crucial to meet customer expectations while still being cost-competitive.

1.2. Research Problem

Considering the customer satisfaction and cost-competitiveness, the distribution network requires (re)design because the area of distribution may expand or shrink in years based on customer portfolio and maintenance service agreements. Following this, the distribution center locations and customer allocation to these facilities need to be (re)organized to improve the effectiveness of the network. Moreover, product portfolio is modified in time as new technologies are introduced in the market, meaning that the types of demanded parts and volumes vary. Therefore, stocking capacities and transport operations should be (re)considered.

When it comes to medical devices service parts, there is a combination of four main characteristics that makes it a specific research field within distribution network studies: (1) high service requirements, (2) low and dispersed demand rate, (3) high variety, and (4) high prices (Candas & Kutanoglu, 2007; Huiskonen, 2001). High service level requirements imply that customer demand must be satisfied in a timely manner so stock-out is not an option. Also, delivery emergency is high due to its direct impact on healthcare quality. However, because demand rate is low and dispersed, variety and prices are high, inventory holding can be very costly to meet these desired service requirements.

Considering these characteristics, the researchers focused mostly on the inventory management of service parts to optimize the costs, see Candas & Kutanoglu (2007), Caggiano, Jackson, Muckstadt, & Rappold (2007), Kutanoglu & Lohiya (2008), Kutanoglu & Mahajan (2009), Altay & Lewis (2011). However, distribution network design involves many decisions such as number of facilities, facility locations, allocation of customer demand to the facilities, transport modes, and storage capacities. Besides, there exists holistic studies about distribution network design of service parts as well, which discuss the managerial aspects and strategies. See Cohen & Lee (1990), Cohen, Zheng, & Agrawal (1997), Fortuin & Martin (1999), Pfohl & Ester (1999), Huiskonen (2001). But the suggestions in these studies are based on electronic, automotive or aviation industries. In general, each industry has its own characteristics, meaning that the suggestions from other industries might not be directly applicable to the healthcare industry. Based on these, this thesis addresses the scientific knowledge gap about designing a distribution network for service parts in the healthcare industry.

The practical relevance of this study is achieving higher customer satisfaction and higher cost-effectiveness at GE Healthcare with a new distribution network design. A common feature in service parts distribution is outsourcing warehousing and delivery services. OEM companies prefer logistics companies to manage daily logistics operations so that they can focus on long-term strategic and tactical decisions for customer satisfaction. According to Candas & Kutanoglu (2007), due to the outsourced warehousing and delivery services, frequent redesign of the distribution networks in response to changing market expectations, products and customer portfolio becomes increasingly common. Because companies such as UPS, TNT and

DHL provide full access to their global logistics network, it becomes easier for companies to adjust their network without much difficulty. Indeed, once an agreement with a particular logistics company terminates, it is even possible to switch to another company without extra costs. The results of this distribution network design study can support the decisions of the practitioners regarding how they can seize the global logistics network of third-party logistics providers.

1.3. Research Objective and Research Questions

The objective of this study is to explore how a medical devices service parts distribution network can be designed. In line with this research objective, the main research question is formulated as follows:

How can a medical devices service parts distribution network be designed to minimize the costs while meeting the customer service level requirements?

The sub-research questions to answer this main question are:

1. What are the decisions involved in designing a distribution network?
2. What are the current state-of-the-art distribution network design mathematical modelling algorithms?
3. What are the alternative distribution network designs with regards to the decisions involved?
4. Which of these distribution network design alternatives minimize the costs while meeting the customer service level requirements?

1.4. Research Methods

In this thesis project, three research methods have been used to answer the research questions.

1.4.1. Desk Research

Desk research compromises of two variants: literature survey and secondary research. The literature survey was conducted to specify the decisions that are involved in distribution network design and explore the current state-of-the-art distribution network design algorithms (sub-questions 1&2) by scanning publications that are in the field of logistics and supply chain. The relevant publications were in the form of scientific articles, conference proceedings, books, and industry reports.

Google Scholar, Scopus, and ScienceDirect, were searched with the following keywords: *service parts*, *spare parts*, *distribution network*, *healthcare logistics*, *logistics chain, distribution planning, and transportation*. The snowballing research method was commonly used i.e. the referred articles which are of interest were distinguished from the references of the preliminarily collected articles. This way, an in-depth understanding about most recent service parts distribution network (re)design decisions, trends and methods could be gained. Finally, the results of literature survey were systematically grouped under three sub-headings, which could be found in Chapter 2.

Secondary research was carried out in order to collect background information for the empirical study. The company's current parts distribution strategy, customer service contracts, and healthcare industry requirements were investigated through presentations and reports. More specifically, the current network structure (i.e. customer and distribution center locations), demand volume, product types, transportation options, delivery performance, and service level requirements were explored.

1.4.2. Interview

Semi-structured interviews were conducted for the purpose of gaining a deep understanding of the current distribution network and related challenges that the service parts delivery team face with in daily operations. The first interview was conducted with the company supervisor and this interview was a guidance to reach other key actors in the operations. Eventually, the output from the interviews gave the sufficient background information to be able to perform the empirical study. Also alternative distribution network configurations were defined in consultation during follow-up interviews (sub-question 3). The interview debriefs can be found in Appendix 1.

1.4.3. Mathematical Programming

A mixed-integer mathematical model was developed to obtain an optimal distribution network design and this model was run in the IBM ILOG CPLEX Optimizer Version 12.7. The model provided results about the optimal number and type of distribution centers that should be opened as well as their locations. Moreover, customer demand allocation to each distribution center was identified. The details regarding the formulation of the problem, assumptions made, processing the data for the model could be found in Chapter 3. Using this mathematical model, alternative distribution networks has been studied. The details of the alternative designs are presented in Chapter 5.

1.5. Research Framework and Thesis Outline

This research was executed in four phases as shown in Figure 5 below, which also indicates the outline of this thesis report.

Phase 1 consists of literature review, which provides a theoretical basis about network design decisions, network modelling algorithms, and characteristics of service parts logistics. In the end of this phase, sub-research questions 1 and 2 are answered.

Phase 2 starts with exploration of current distribution network configuration of the company and collection of details about the logistics operations. These provides an input for determining the scope of the study, the mathematical model and the required data. Phase 2 is finalized by performing the verification and validation of the mathematical model and the results.

After mathematical model is ready, the model run results are discussed in Phase 3. Later, alternative distribution networks are built and compared. In the end of Phase 3, sub-research question 3 is answered.

As the last step, Phase 4 concludes this thesis by presenting the comparative results of the alternative distribution network designs, answering the sub-research question 4. Eventually, the recommendations about the optimal design that should be adapted are discussed, which answers the main research question.

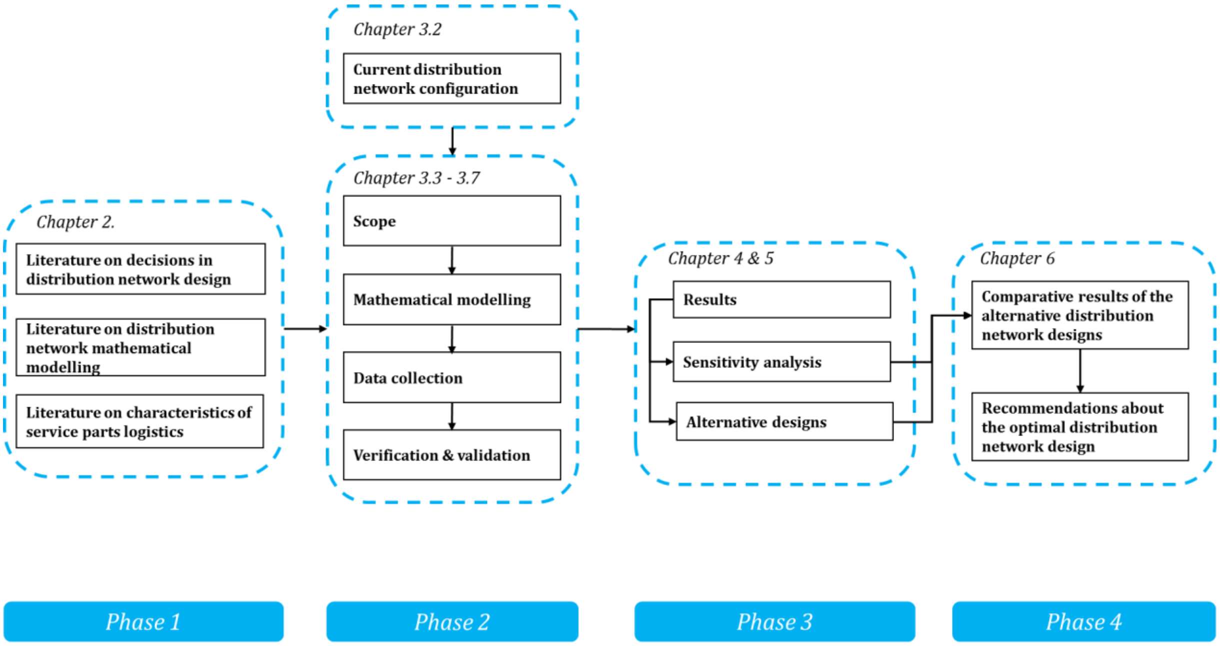


Figure 1. Research framework and thesis outline

2 Literature Review

In this chapter, three streams of literature review are discussed, which elaborate on distribution network design decisions, mathematical modelling for distribution network design and characteristics of service parts logistics. Because distribution network design has multiple components such as facility location, transportation, inventory, and routing, reviewing studies that discuss network configuration decisions is of help to understand and explain the interactions among these decisions and their effects on the performance of the network. The second stream elaborates on the current state-of-the-art mathematical modelling methods and this is of help to be able to formulate the objective and constraints of the distribution network design problem at hand. Finally, investigating the characteristics of service parts logistics enlightens its specific aspects compared to regular products so that a valid mathematical model can be built considering these aspects.

2.1. Decisions in Distribution Network Configuration

Distribution network involves many integrated decisions, which makes it difficult to consider them altogether (Ambrosino & Grazia Scutellà, 2005). These integrated decisions are classified into three levels depending on the time horizon, which are namely strategic, tactical and operational. The strategic level decisions consider a longer time horizon, mostly more than a year and these types of decisions require aggregate data. Unlike this, the operational level consists of short-term decisions that have an impact on daily business operations and requires transactional data. The tactical level falls between these two with respect to the time horizon and amount and accuracy of data needed (Vidal & Goetschalckx, 1997).

Typical strategic level decisions address number, location and capacities of warehouses and manufacturing plants, number of layers/echelons between supplier and customer, transportation channels, and the flow of the material through the logistics network. It goes without saying that opening a new facility or increasing the capacity requires large amount of investments and this particular reason shows strategic decisions have long-lasting effects. Allocating customer demands to warehouses is an example to tactical level decisions. These decisions can change more frequently than the strategic ones without requiring a large amount of resources. Choosing the mode of transportation could be an operational decision that is made based on the daily operations requirements and they are recognized with minor or no impacts in a long time horizon (Melo, Nickel, & Saldanha-da-Gama, 2009; Rangan & Jaikumar, 1991).

Based on 16 scientific articles, a comprehensive list of decisions is presented in Table 1 below, with the intention of providing an overview of the aspects that are considered in configuring a distribution network. The grey cells imply the decisions covered in each of these articles and white cells mean that the particular decision is not covered. As seen in this table, the scholars have been always addressing a subset of decisions due to high complexity to consider the decisions altogether.

Table 1. List of distribution network configuration decisions

Decisions	(Ambrosino & Grazia Scutellà, 2005)	(Huiskonen, 2001)	(M. a Cohen & Lee, 1990)	(Cohn & Barnhart, 2006)	(Shang, Yildirim, Tadikamalla, Mittal, & Brown, 2009)	(Shen, 2007)	(Melo et al., 2009)	(Bramer & Simchi-Levi, 1997)	(Cintron, Ravindran, & Ventura, 2010)	(Ross, Venkataramanan, & Ernstberger, 1998)	(Kutanoglu & Lohiya, 2008)	(M. a. Cohen et al., 1997)	(Vidal & Goetschalckx, 1997)	(Rangan & Jaikumar, 1991)	(Chopra, 2003)	(Hiremath, Sahu, & Tiwari, 2013)
Location of distribution facilities	■	■	■	■	■	■	■	■								
Number of distribution facilities	■			■	■	■		■			■	■	■	■	■	
Throughput and storage capacity			■	■	■	■	■									■
Routing	■				■		■		■	■						
Transport modes	■		■	■			■				■	■	■			
Number of layers/echelons	■	■	■	■					■		■	■		■		
Inventory stocking policies	■		■	■		■	■	■				■	■			
Demand allocation to warehouses			■		■		■					■				■
Production allocation to manufacturing facilities			■			■		■								■

According to the evidence from the field, Rangan & Jaikumar (1991) argues that these integrated decisions are in fact interactive, as illustrated in Figure 2 below. For instance, by nature strategic decisions affect operational and tactical decisions. As an example, customer demands can only be allocated to the warehouse locations that are determined in strategic level. At the same time, the researchers discuss that the interaction is not only one-way but two-ways, meaning that tactical and operational level decisions influence strategic level decisions as well. For example, if a particular mode of transportation or a route is preferred in the operational level based on available shipping lanes of the logistics service provider companies, then it has a significant impact on decisions regarding the location of warehouses. Likewise, Shang, Yildirim, Tadikamalla, Mittal, & Brown (2009) explains that operational decisions such as order cycle time affect strategic decisions about number of warehouse locations.

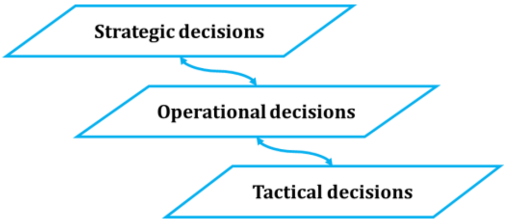


Figure 2. Interaction among three levels of distribution network decisions

While making decisions in these levels, some trade-offs emerge, for example between costs and time (Hiremath et al., 2013). Increasing number of warehouse locations will improve the customer satisfaction. Since there are more customers who are close to the warehouses, they will be delivered in a shorter cycle time. However, operational costs will increase, which can be conflicting with the operational costs budget, determined in the strategic level. To examine this kind of trade-offs thoroughly, it is important to observe their effects on the distribution network design and decide the optimal design accordingly.

Besides costs and time trade-offs, nature of the business, competition in the market, customer expectations, product value and product variety determine the distribution network configuration choices as well. For instance, sometimes even if there is a cheaper option available, it might not be chosen to stay competitive in the market and to exceed customer expectations (Chopra, 2003).

2.2. Distribution Network Mathematical Modelling

In Table 1 above, nine different decisions about distribution network configuration has been presented. Considering these decisions all together to find an optimal distribution network is too complex, therefore the scholars in the operations research field commonly formulate the distribution network related problems by addressing a subset of these decisions. The amount of research in this field grows in time due to the increasing computational capabilities. Nevertheless because computational power is still relatively limited, adopting simplifying assumptions in the models is also very common (Vidal & Goetschalckx, 1997).

Hiremath et al. (2013) points out that the most common objective in distribution network mathematical modelling is minimization of the total cost. Maximization of profit, minimization of inventory levels, and maximization of responsiveness through shorter delivery lead times are other objectives that some researchers also considered. While modelling, the objective function(s) are to be determined based on the context of the problem and the organizational targets.

A distribution network problem can be modelled by using various algorithms such as location set covering, maximum covering, p-median/center problem, (multi-objective) capacitated/uncapacitated facility location problem, single-source capacitated facility location problem, (mixed) integer linear/non-linear programming, (Lagrangian) heuristic, and goal decomposition. A modelling algorithm can be an exact or a heuristic algorithm. An exact algorithm guarantees to provide and optimal solution in a finite time. But heuristic algorithms do not guarantee optimality. Nevertheless they provide an improved result by scanning the neighbourhood of the first arbitrarily selected feasible solution. Heuristics algorithms are especially developed for NP-hard mixed-integer linear programming problems. The researchers choose the most appropriate algorithm based on the decisions that the problem at hand contains and the objective function. Reviewing the literature, a list of studies with these algorithms and the addressed decisions is prepared, as shown in Table 2 below. The grey cells indicate the decisions that are addressed in these algorithms and white cells imply that the decision is not covered in that particular study.

Table 2. Distribution network mathematical modelling algorithms

Source	**Algorithm**	Location of distribution facilities	Number of distribution facilities	Throughput and storage capacity	Routing	Transport modes	Number of layers/echelons	Inventory stocking policies	Demand allocation to warehouses	Production allocation to manufacturing facilities
(Owen & Daskin, 1998) (Bramer & Simchi-Levi, 1997) (Melo et al., 2009)	Median problem	▨	▨							
(Owen & Daskin, 1998)	Covering problem	▨	▨							
(Owen & Daskin, 1998)	P-center problem	▨	▨							
(Daskin, Snyder, & Berger, 2003) (Balinski, 1965) (Owen & Daskin, 1998) (Melo et al., 2009)	Uncapacitated fixed charge facility location problem	▨	▨						▨	▨
(Bramer & Simchi-Levi, 1997)	Single-source capacitated facility location problem	▨	▨	▨					▨	
(Candas & Kutanoglu, 2007)	Integer programming	▨	▨					▨	▨	
(Kutanoglu & Lohiya, 2008)	Integer programming		▨			▨		▨		
(Wong, Van Houtum, Cattrysse, & Van Oudheusden, 2006)	Lagrangian heuristic							▨		
(Daskin et al., 2003) (Shapiro, 2007)	Mixed integer linear programming	▨	▨		▨	▨			▨	
(Owen & Daskin, 1998) (Shapiro, 2007)	Stochastic problems	▨	▨							
(Daskin et al., 2003)	Non-linear programming	▨	▨					▨	▨	
(Sabri & Beamon, 2000) (Shapiro, 2007)	Multi-objective problem	▨	▨						▨	
(Xifeng, Ji, & Peng, 2013) (Shapiro, 2007)	Multi-objective uncapacitated facility location problem	▨	▨						▨	
(Cohn & Barnhart, 2006)	Composite-variables	▨	▨	▨				▨	▨	
(Shang et al., 2009)	Non-linear mixed integer programming	▨	▨						▨	

Table 2 shows once again that there is no single study that addresses all decisions at once because it is too complex. Among all, decisions related to location and number of facilities and demand allocation to warehouses are the most common addressed. Inventory stocking policies is also a decision that many studies explored. The rareness of throughput and storage capacity, routing, transport modes might be because these decisions are not the backbone of the distribution network, meaning that they can be made in time according to operational requirements. Number of layers/echelons is not addressed in any of the selected studies which might imply that this has not been a major decision yet that researchers have focused on in mathematical modelling.

Among the studies listed in Table 2, Candas & Kutanoglu (2007), Kutanoglu & Lohiya (2008), Wong, Van Houtum, Cattrysse, & Van Oudheusden (2006), and Cohn & Barnhart (2006) specifically focused on service parts distribution networks and in all of these studies, inventory stocking policy is a core decision. Putting this particular decision aside, there is a lack of studies about service parts distribution network modelling, which elaborate on other types of decisions. The question of how a service parts distribution network can be optimally configured considering warehousing and transportation is not answered yet.

2.3. Characteristics of Service Parts Logistics

Previously, it has been argued that service parts distribution network modelling is majorly studied from inventory stocking perspective but there is a lack of knowledge about how to design it, taking warehousing and transportation aspects into account. The first step towards filling this knowledge gap is explaining what service parts logistics is about, then discussing the characteristics of service parts logistics and finally, explaining how these characteristics affect the distribution network design.

Service/spare parts logistics is defined as the flow of service parts from manufacturers and vendors to field engineers who use these parts for repairing technical systems. Field engineers, being a part of service delivery teams, use the service parts to repair a malfunction of the technical systems installed in the field (installed base). This service is provided to the customers under the service maintenance agreement (Draper & Suanet, n.d.). Due to the high revenue rates in service operations, companies are motivated to invest and optimize their service parts logistics so that they can respond customer expectations and meet the service deadlines, determined in the service maintenance agreement (Jalil, Zuidwijk, Fleischmann, & van Nunen, 2011). Furthermore, being competitive in service operations by improving the service levels even further results in expanding the installed base as well as extending the service maintenance agreements with current customers (M. a Cohen & Lee, 1990).

The service maintenance agreement is a result of service planning, which describes service levels related to various products. The elements that play a role in service planning are (1) customer needs and expectations, (2) the importance of the service part in terms of its effect on functionality of the technical system (critical, non-critical, (3) geographical area (high-density, medium density, remote) and (4) the allocated budget (Draper & Suanet, n.d.). For instance, the expected service level for critical parts are higher, meaning that the service planning should ensure fast delivery. Also, if it is a remote area, then the delivery time is expected to be longer in the service maintenance agreement, compared to the high-density business areas.

Service parts are stored within the distribution network until they are requested by the field engineers. Some of these parts can be very costly. Also, the lifetime of the parts has a high variance, which implies that while some parts are requested very frequently, some parts can stay in the distribution network even several years or there can be cases that they are never requested (Draper & Suanet, n.d.). The infrequent orders are defined as sporadic/ slow-moving demand. Moreover, when demand occurs, it can be highly variable in size, causing a lumpy demand pattern (Martin, Syntetos, Parodi, Polychronakis, & Pintelon, 2010). On one hand, having high inventory levels implies a huge tied-up capital while on the other hand, limiting the inventory levels means higher possibility of stock-outs. Having an adequate capacity of storage in warehouses and determining the right inventory levels are critical in service planning.

The installed base of products, i.e. the technical systems installed in the field, that must be served is large and geographically dispersed. Therefore, a fundamental element of service parts logistics is an adequate design of the infrastructure, i.e. the positioning of warehouses and the arrangement of transportation connection, spanning a geographical area to meet the service requirements. The design of the infrastructure is developed based on historical decisions and local circumstances and its optimization is an ongoing process due to ongoing changes such as customer locations and shipping lanes. In service parts logistics, it is a common strategy to form partnerships with logistics service providers. These service providers are responsible for managing the warehouses and transportation connections, while gaining advantage of economies of scale, thus reducing the overall costs (M. a. Cohen et al., 1997; Draper & Suanet, n.d.).

Based on the benchmark analysis conducted by M. a. Cohen et al. (1997), a variety of transportation mode are in use in service parts delivery operations. Trucks are currently the predominant mode but use of air shipment is also rapidly increasing, both for regular and emergency shipments. Although it is costly to use air shipment, there is a considerable gain due to less inventory holding and meeting the service requirements.

These characteristics in service parts logistics lead to several specific aspects in distribution network design. One of them is respecting the delivery deadlines. When a part is ordered, companies strive for delivering on a very short term, sometimes within hours because of competitiveness (Draper & Suanet, n.d.). For this reason, the demand fulfilment emergency for service parts is considered high. Because logistics service providers are responsible for managing the warehousing and transportation, the companies have an access to a wide network and therefore have the opportunity to make strategic decisions about warehouse locations. Moreover, the possibility of delivering both via air and road transportation implies that physical distances and delivery time are not correlated. Last but not least, warehouse capacities deserves a special attention since the variety of the parts is high and the demand is sporadic, meaning that there is a need for a good balance between tied-up capital and available stock.

2.4. Research Gap

Based on the three streams of literature review about distribution network design decisions, distribution network mathematical modelling, and characteristics of service parts logistics the research gap that will be addressed in this study will be using mixed integer mathematical modelling to address the strategic decisions about (1) location of distribution facilities, (2) number of distribution facilities, (3) throughput and storage capacity, and (4) demand allocation to warehouses decisions to design a service parts distribution network. Decision (1), (2) and (3) could be considered as the core strategic decisions of distribution network design since they require high investments and they are made typically at least for a decade. Even though decision (4) is on the tactical level, due to its effect on decision (3), it is regarded important in strategic level as well.

In Table 2 above, it was already seen that these four decisions are altogether incorporated by Bramer & Simchi-Levi (1997), using single-source capacitated facility location problem algorithm and by Cohn & Barnhart (2006), using composite-variables algorithm. Indeed, in the latter inventory stocking policies have also been addressed besides these decisions. However, the model could not be solved to optimality due to its complexity. In the former, an exact solution method was available but the third stream of literature review about characteristics of service parts logistics reveals that the generic formulation by Bramer & Simchi-Levi (1997) cannot be directly applied in service parts distribution network design without adaptations because these characteristics are not reflected. Some most important characteristics that need to be incorporated are related to minimizing the downtime of the technical systems by faster deliveries, ensuring to be in time in all deliveries, having the capability of serving in a geographically dispersed area, and organizing the DC capacities with respect to service parts demand characteristics.

Furthermore, healthcare industry specific insights in service parts logistics have not been discussed in the literature so far. These insights, which can be gained through an empirical study, may lead to further important adaptations in the generic distribution network design algorithms. Therefore, using mixed integer programming in medical devices service parts distribution network design by adapting an existing exact algorithm is recognized as the scientific contribution of this study.

3 Empirical Study

This chapter starts with a brief introduction to the company where the empirical study is performed and a discussion about the current service parts logistics. Following this, the scope of the empirical study is clarified. Later on, the mathematical model formulation is explained. The verification and validation of the model are discussed. Finally, the data collection and data processing, which are needed for to solve the mathematical model, are elaborated.

3.1. Company Background

General Electric (GE) was established in 1878 with the merger of two companies, Edison General Electric Company and Thomas-Houston Electric Company which were led by Thomas Edison, the inventor of the light bulb, and Charles Coffin. Currently the company has more than 170 locations and 330,000 employees worldwide and its headquarters is situated in Boston, United States. GE owns a wide range of businesses, which are namely, GE Aviation, GE Capital, GE Digital, GE Energy Connections, GE Healthcare, GE Lighting, GE Oil & Gas, GE Power, GE Renewable Energy, and GE Transportation (“GE Fact Sheet,” 2017).

In the healthcare business, GE is a leading company for manufacturing and providing healthcare systems, life care solutions, life sciences core imaging, life sciences research and bioprocess, and healthcare IT. The healthcare systems, which are in the core of this thesis, consists of products/medical devices that address clinical imaging needs. The product portfolio for healthcare systems consists of Radiography R&F, Mammography, Lunar Densitometry, Interventional Cardiovascular, Surgery, Computed Tomography (CT), AW, Magnetic Resonance (MR), Molecular Imaging, and Ultrasound (GE Healthcare Europe, 2016). With this product portfolio, patients more than 100 countries are served diagnostic imaging (“GE Healthcare Fact Sheet,” 2017).

Global Services business unit within GE helps health systems manage their operational resources to deliver high quality care, efficiently and cost effectively (“GE Healthcare Fact Sheet,” 2017). Service parts delivery can be recognized as a crucial part of the global services since it ensures that maintenance is provided when there is a malfunction in a medical device and this thesis project is specifically about this part of the company’s healthcare business.

The global service unit (internal name: XX) has XX warehouses globally with XX unique part numbers, XX part orders and XX shipments per day. The mission of this unit is providing distribution and fulfilment with competitive costs in material, repair and logistics. The ultimate single goal of these operations is customer satisfaction and in this case, customers are the healthcare provider facilities like hospitals and clinics.

3.2. Current Service Parts Logistics

The service parts delivery process starts with a failure of a medical device at a customer site. The customer calls GE and GE technical customer representatives perform a remote diagnosis. If remote diagnosis is not possible, a local GE field engineer, who has the expertise to investigate the failure and to perform the maintenance activity, goes to the customer location.

Once the diagnosis is completed, the field engineer places a part order. This order is processed by the XX team. The part availability is checked firstly in the regional warehouse, then in the central distribution center. Once the part is found in a warehouse, shipment process is initiated. The shipment is delivered by logistics service providers such as XX. Depending on which of them serve in that specific region and their shipping lane, price, and delivery time offerings, a courier is selected automatically by the XX.

A field engineer is assigned to perform the repair when the service part arrives on site. In this point, it is important to synchronize the arrival of the field engineer and service part. Currently, there is another ongoing project to improve this synchronization. The delivery process is completed when repair action is completed and the medical device is functional again. This process is summarized in Figure 3 below.

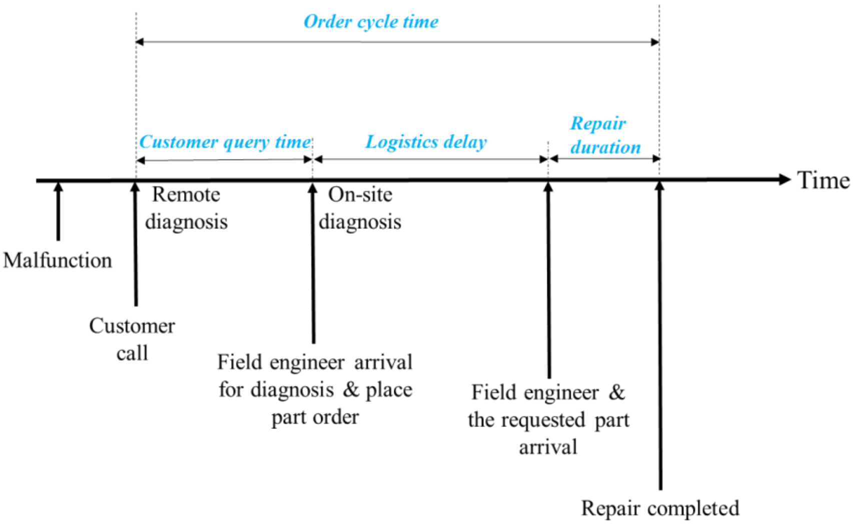


Figure 3. Service parts delivery process
(adapted from M. A. Cohen & Agrawal, 1999)

To have a smooth delivery process, the XX's support and a well-established distribution network are crucial. The service parts distribution is organized in a multi-echelon structure. There are three source poles globally that are situated in the United States, Europe, and Asia. The parts are procured from these source poles. The parts are then transported to central distribution centers (CDC). Later, the parts in the CDCs are distributed to the regional distribution centers (RDC). The benefit of having the RDCs rather than using only CDCs is being closer to customer sites. The confidence of delivering in time increases and this way, customer satisfaction is enhanced. When a part is requested after a malfunction diagnosis, it is shipped from one of these RDCs or from the closest CDC. The distribution network structure is visualized in Figure 4 below. There is also reverse flow of parts due to repair activities. However, reverse logistics is not discussed in this report as it is out of scope of this thesis project.

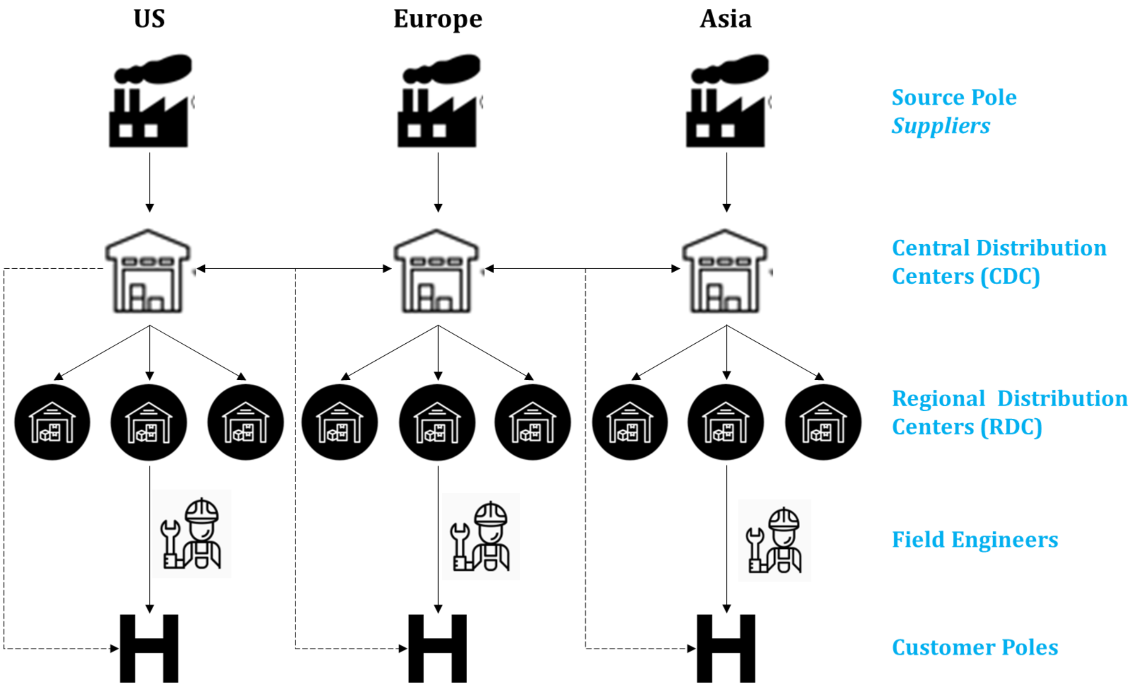


Figure 4. Multi-echelon service parts distribution network structure

One of the main objectives of the XX is ensuring that the part arrives at the customer site the next day before 9.00 am. As of now, this objective is not achieved in everywhere, meaning that order cycle time is longer than desired.

Moreover, as seen in Figure 4, customer orders are satisfied either from the RDCs or the CDCs. In fact, the deliveries in the Europe pole are majorly shipped from the CDC by air transportation even if there is a much closer RDC location to the customer. By nature, shipment from the CDC costs much more than the RDC. However, shorter distances do not directly imply that in time delivery can be achieved. Sometimes, even if there is a closer RDC than the CDC, if there is not an express shipping lane or if it is an infrequent route between the customer and the RDC, the shipment is delivered much quicker from the CDC by air transportation. This phenomenon implies that minimizing the distances between the RDCs and customers is not an appropriate approach to the problem at hand. Furthermore, in shipments from the DCs to the customers, maintaining cost advantage (economies of scale) by consolidating service parts in transportation or storage could be relevant in this problem setting but it is not a common practice. Service parts are shipped to customers individually, therefore economies of scale solutions such as bundling are not used.

A significant difference between the service parts logistics in Europe and in the United States stems from the country borders in Europe, which introduces extra complexity to the distribution network. Because third party logistics companies organize their networks domestically, it is more expensive to use the transborder shipping lanes. Due to this reason, these routes become infrequent or sometimes there is simply no connection.

3.3. Scope

To highlight the borders of this empirical study, the scope is defined in the following lines.

Even though GE Healthcare has service delivery to many locations globally, this thesis project considers only the distribution network in Europe. This scope avoids the difficulties that comes along with customs operations in shipments to and from non-European countries. This scope covers 23 European countries, as listed in Appendix 2.

Because the focus is in Europe, only the parts that are currently stocked in the European central distribution center and in the European regional distribution centers are incorporated.

Service part shipments for preventive maintenance are excluded since these activities are planned ahead and does not require next day 9.00 am deliveries. Also reverse logistics for repair activities is excluded.

Because consolidation is not a common practice in storing or transporting the medical devices service parts, economies of scale is not regarded relevant within the scope of this study.

3.4. The Mathematical Model

The problem at hand involves four important and related strategic distribution network configuration decisions: (1) number of distribution centers to open, (2) location of distribution centers, (3) size of the distribution centers, and (4) which customers to deliver from each distribution center. These decisions are to be made to minimize the total delivery costs, which consist of the shipment costs, the facility opening costs and the penalty costs in case of late deliveries.

These decisions are interrelated as shown in Figure 7 below. Under the objective of costs minimization, (R1) implies that number and sizes of distribution centers are affecting each other because with small number of distribution centers, the size (i.e. handling capacities) of these facilities should be larger to meet the entire customer demand. Because late deliveries costs extra, (R2) explains that number of distribution centers affect the decision of how to locate them to have as less delay penalty as possible. (R3) shows customers are allocated depending on existed distribution center locations to minimize shipment and delay penalty costs. According to (R4), demands of customers can be allocated to a distribution center as much as its size allows.

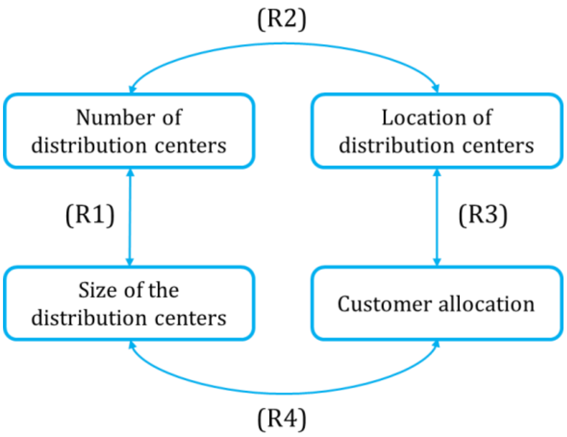


Figure 5. Interrelated decisions in distribution network design

(1) Number of distribution centers, (2) location of distribution centers, (4) which customer to deliver from each distribution center decisions are addressed in the uncapacitated fixed charge facility location problem (UFCFLP). In fact, the UFCFLP is recognized as a classical location problem, forming a basis for many of the location models in supply chain design. In this problem, customer locations with known demands and a set of candidate facility locations are given. There is a known fixed cost incurred once a facility is opened in one of the candidate locations. There is a known unit shipment cost for transportation from each candidate facility location to each customer. The problem aims to minimize the combined cost of facility location and shipment costs while meeting the entire customer demand (Daskin et al., 2003). The notation of the problem is:

Indices:

k	index for customer locations	$k \in \{1, \dots, K\}$
j	index for candidate facility locations	$j \in \{1, \dots, J\}$

Parameters:

D_k	yearly demand at customer location $k \in \{1, \dots, K\}$
f_j	fixed cost of locating a facility at candidate site $j \in \{1, \dots, J\}$
e_{jk}	unit cost of shipping from the candidate facility site $j \in \{1, \dots, J\}$ to the customer location $k \in \{1, \dots, K\}$

Decision variables:

$$Y_j = \begin{cases} 1, \text{if a facility is located in candidate site } j \\ 0, \text{otherwise} \end{cases}, \qquad \forall j \in \{1, \dots, J\}$$

X_{jk}	fraction of the demand at customer location $k \in K$ that is served by a facility at site $j \in j \in \{1, \dots, J\}$, where $0 \le X_{jk} \le 1$

The problem can be formulated as follows (Balinski, 1965):

Minimize $$\sum_{j=1}^{J} f_j Y_j + \sum_{k=1}^{K} \sum_{j=1}^{J} D_k e_{jk} X_{jk} \tag{1}$$

Subject to $\sum_{j=1}^{J} X_{jk} = 1 \qquad \forall k \in \{1, \dots, K\}$ (2)

$X_{jk} - Y_j \leq 0 \qquad \forall j \in \{1, \dots, J\}; \forall k \in \{1, \dots, K\}$ (3)

$Y_j \in \{0,1\} \qquad \forall j \in \{1, \dots, J\}$ (4)

$X_{jk} \geq 0 \qquad \forall j \in \{1, \dots, J\}; \forall k \in \{1, \dots, K\}$ (5)

The objective function (1) minimizes the sum of the facility opening costs and shipment costs. Constraint (2) states that each demand node is assigned to a facility. Constraint (3) implies that a demand node can only be assigned to an open facility. Constraint (4) is an integrality constraint and Constraint (5) ensures non-negativity.

This UFCFLP formulation assumes that the facilities have unlimited capacities and therefore the decision (3) about the size of the distribution centers is not elaborated. It is important to note that although another facility location problem formulation by Bramer & Simchi-Levi (1997) addresses the decision (3) together with others, their formulation ensures that customers are served only from a single facility, which is not a requirement for the problem at hand. As a result, the UFCFLP formulation is used as the basis model and it is adapted for the problem at hand.

Before doing so, all the assumptions that have been made in the adapted mathematical model formulation are listed and explained below:

1. **Demand is known.**
   In the literature about inventory models, independent Poisson processes is a common assumption for the demand of service parts because replenishment policies are substantially affected from uncertain malfunction rate. However, this problem at hand covers strategic decisions that are effective in the long-term. When making strategic decisions, using aggregated data is preferred since fluctuations and trends in the demand will remain minor in the big scale planning. That is to say, distribution center location and capacity will not change daily or monthly due to sporadic demands or infrequent peaks in particular regions of the network. Following this, the aggregate yearly demand data is used in the model.

2. **Customer locations are known.**
   Since service parts are requested for an existing installation, the set of installed base gives the customer locations.

3. **Candidate locations for regional distribution centers are known.**
   Distribution centers are rented from logistics service providers. Existing facilities of active logistics service providers in the given geographical area are obtained, which gives a discrete and deterministic set of candidate locations for the model.

4. **The service parts that customer requests are always available in the assigned distribution center.**
   Since inventory stocking decisions are not incorporated in this problem, the fill rate is assumed to be 100%.

5. **Customers can be served from multiple facilities.**
   The customers can receive their orders from different distribution centers. There is no obligation of single sourcing.

The adaptations to the UFCFLP model by Balinski (1965) can be explained as follows:

- There are multiple items that are delivered from facilities to the customers. Hence a new index *i* for service parts types is introduced.

- There are three types of facilities that can be opened in the candidate set of facility locations: CDC, RDC or PuDo. Customers can be delivered from all these types of facilities. That is why, a new index *t*, which stands for the type of the facility, is added to the model.

1. Since the decision about the size of the facilities will be made, a new parameter g_t is added, which specifies total number of deliveries that can be handled in distribution center type *t*.

2. In the classic UFCFLP formulation, Balinski (1965) allocates customers to the facilities to minimize costs. However, in the problem at hand, it is important to deliver in time. Thereby, a parameter that denotes maximum acceptable order to delivery travel duration (PT) is added.

3. To incorporate the mean travel duration between each distribution center and each customer and to track in time delivery, a new parameter p_{jk}, which stands for the mean travel duration between distribution center j and customer k, is added as well.

4. Because late deliveries are undesired, a penalty cost, M, for late deliveries is included.

- A new decision variable u_{jk} to incorporate the costs of late deliveries is added, which indicates the difference between the actual delivery time and the promised delivery time.

Considering these adaptations, the final mathematical model is below:

Indices:

i	index for service parts	$i \in \{1, \dots, I\}$
j	index for distribution centers	$j \in \{1, \dots, m+1\}$
k	index for customer locations	$k \in \{1, \dots, K\}$
t	index for type of distribution centers	$t \in \{1, 2, 3\}$

The index *j = 1* represents the location of the CDC, while remaining indices stands for the candidate m locations for the RDCs. The index t distinguishes between the CDC, RDC and PuDo's. More specifically, *t=1* implies central distribution center (C), *t=2* implies regional distribution center (R_{large}), and *t=3* implies PuDo's (R_{small}).

Parameters:

D_{ik}	amount of service parts *i* demanded by customer k (unit)
e_{ijk}	unit cost of shipment of item *i* from distribution center *j* to customer k (€/unit)
f_t	fixed yearly rental cost of a distribution center type t (€)
g_t	total number of deliveries that can be handled in a distribution type t (unit)
p_{jk}	mean travel duration between distribution center *j* and customer k (hour)
PT	maximum acceptable order to delivery travel duration (hour)
M	penalty cost in case of delayed deliveries (€)

As D_{ik} implies, customers demand different types of service parts, depending on the installed base they have. The unit cost of shipment e_{ijk} covers handling and transportation costs. In this context, handling costs include loading and unloading individual items to the vehicle. The unit cost of shipment is calculated per item. Consolidation is not a common practice in outbound logistics or storage in this problem setting.

Unit cost of shipment = Unit cost of handling + Unit cost of transportation

The unit cost of shipment depends on the mode of transportation, distance, shipping lane, delivery service type (for example, express delivery), weight and volume of the item as shown in Figure 8. Road shipment is cheaper than air shipment. Short distances cost less than long distances. If the shipping lane is between two major cities, it is cheaper than sending an item to a smaller city and this is due to economies of scale. Because the number of shipments between two major cities is larger, logistics providers charge less money per item. An express delivery service is more expensive than a regular delivery service because it is much faster and lastly, as weight and volume of items increase, the unit cost of shipment becomes higher as well.

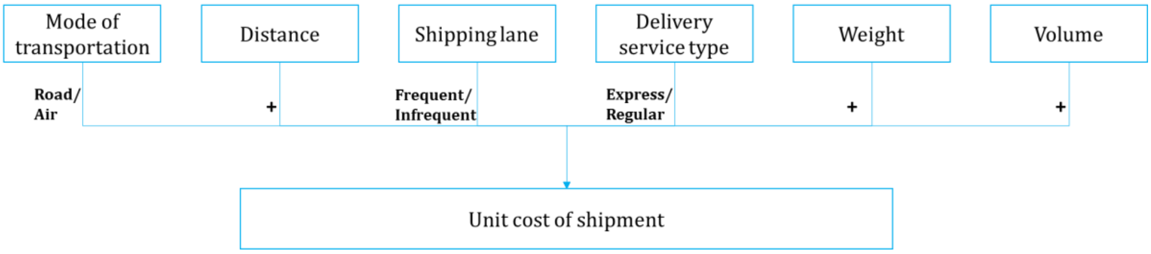


Figure 6. Factors affecting the unit cost of shipment

The holding cost is incorporated with the fixed yearly rental cost of a distribution center (f_t). The rent varies depending on the machinery needed to store the items in place, the maintenance costs, and the labor costs as shown in Figure 9. The positive signs on the arrows imply that rental cost rises once the need of labor, machinery or maintenance increases due to increase in the number of stored items. For this reason, the fixed yearly rental cost depends on the type of the distribution center (CDC, RDC, PuDo). Naturally, the number of deliveries sent from the CDC is more compared to the number of deliveries sent from RDC or PuDo, which is incorporated with the parameter g_t.

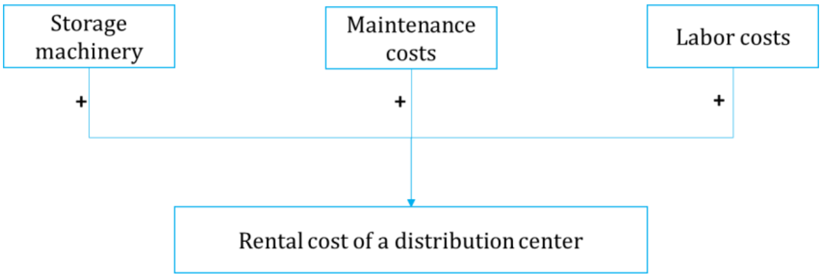


Figure 7. Factors affecting rental cost of a distribution center

The parameter p_{jk} indicates how much time it takes between an order is received and it is delivered. An order is sent either via road if it is domestic shipment or via air transportation if it is an international shipment. PT is the parameter which determines whether in time delivery happens or not. If $p_{jk} > PT$, the delivery from distribution center j to customer k will be delayed and there will be a penalty cost M incurred. If the demand by customer k is delivered from another j with $p_{jk} \leq PT$, then the penalty cost M will not be incurred.

Decision variables:

$$Y_{jt} \quad = \begin{cases} 1, \text{if distribution center type } t \text{ is opened at site } j \\ \qquad\qquad 0, \text{otherwise} \end{cases}$$

$$\text{for } \forall j \in \{1, \dots, m+1\}, \forall t \in \{1, \dots, s+1\}$$

d_{ijk} amount of service parts i delivered from distribution center j to customer k

u_{jk} difference between delivery time and promised time from distribution center j to customer k

Y is the binary decisions variable that indicates whether a distribution center type t will be opened or not in the candidate locations j. The variable d_{ijk} displays from which distribution center each service part is delivered to each customer. It should be remarked that there is no restriction in terms of the number of distribution centers by which customers can be delivered. In other words, customers may be served from multiple DCs in case the capacity of a single DC is not sufficient to cover the entire demand. u_{jk} can be either positive, u_{jk}^{+} or negative, u_{jk}^{-} . u_{jk}^{+} implies the delivery delay to the customer, which is undesired, while u_{jk}^{-} indicates the delivery is in time.

The objective function of this mathematical model is minimization of the total costs, which consists of shipment costs, facility renting costs, and delivery delay penalty costs. The objective is formulated as follows:

Minimize $\sum_{i=1}^{I}\sum_{j=1}^{m+1}\sum_{k=1}^{K} e_{ijk}d_{ijk} + \sum_{j=1}^{m+1}\sum_{t=1}^{s+1} f_t\, Y_{jt} + \sum_{j=1}^{m+1}\sum_{k=1}^{K} u_{jk}^{+}\mathrm{M}$

Subject to

$$\sum_{j=1}^{m+1} d_{ijk} = D_{ik} \qquad \forall i \in \{1,\dots,I\}, \forall k \in \{1,\dots,K\} \tag{1}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} d_{ijk} \le \sum_{t=1}^{s+1} g_t Y_{jt} \qquad \forall j \in \{1,\dots,m+1\} \tag{2}$$

$$\sum_{t=1}^{s+1} Y_{jt} \le 1 \qquad \forall j \in \{1,\dots,m+1\} \tag{3}$$

$$\sum_{j=1}^{m+1} Y_{j1} = 1 \qquad \forall j \in \{1,\dots,m+1\} \tag{4}$$

$$p_{jk} - PT - u_{jk}^{+} + u_{jk}^{-} = 0 \qquad \forall j \in \{1,\dots,m+1\}, \forall k \in \{1,\dots,K\} \tag{5}$$

$$u_{jk}^{+}u_{jk}^{-} = 0 \qquad \forall j \in \{1,\dots,m+1\}, \forall k \in \{1,\dots,K\} \tag{6}$$

$$u_{jk}^{+}, u_{jk}^{-} \ge 0 \qquad \forall j \in \{1,\dots,m+1\}, \forall k \in \{1,\dots,K\} \tag{7}$$

$$Y_j \in \{0,1\} \qquad \forall j \in \{1,\dots,m+1\} \tag{8}$$

$$d_{ijk} \ge 0 \qquad \forall i \in \{1,\dots,I\}, \forall j \in \{1,\dots,m+1\}, \forall k \in \{1,\dots,K\} \tag{9}$$

Constraint (1) ensures that the entire customer demand is met. Constraint (2) implies that amount of service parts delivered from any facility does not exceed that facility's capacity. Constraint (3) guarantees that there is maximum one type of facility located in each candidate geographic location for a distribution center. Constraint (4) states that there will be one and only one central distribution center. Constraint (5), (6) and (7) indicates that the delivery delay is the positive time difference between the mean travel duration and maximum acceptable order to delivery travel duration. If this time difference is negative, i.e. a service part is delivered earlier than the maximum acceptable order to delivery travel duration, this shipment happens in time and therefore has no penalty costs. In Constraint (5), when the decision variable $u_{jk}^{+} \ge 0$, its effect to the solution of this problem is choosing a new distribution center from where the customer can be delivered in time. Finally, constraint (8) is an integrality constraint and constraint (9) ensures non-negativity.

This mathematical model is run in at a single point in time for the entire year, which implies there is no time index. This is due to the uniform distribution of demand throughout the months, which is confirmed with a one-sample Kolmogorov-Smirnov Test. The details of the statistical test can be found in Appendix 3.1. There are fluctuations but there is not a significant difference in demand between the months. In this regard, aggregating the demand and running the model at a single point in time do not cause major inaccuracies, especially about the utilization percentages of the distribution centers. If significant fluctuations in demand are observed in such a problem, time index should be introduced to the formulation and the effect of demand fluctuation on the selection of DC locations should be explored for an optimal distribution network design. However, this would imply that the open facilities per time index (for instance, each month) can potentially change, which can introduce significantly higher costs and operational complexities.

3.5. Verification

To check whether the general mathematical model is built right, verification is performed by testing the model with different sets of parameters. The model was run multiple times with a small arbitrary data set and changing parameters.

In the initial arbitrary small data set for performing the verification, there were:

- One type of service part,
- Three candidate DC locations,
- Five customer locations,
- Three types of DCs.

The initial parameters for the demand, unit shipment costs, fixed yearly rental costs of DCs, capacity of DCs, mean travel duration between DCs and customers, maximum acceptable order to delivery travel duration, and penalty cost in case of delayed deliveries are presented in Appendix 4. These parameters are later on changed to conduct the verification tests, as shown in Table 3 below. The details of these tests results can be found in Appendix 4.

Table 3. Verification tests

Test number	Explanation
Test 1	Demand is zero.
Test 2	Unit cost of shipment is zero.
Test 3	Fixed yearly rental cost of the distribution centers is zero.
Test 4	Total number of deliveries that can be handled in the distribution centers is zero.
Test 5	Total number of deliveries that can be handled in the central distribution centers is 100, which is bigger than the total demand.
Test 6	Total number of deliveries that can be handled in the central distribution center is zero.
Test 7	All mean travel duration between distribution centers and customers are zero.
Test 8	Maximum acceptable order to delivery travel duration is zero.
Test 9	Penalty cost in case of delayed deliveries is zero.

Later, the results of the verification tests were critically examined. They have shown that the mathematical model gives reasonable results. As a result, it is concluded that the general mathematical model is built right and can be used to analyse the problem at hand.

3.6. Data Collection and Data Processing

The formulated mathematical model indicates the need for collecting the following data:

- Customer demand,

- Customer locations,
- Distribution center types
- Location of candidate distribution centers,
- Unit cost of shipment,
- Yearly rental costs of distribution centers,
- Capacities of distribution centers,
- Service quality requirements.

As D_{ik} in the mathematical model implies, customers demand different types of service parts, depending on the installed base they have. The unit cost of shipment e_{ijk} covers handling and transportation costs. In this context, handling costs include loading and unloading individual items to the vehicle. The unit cost of shipment is calculated per item. Consolidation is not a common practice in outbound logistics or storage in this problem setting.

Unit cost of shipment = Unit cost of handling + Unit cost of transportation

The unit cost of shipment depends on the mode of transportation, distance, shipping lane, delivery service type (for example, express delivery), weight and volume of the item as shown in Figure 11. Road shipment is cheaper than air shipment. Short distances cost less than long distances. If the shipping lane is between two major cities, it is cheaper than sending an item to a smaller city and this is due to economies of scale. Because the number of shipments between two major cities is larger, logistics providers charge less money per item. An express delivery service is more expensive than a regular delivery service because it is much faster and lastly, as weight and volume of items increase, the unit cost of shipment becomes higher as well.

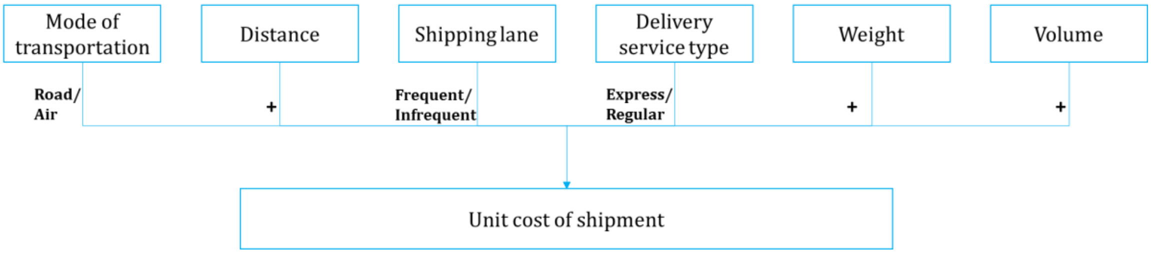


Figure 8. Factors affecting the unit cost of shipment

The holding cost is incorporated with the fixed yearly rental cost of a distribution center (f_t). The rent varies depending on the machinery needed to store the items in place, the maintenance costs, and the labor costs as shown in Figure 12. The positive signs on the arrows imply that rental cost rises once the need of labor, machinery or maintenance increases due to increase in the number of stored items. For this reason, the fixed yearly rental cost depends on the type of the distribution center (CDC, RDC, PuDo). Naturally, the number of deliveries sent from the CDC is more compared to the number of deliveries sent from RDC or PuDo, which is incorporated with the parameter g_t.

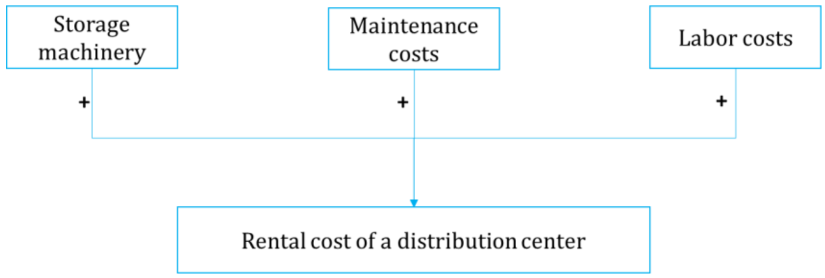


Figure 9. Factors affecting rental cost of a distribution center

The parameter p_{jk} indicates how much time it takes between an order is received and it is delivered. An order is sent either via road if it is domestic shipment or via air transportation if it is an international shipment. PT is the parameter which determines whether in time delivery happens or not. If $p_{jk} > PT$, the delivery from distribution center j to customer k will be delayed and there will be a penalty cost M incurred. If the demand by customer k is delivered from another j with $p_{jk} \leq PT$, then the penalty cost M will not be incurred.

To run the mathematical model and get results to make the distribution network decisions, the data were collected from the company databases and the performance reports from logistics service providers. Microsoft Office Excel and R (a free software environment for statistical computing and graphics) has been used for processing the data and the model was run in IBM ILOG CPLEX Optimization Studio Version 12.7.

Looking at the variety of the data for the mathematical model, the amount of the information is considerably large. For example, because the shipment items are service parts and given the fact that each product consists of many components, the product variety is high. Since the geographical scope of the study is Europe, the customers are in a wide geographical area. For that reason, data aggregation for the items and customer locations is required. Data aggregation does not only provide convenience for the analysis but also is of importance to obtain an acceptable run time in CPLEX.

Bramer & Simchi-Levi (1997) suggest below guidelines for data aggregation:
1. Aggregate the demand points in 150-200 zones.
2. Aggregated points should be placed at the center of gravity of respective zone.
3. Aggregate the items into 20-50 groups.
4. Each zone should have approximately same amount of total demand. Hence, the zones can be of different sizes.

The scholars have determined these guidelines based on their experience with development of a decision support system, called LogicTools. LogicTools includes a geographical information system, database features and optimization tools, aiding supply chain practitioners in various business cases. Guideline 1 and 3 are of help to reduce the data size and guideline 2 ensures that aggregated point is in the same distance to all customers in that respective zone. These three guidelines will be followed in scope of this study. However, guideline 2 is likely to be a specific requirement for the algorithm used in LogicTools to improve the run time. However, because this algorithm will not be used in this study, this guideline is neglected.

Depending on the large number of candidate distribution center locations considered and due to the variety of distribution center types in these locations (CDC, RDC, PuDo), further data aggregation may be required to solve the distribution network design problem with mixed integer linear programming within an acceptable run time. This chapter of the report describes the collected data and discusses how the data was processed and aggregated (when it is necessary) to be able to use in the model run.

3.6.1. Customer Demand

The total customer demand from the year 2016 was collected from the company database. This implies that only the service parts which were requested at least once by the customers during 2016 are included.

Each of these service parts are used in a particular product group, which is called modality.

These service parts were demanded in different frequencies. While some parts are requested more than [redacted] throughout the year, some parts were ordered only once in a year. The original demand data is considerably large for the model run. Instead of using this data, a subset of 500 ‘A type’ service parts was chosen based on ABC analysis. These 500 items are the most frequently ordered service parts and they account for roughly 80% of the total demand. The reason for conducting ABC analysis and using ‘A type’ items in the analysis is because these parts stand for the largest portion of the total demand. Designing the distribution network based on the items with highest frequency of demand will contribute on a higher customer satisfaction compared to a distribution network that is designed for items that are ordered only a couple of times a year. Nevertheless, it is important to ensure that the subset represents the original demand data in terms of the variety of orders (demand per modality) and distribution of demand among countries.

Firstly, the demand per modality has been checked. According to the Chi-Square statistical test results performed in SPSS, the demand per modality in the subset data is not significantly different than in the original total demand data.

Secondly, the total demand per country has been checked in the original and subset data. It is important that the demand per country is not significantly different in the original and subset data to be able to have the correct geographical demand spots. This way, the chosen locations for distribution centers in the model with the subset data can be generalized. Based on Chi-Square statistical test, it can be concluded that the demand from the subset of item represents is not significantly different than the original demand in terms of distribution among countries.

Following the data aggregation guidelines of Bramer & Simchi-Levi (1997), the subset of 500 items needs to be further aggregated into item groups. In this point, it is crucial to take the model’s effectiveness into consideration due to replacing the original detailed data with the aggregated data. On one hand, grouping the items implies less precision in the results, especially regarding the items flow matrix from each DC to each customer. On the other hand, there are computation power limitations to use the original detailed data and to get precise results.

In fact, the computer (Intel® Core (TM) i5-6500 processor, 3.20 GHz CPU, 8 GB RAM and 64-bit operating system) runs out of memory and gives no result when the 500 items data is used. Therefore, the data must be aggregated to be able to complete the model run and obtain results.
In this problem, number of items has been chosen to rescale the problem rather than number of customer locations (in total 166) and number of candidate distribution center locations (in total 70) because the latter two are of importance for the model to define the all possible connections between customers and distribution centers. Based on these connections, the model decides where to open the distribution centers and which distribution center each customer should be allocated, which are the main questions of this study. In current customer groups, it has been ensured that each customer are within a reachable distance for in time delivery. If the customer groups are expanded to decrease the total number, some customers would not be able to receive the service parts in time. Eliminating some candidate distribution center locations would imply a sub-optimal result. Based on this reasoning, the items are regarded as the best option to rescale the problem by creating item groups.

The items can be aggregated into groups considering their weights and volumes. If two items are similar in terms of these two features, there is no difference of shipping one or another in terms of costs. Indeed, the logistics service providers specify a "pay weight" per item which is calculated with the formula MAX(weights, 200*volumes) and charge accordingly. In other words, items with similar weights and volumes can be considered as identical shipments in terms of costs.

Based on the experiments for the computation time with respect to number of item groups as presented in Appendix 5, it has been decided that the items should be divided into 3 groups based on their pay weight. Otherwise, no results could be obtained because the computer runs out of memory or the computation time is considerably long, which is in this case more than 6 hours. The pay weight range and number of items in each group is presented in Table 4 below.

Table 4. Item groups

Item group	**Pay weight**	**Number of items**
1	[redacted]	167
2	[redacted]	167
3	[redacted]	166

As seen in the table, the pay weight ranges per item group are large. The median value of the pay weight range of each item group is considered as the common pay weight of all the items in that group. This way, a single too low or a too high pay weight do not have a major effect like in the average/mean value calculation.

Due to grouping of items, information is lost about the exact pay weight of the items. Because of this, error in transport cost calculations (which is discussed in Chapter 3.6.6 in detail) is indispensable. However, this error remains less than 3% of total transport costs. Given the computational boundaries, to be able to obtain results from the model result, 3% error in costs is regarded acceptable.

Besides the error in transport cost calculations, there are inaccuracies regarding the flow of items as a consequence of the aggregation. In the customer - DC pairing matrix, the pairs are based on three item groups. In reality, items within these groups could be flowing to customers from different DCs to minimize the costs without this aggregation. In a bigger scale, there is even a possibility that the selected DC locations is different when the demand is not aggregated in item groups.

Errors in transportation cost calculations, customer – DC pairing matrix per item are the major limitations that comes along with aggregation of the customer demand. Reflecting on these limitations, it can be argued that the possibility of having drastic differences in the network design with and without customer demand aggregation is low because in general, forecasts about the customer demand per item are usually poor. Aggregating the customer demand decreases the inaccuracies due to forecasting and reduces the variances in demand. As a result, acknowledging the limitations, demand aggregation is still found useful in rescaling the large network problem and in reducing the potential inaccuracies due to forecasting.

3.6.2. Customer Locations

There are more than XX installed GE medical devices in hospitals and clinics in Europe, which are referred as customer locations. In each customer location, there can be more than one installed device. The town names of the customer locations were available in the company database. Firstly, the customers who have ordered at least one service part during 2016 have been identified, which were scattered in approximately XX towns in total. Secondly, using the ggmap package (by David Kahle, Hadley Wickham) in R, the town names of these customers were transformed into geographical coordinates i.e. latitudes and longitudes.

Based on the geographical coordinates, customer locations were also divided into groups, following the data aggregation guidelines of Bramer & Simchi-Levi (1997). The borders between countries were respected since logistics service providers organize shipping lanes domestically and domestic and trans-border shipments have different shipment costs. This implies that customers from different countries should not be in the same group. While determining the size of the customer groups, the distances based on geographical coordinates were considered and each country was divided into squares with a maximum size of 150 km in latitude and longitude. This 150 km distance is determined thinking that the time to reach the customers from a border to another border within the customer group should take less than 3 hours considering the 15 hours' time window for the next day 9 am deliveries and an average speed of 50 km/h. As a result, countries are divided into 197 groups in total and 166 of these groups contain at least one customer. The customer groups per country are shown in Figure 19 below. Estonia, Latvia, Lithuania, Belarus, Ukraine, and Moldova are excluded because the demand rate of these countries in 2016 were very low and for the sake of simplicity, they were neglected.

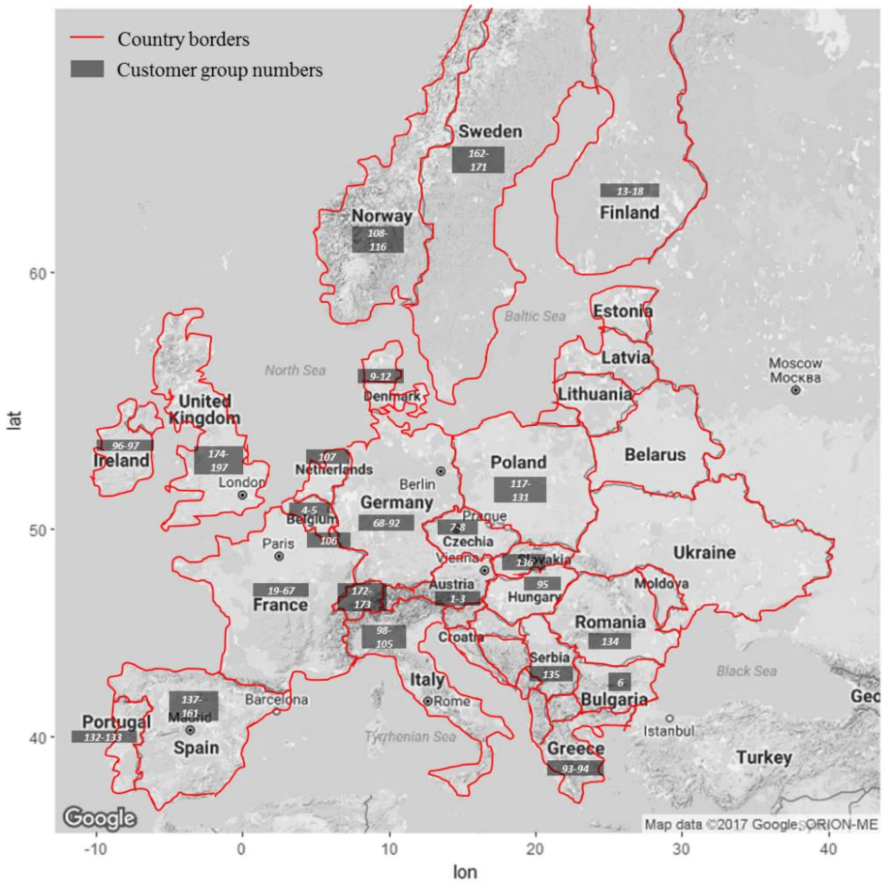


Figure 10. Customer groups per country in Europe

3.6.3. Location of Distribution Centers

A list of candidate locations was prepared from which the model will choose where to locate the distribution centers. The (candidate) regional distribution center locations were determined based on the hubs of the logistics service providers. However, only the hubs that were located close to an airport were considered as a candidate location based on the assumption that the transport network nearby the airports is good, not only for road but also for air transport. In total, 70 hubs were selected as candidate.

There are two types of regional distribution centers, which differ in terms of their capacity. The small one is called PuDo (Pick up Drop off) and it is conceptually the small scale of a regular warehouse with lower warehousing costs. The candidate locations for a regular warehouse or a PuDo are the same.

3.6.4. Demand Fulfilment

A customer orders can be fulfilled with a shipment either from a regional distribution center or the central distribution center. The model makes the decision about assignment of customers to the distribution centers based on cost minimization objective and in time delivery constraint.

If the duration between the customer and initially assigned distribution center, considering the minimum transport cost, is longer than the maximum acceptable ship to delivery travel duration, it is very likely that shipment will be delayed. In this case, the customer should receive the order from another facility with a shorter delivery duration. Overall, the demand fulfillment contains a trade-off between minimization of transport costs and achieving in time deliveries.

For the problem at hand, the maximum acceptable ship-to-delivery duration 15 hours for the next day 9.00 am deliveries. Assuming that the shipment departs from the distribution center to customer at 18.00 pm, the logistics service providers are able to deliver it in time within 15 hours. The transport mode can be air or road from a distribution center to the customer, depending on the distance in between. If there is a distribution center which is 500 km far at maximum to a customer, road transportation is chosen because it is less costly and delivery in time is possible. Otherwise the shipment is sent from the central distribution center via air transportation. The distance between the distribution centers and customers were calculated with Haversine formula in Excel. These distances are then multiplied with a road factor (also known as circuitry factor), which is assumed to be 1.3 for all countries (Bramer & Simchi-Levi, 1997).

3.6.5. Capacities of Distribution Centers

Since the model will decide where to open a distribution center (DC) and whether it will be a PuDo or an RDC, specifying the capacities of all three types of DCs is crucial. In this problem, the capacity of a DC is determined in terms of the number of deliveries that it can handle. In fact, General Electric Healthcare is charged for the warehouses of logistics service providers based on a contracted volume, i.e. number of items that are shipped from specific warehouses.

3.6.6. Costs

The mathematical model incorporates three different costs: unit shipment costs, fixed yearly rental cost of distribution centers, and penalty cost of late deliveries and the objective is minimizing the summation of these costs.

3.6.6.1. Unit shipment costs

The unit shipment costs are calculated with respect to the mode of transportation, weight and volume of the shipment. Also, it is important to consider for road transportation whether it is domestic or international shipment, since the international charges are higher.

Although the domestic road transportation shipment rates can slightly vary per country, it is assumed the same for all countries because the only available paired pay weight-shipment cost data was available for Poland. For the international road transportation, the unit shipment costs are roughly five times higher than the domestic road transportation.

The distance between the distribution center and customer does not affect the shipment although in road transportation, one can expect that the shorter distances cost less than longer distances. However, looking at the available data, this relation has not been recognized. On the contrary, sometimes the shipment costs are less for a longer distance compared to its shorter distance counterpart. This can be explained with the shipping lane and whether it is a frequent route. In frequent routes, for example between two big cities, it is cheaper to deliver to longer distances. However, because the calculation method is not shared by the third-party logistics, the shipment rates are assumed static for different distances.

The deliveries from the central distribution center is sent via air transportation if the customer location is further than 500 km, which implies that a road delivery will not be in time for next day 9 am. Again, from the performance reports of the logistics service providers, the relation between pay weight and shipment costs has been identified. It has been realized that the unit shipment rates vary per destination and this can be depending on the frequency of air cargo deliveries to the destination. If the shipping lane is a frequent route, then the charges are lower.

Unfortunately, not all countries that are within the scope of this study are presented in the figure since there is no available data at hand. Based on what is available, it is concluded that the countries can be grouped into two, based on the unit shipment costs: low cost, high cost. The countries that are not present in the figure are assumed to belong one of these two groups, based on the geographical proximity to the countries with available data.

3.6.6.2. Fixed yearly rental cost of distribution centers

Instead of company-owned warehouses, GE Healthcare rents warehouses from logistics service providers and pays a fixed cost depending on the capacity that will be used in the facility. Later, if more capacity is used than it is agreed upon, the company is charged extra. The rental costs information for the distribution centers is collected from the pricing and billing reports and presented in Table 8 below.

Table 5. Yearly rental cost of distribution centers

Distribution center type	Rental cost (Yearly)
Central	€5,520,000
Regional	€480,000
PuDo	€84,000

3.6.6.3. Penalty cost for the late deliveries

If a customer is not delivered a service part within the maximum acceptable ship-to-delivery duration, which is 15 hours for the next day 9.00 am deliveries, then the delay is recorded by the model with the decision variable u_{jk}^{+}. With the term $\sum_{\mathrm{j=1}}^{\mathrm{m+1}}\sum_{\mathrm{k=1}}^{\mathrm{K}} u_{jk}^{+} M$, there is a penalty cost added per hour to the objective function where M is a very big number, say 999999. Because the objective function aims to minimize the costs and the penalty costs is very high in this case, the model can choose to open a number of distribution centers to avoid late deliveries for some certain customers.

3.7. Validation

The validation is performed for the mathematical model and the data used in this model. To represent the distribution network in a mathematical model, certain assumptions has been made in the model itself and in the data. Validation of the mathematical model is performed to ensure that assumptions are reasonable, it is the right model to serve to the purpose of this study, and the model results are applicable to the system. Regarding the assumptions in the model in Chapter 3.4, they have been discussed with the General Electric Healthcare XX team and the academic supervisor and found reasonable. The validity of the data is checked to ensure that the data at hand for the empirical study about General Electric medical devices service parts distribution network is adequate and correct. For this aim, the data were directly retrieved from the company databases and if possible, cross-checked with the reports that have been prepared by the team or the third-party logistics providers. In case of data unavailability, assumptions have been made (which are discussed in detail in Chapter 3.6) and they have been checked with the supervisors. As a conclusion of this verbal validation, the mathematical model and the data that is used in the modelling were found adequate to fulfil the aim of this study. A post-validation is later performed to check if the results of the mathematical model are applicable to the system. The post-validation is discussed below in Chapter 4.2.

4 Results

This chapter is structured in three parts. Firstly, the results of the empirical study are presented based on the current demand data. The results are based on the mathematical model run in IBM CPLEX and answers the strategic distribution network design questions about the (1) number of distribution centers to open, (2) location of distribution centers, (3) size of the distribution centers, (4) which customers to deliver from each distribution center.

In the second part of this chapter, post-validation of the mathematical model is performed. To be able to do this, the problem is formulated with a different objective function and the results have been compared with the initial mathematical model run results, which is explained in the first part of this chapter.

Since the model run results are based on the current demand data and these design decisions are in effect in the long run, possible future changes should be taken into account. In this regard, possible changes in the demand and in the costs have been studied in the third and the last part of this chapter, sensitivity analysis. More specifically, the changes in the parameters of (1) demand, (2) unit cost of shipment, and (3) fixed yearly rental costs have been investigated. The changes in demand are based on the past demand data collected from the company database. It has been observed that there is a demand increase trend in some countries. This increase has been reflected and the outcomes are discussed thoroughly. Considering the costs, both increase and decrease possibilities are taken into account. Because there was no available past data about these, the changes are only studied in +/- 5% and 10% margins to gain an initial understanding about possible effects on the network design.

4.1. Mathematical Model Run Results

The duration of the mathematical model run was 1 hour 10 minutes in a computer with Intel® Core (TM) i5-6500 processor, 3.20 GHz CPU, 8 GB RAM and 64-bit operating system, which is an acceptable solution time for such a big distribution network, consisting of 166 customer locations, 70 candidate distribution network locations and 3 item groups.

The objective function value equals to the total costs of service parts logistics activities, which consists of shipment costs and fixed facility rental costs for the distribution centers. Approximately XX of total costs is spent for the rental of the distribution centers and the rest is paid for the outbound transportation costs for next day 9 am deliveries. According to the financial documents of the XX department, XX of the total spending is for renting while XX of the total spending is for inbound and outbound transportation. Because this study excludes the inbound logistics, the percentages differ but it is a reasonable that the percentage of transportation costs is lower when inbound logistics are excluded so the model run results are logical.

There is no delay in any of the customer deliveries, hence there is no penalty cost included in this objective function. This implies that with the distribution network design suggested, theoretically the entire customer demand can be fulfilled 100% in time.

Answering the question (1), the model run suggests that there should be one CDC and five RDCs in this distribution network. Responding to the question (2), the CDC is in Paris (France) while the RDCs are in Manchester (United Kingdom), Berlin (Germany), Stuttgart (Germany), Liege (Belgium), and Rome (Italy). The selected locations are shown in Figure 25 below.

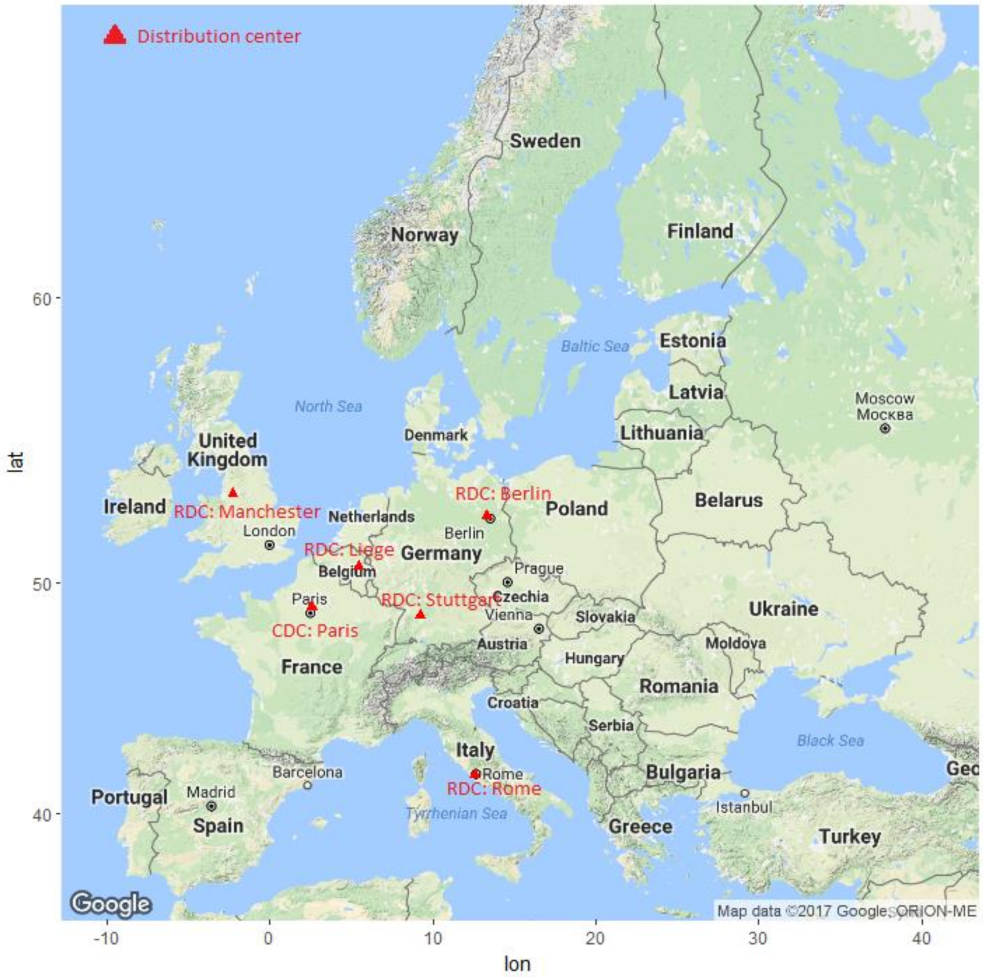


Figure 11. Selected distribution centers

Regarding the question (3), the model results do not suggest to locate a PuDo. This result is particularly interesting because it shows that there is no region where customers with frequent orders are located and not reachable from the CDC or one of the RDCs for in time deliveries. This result is contradictory with the current distribution network of the company as there are XX PuDo's in total to ensure in time delivery. However, because the new distribution network design suggest relocating all of the current regional distribution centers, it is reasonable that there is no need for PuDo's anymore.

Lastly, the allocation of the customers to the distribution centers (question 4) is visualized in Figure 26 below. Customers are delivered either from the CDC or from one of the RDCs. Some of the customers receive all the service parts from the same distribution center while there are also cases in which the customer is delivered from different distribution centers. It is due to the capacity limit of the distribution centers. In fact, the capacity of the RDCs in Manchester (United Kingdom), Berlin (Germany), Stuttgart (Germany), and Rome (Italy) are fully used. The capacity use of the CDC in Paris (France) is approximately 99% and the capacity use of the RDC in Liege (Belgium) is approximately 80%.

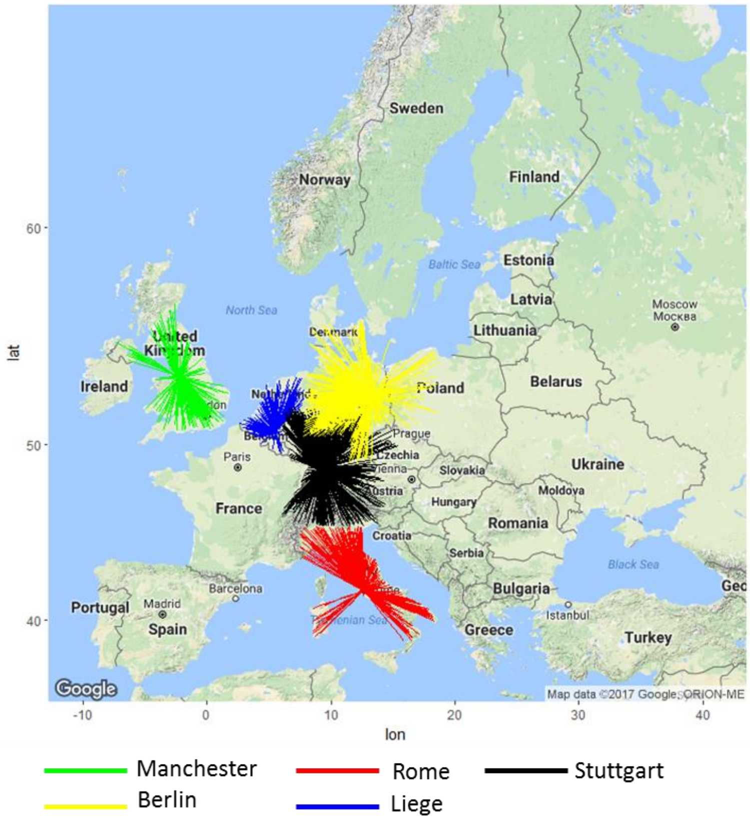


Figure 12. Allocation of the customer demand to the selected RDCs

As seen in this figure, the RDC in Manchester (United Kingdom) meet the demand in the United Kingdom and in the northern part of Ireland. Similarly, the RDC in Italy covers the demand in Rome (Italy). In general, it can be concluded that these two RDCs majorly meet the domestic demand.

However, the RDCs in Berlin (Germany), Stuttgart (Germany) and in Liege (Belgium) are slightly different. Besides meeting the domestic demand, the RDC in Berlin satisfies the demand in Denmark and Poland partially. Likewise, from the RDC in Stuttgart (Germany), service parts are shipped to the customers not only around Stuttgart but also to Austria, Czech Republic, France, and Switzerland. The customers in the Netherlands, Belgium and Luxemburg receive the shipments from Liege (Belgium).

Interestingly, even though there are two RDCs in Germany, some customers there, who are close to the Belgium border receive their shipments from Liege, so cross border shipment is possible and preferred in some certain locations. The reason for this is achieving in time delivery by choosing a distribution center with a shorter travel time. Another interesting result is that there is no RDC opened in Spain although it is the fifth country with the highest demand rate. This is due to the fact that opening an RDC in Spain and supplying customer with a mixture of road transportation (from the RDC in Spain) and air transportation (from the CDC in France) is more expensive than supplying all customers only via air transportation (from the CDC).

The shipments from the CDC in Paris (France) are shown in Figure 27 below. The customers (except the ones close to the German border) receive the service parts from this distribution center. Moreover, the customers in Spain, Portugal, Norway, Sweden, Finland, Slovakia, Hungary, Greece, Bulgaria, Romania, and Serbia receive service parts only from the CDC because there is no open RDC with available capacity that can serve in time. Because the shipments from the CDC are sent via air transportation to these locations, it reaches in time for next day 9 am deliveries.

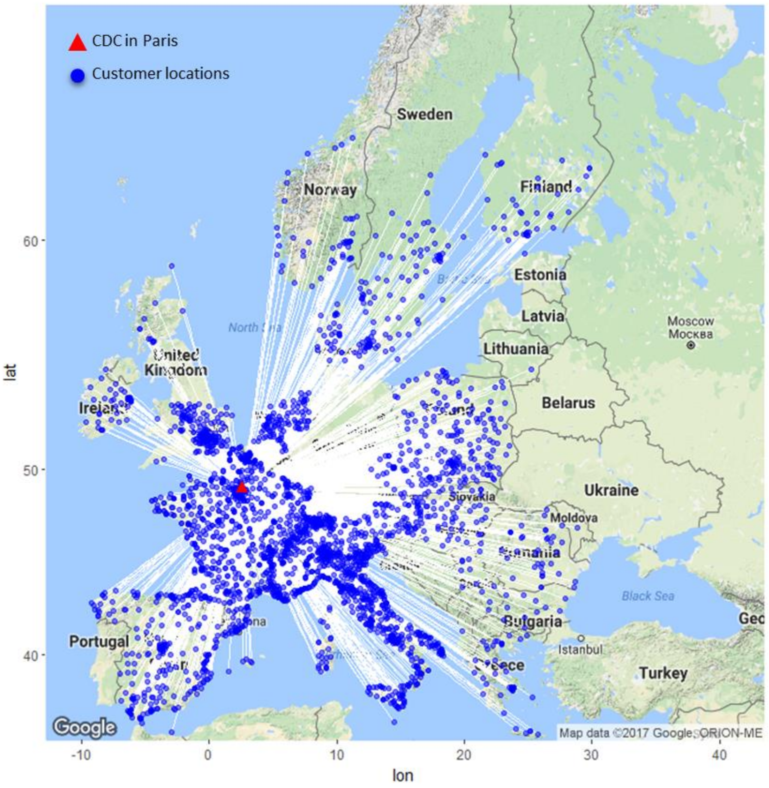


Figure 13. Customer demand allocated to the CDC in France

4.2. Post-validation of the Mathematical Model

The verbal validation of the mathematical model and the data used in this model in consultation with the company supervisors was explained in Chapter 3.7. This part of the validation was to check the assumptions are reasonable, if it is the right model to serve to the purpose of the study. In this post-validation part, the results of the model will be discussed in terms of whether they are applicable to the system.

4.2.1. Description of the post-validation

The post-validation is performed in two stages. The first stage is completed by verbally discussing the mathematical model run results with the company supervisor. More specifically, the number of DCs and the chosen location for the DCs found reasonable by comparing the model run results with the current distribution network. The number of the DCs remained the same while the chosen location for the DCs showed significant differences. But these differences could be justified by examining the geographical distribution of the customer demand, the demand volume, and allocation of the customers to the selected DCs. In the end, it is concluded that the model is valid and it is applicable to the system.

In the second stage of the post-validation, a mathematical model is formulated with a different objective function. The initial objective function was minimizing the costs while this time, it is minimizing the maximum shipment time. In other words, the objective function maximizes the customer service level. Both model run results are compared and this way, the model post-validation is performed quantitatively with another approach.

4.2.2. Post-validation model formulation

The post-validation mathematical model is formulated as a p-center problem or minimax problem. In the regular p-center problem, the objective is minimization of the maximum distance and is formulated by Owen & Daskin (1998) as follows:

Indices:

j	index for distribution centers	$j \in \{1, \dots, m+1\}$
k	index for customer locations	$k \in \{1, \dots, K\}$

Parameters:

a_{kj}	distance between demand node k and facility at site j
P	number of facilities to be located

Decision variables:

Y_j $\begin{cases} 1, \text{if distribution center is opened at site } j \\ 0, \text{otherwise} \end{cases}$ for $\forall j \in \{1, \dots, m+1\}$

Q_{kj} $\begin{cases} 1, \text{if demand in } k \text{ is satisfied by a facility at site } j \\ 0, \text{otherwise} \end{cases}$ for $\forall k \in \{1, \dots, K\}$, $\forall j \in \{1, \dots, m+1\}$

X maximum distance between a demand node and the nearest facility

Minimize X

Subject to

$$\sum_{j=1}^{m+1} Y_j = P \qquad (1)$$

$$\sum_{j=1}^{m+1} Q_{kj} = 1 \qquad \forall k \in \{1, \dots, K\} \qquad (2)$$

$$Q_{kj} - Y_j \leq 0 \qquad \forall k \in \{1, \dots, K\}, \forall j \in \{1, \dots, m+1\} \tag{3}$$

$$X \geq \sum_{j=1}^{m+1} a_{kj}\, Q_{kj} \qquad \forall k \in \{1, \dots, K\} \tag{4}$$

$$Y_j \in \{0,1\} \qquad \forall j \in \{1, \dots, m+1\} \tag{5}$$

$$Q_{kj} \in \{0,1\} \qquad \forall k \in \{1, \dots, K\}, \forall j \in \{1, \dots, m+1\} \tag{6}$$

In this p-center problem formulation by Owen & Daskin (1998), constraint (1) requires that exactly P distribution centers are located. Constraint (2) ensures that every demand is allocated to a distribution center. Constraint (3) states that customer demand can be allocated to the distribution centers only if they are open. Constraint (4) identifies the maximum distance between a demand node and distribution center. Constraint (5) and (6) are the binary requirements.

This p-center problem formulation is adapted to the problem at hand. First, instead of minimization of the maximum distance, the objective function is determined as the minimization of the maximum delivery time. This is because, in the problem at hand, distances and delivery time are not always correlated. If air transportation is used, the delivery time is shorter than a delivery from a distribution center with shorter distance via road transportation. The constraints are also adapted considering multiple items and capacity of the facilities.

Let X be the maximum travel duration from a distribution center to a customer. The adapted p-center problem formulation is as follows:

Indices:

i	index for service parts	$i \in \{1, \dots, I\}$
j	index for distribution centers	$j \in \{1, \dots, m+1\}$
k	index for customer locations	$k \in \{1, \dots, K\}$
t	index for type of distribution centers	$t \in \{1, \dots, s+1\}$

Parameters:

D_{ik}	amount of service parts i demanded by customer k (unit)
g_t	total number of deliveries that can be handled in a distribution type t (unit)
p_{jk}	mean travel duration between distribution center j and customer k (hour)
P	number of facilities to be located

Decision variables:

$$Y_{jt} \quad \begin{cases} 1, \text{if distribution center type } t \text{ is opened at site } j \\ \qquad\qquad 0, \text{otherwise} \end{cases} \qquad \text{for } \forall j \in \{1, \dots, m+1\}, \; \forall t \in \{1, \dots, s{+}1\}$$

d_{ijk}	amount of service parts i delivered from distribution center j to customer k
X	maximum travel duration from a distribution center to a customer

Minimize X

Subject to

$$\sum_{j=1}^{m+1} d_{ijk} = D_{ik} \qquad \forall i \in \{1, \dots, I\}, \forall k \in \{1, \dots, K\} \qquad (1)$$

$$\sum_{i=1}^{I} \sum_{k=1}^{K} d_{ijk} \leq \sum_{t=1}^{s+1} g_t Y_{jt} \qquad \forall j \in \{1, \dots, m+1\} \qquad (2)$$

$$\sum_{t=1}^{s+1} Y_{jt} \leq 1 \qquad \forall j \in \{1, \dots, m+1\} \qquad (3)$$

$$\sum_{j=1}^{m+1} \sum_{t=1}^{s+1} Y_{jt} = P \qquad (4)$$

$$X \geq p_{jk} Y_{jt} \qquad \forall j \in \{1, \dots, m+1\}, \forall k \in \{1, \dots, K\}, \forall t \{1, \dots, s+1\} \qquad (5)$$

$$Y_j \in \{0,1\} \qquad \forall j \in \{1, \dots, m+1\} \qquad (6)$$

$$d_{ijk} \geq 0 \qquad \forall i \in \{1, \dots, I\}, \forall j \in \{1, \dots, m+1\}, \forall k \in \{1, \dots, K\} \qquad (7)$$

Constraint (1) ensures that the entire demand is satisfied. Constraint (2) respects the capacities of the DCs. Constraint (3) states that in each candidate location, there can be only one type of DC. Constraint (4) specifies the total number of DCs that can be opened. Constraint (5) identifies the maximum distance between a demand node and DC. Constraint (6) and (7) are the binary requirements.

4.2.3. Post-validation model results

In this post-validation model, formulated as the p-center problem, the P equals to 6. There are two variants studied in this post-validation model: Firstly, it is assumed that the DCs are capacitated, as determined by constraint (2) in the mathematical formulation above in Chapter 4.2.2. In this case, three out of six DCs were opened in France due to the high demand rate in this country. However, the capacity limitation became a boundary to minimize the maximum shipment time, which was the objective of this formulation.

To solve this issue, in the second variant of this model, the capacity constraint for the DCs is eliminated. But this time, all the items are delivered to the customers from the DC in Paris. This is due to the fact that the shipments from Paris are sent via air transportation and all customers are reachable within 15 hours, which is the minimum maximum delivery time that can be obtained. Therefore, the capacity limiting constraint is kept for the DC in Paris and eliminated for the other DCs. The model is solved in these two variants and the results are presented in Table 10 in comparison with the original model results.

Table 6. Post-validation model results

	Original model	**P-center model (capacitated)**	**P-center model (uncapacitated*)**
Objective	Minimization of costs	Minimization of maximum shipment time	Minimization of maximum shipment time
Number of DCs	6	6	6
Location of the DCs	Paris (France) Berlin (Germany) Stuttgart (Germany) Manchester (UK) Rome (Italy) Liege (Belgium)	Rennes (France) Lyon (France) Paris (France) Leipzig (Germany) Derby (UK) Bologna (Italy)	Lyon (France) Paris (France) Nuremberg (Germany) Birmingham (UK) Bologna (Italy) Vitoria (Spain)

** All DCs are uncapacitated except Paris (France).*

Under the cost minimization objective, the selected DC locations in the original model run results were in France, Germany, UK, Italy and Belgium. The first four countries were chosen due to high density of customer locations while Liege (Belgium) was selected because of its convenient location to serve within Belgium and also in neighbouring countries. Moreover, serving Spain and other countries from the CDC in Paris was found more cost effective instead of opening an RDC.

As mentioned before, the capacitated p-center model selected three DC locations in France due to limited capacity of the DCs and high customer demand in this country. For this reason, the results are not good enough to compare and validate the model. But still this result is logical in the sense that DC locations in the four countries with the highest demand (France, Germany, Italy and UK) have been chosen to deliver in short times to as many customers as possible.

Under the minimization of maximum shipment time objective, the uncapacitated p-center model results indicate opening DCs in France, Germany, UK, Italy and Spain. Comparing this result with the original model result, apart the differences in selected cities, four out of five countries selected to open a DC are the same: France, Germany, UK, and Italy. The original model chooses Belgium and the uncapacitated p-center model chooses Spain as the fifth country. This implies that on one hand, if costs is prioritized, serving from Belgium is more efficient and this is because of its convenient location to reach the neighbouring countries. On the other hand, prioritizing the customer service level requires a DC in Spain and this is because of its fifth place in the highest customer demand ranking. Opening a DC in Spain potentially improves the service level by shortening the delivery time to customers in there.

To conclude, the original model and the p-center model give similar results and the major differences could be explained and justified in the discussions above. Eventually, it is concluded that the model is robust, the results prove to be applicable to the system, therefore the model is valid to be used in this study.

4.3. Sensitivity Analysis

In this study, demand and costs (unit shipment costs and yearly rental costs) are regarded deterministic but it is admitted that these are not absolutely certain. So it is important to measure their impact on the network design and this is done by conducting a sensitivity analysis. At the same time, it is important to note that within the scope of this study, the sensitivity analysis does not go beyond checking the robustness of the results. Since there is already prior knowledge about these two parameters, the sensitivity analysis does not aim at exploring the “Black Swan” (Walker, Lempert, & Kwakkel, 2013).

In fact, all parameters could be subject to sources of uncertainty but demand, unit shipment costs, and yearly rental costs are paid the most attention because they are influenced by external factors and the impact of these parameters can have significant effects on the distribution network structure. The uncertainty in the demand is due to the increasing installed base in customer locations. The data from company database show that there is a demand increase trend in some countries. Acknowledging this increase and checking its impact on the network design is of use to be prepared to meet the entire customer demand in the upcoming years. The uncertainty regarding the unit shipment costs can be due to increases and decreases in fuel costs or possibly improved domestic and trans-border logistics networks of the logistics service providers, which could lead to cheaper shipment costs. The yearly rental costs of the DCs can show variations due to changing labor costs and technological advancements in the warehouses. The uncertainty in these costs could influence the number and location of the DCs as well as the allocation of the customer demand to DCs.

The sensitivity analysis is performed on the original mathematical model, meaning that the demand increase and changes in the costs are not studied on the post-validation model. This is because the post-validation model gives similar results to the original model. Since post-validation model proves the robustness of this original model and similar results are expected, it is concluded that studying demand increase in post-validation model is not necessary.

4.3.1. Sensitivity Analysis for Demand

Firstly, the demand increase possibilities during the upcoming years have been explored so that the distribution network is capable of responding to the customer needs for longer years. To do so, aggregate demand data per year from 2013 to 2016 have been collected from the company database. As a result, there is a steady demand for service parts for the existing installed base.

However, deep-diving the demand data, it is possible to find out countries which can be considered as a growing market for GE Healthcare. In these counties, between the years 2013-2016, there is a rising demand for service parts because of the growing installed base. As seen in Figure 29, these countries are XX. The increase in these countries can be explained with increasing preference for GE products or improving healthcare system. It is of importance to study the impact of this increase on the distribution network design because it may imply a need for new distribution centers or a change of location.

The demand increase has been studied until the year 2030 and the demand increase is assumed to be a logarithmic trend line because in logarithmic line, there is an increase and after reaching to a certain point, it remains in the same level. This could be a good representation of the service parts demand. Due to growing installed base, the service parts demand per year will rise as well and once the installed base investments are completed, the total service parts demand will continue in a certain level.

Eventually, the mathematical model is run with the new demand data and the results show that the impact of the demand increase on the distribution network is relatively low. This can be explained with the fact that these countries only represent a small portion of the total demand and there is no need to open a new distribution center to satisfy this relatively small increase. Instead, the customers in these countries will continue receiving the service parts from the CDC.

There is not a remarkable increase in the total costs either. Because there is no new distribution center, the spending for renting the distribution centers will remain the same while transportation costs increase due to larger number of deliveries. This sensitivity analysis has shown that the mathematical model results are robust with respect to the demand increase.

4.3.2. Sensitivity Analysis for Costs

Secondly, the increase and decrease possibilities in unit shipment costs and fixed yearly rental costs of DCs during the upcoming years have been explored. There was no past data available that shows the increase or decrease trend in these costs. Therefore, firstly changes in small margins such as XX and XX were explored. However, no change in distribution network was observed. The number of DCs and their locations remained the same both in the case of increase and decrease. Later, XX change is examined but this also only increased or decreased the total costs, in the amount of the respective change. These analysis lead to the following conclusion.

The original model run results showed earlier that roughly XX of the total logistics costs belongs to yearly rental costs of the DCs while only XX is the transportation cost. Because there is such a big difference between these two percentages, there is no trade-off observed such as opening of new DCs against the increase in transportation costs. Even though unit shipment costs increase by XX, the transportation cost is still only XX of the total costs. In line with this argumentation, similar conclusion can be derived for changes in yearly rental costs as well. Even though these costs decrease by XX, it still represents roughly XX of the total costs. Therefore, XX cheaper rental costs do not lead to opening new DCs instead of transporting from the current ones. This sensitivity analysis has shown that the model results are robust with respect to possible changes in the costs.

5 Alternative Designs

In this distribution network design study, there were two critical choices made in advance: (1) delivering all the customers in time, i.e. 100% service level, (2) shipping to the customers not only from the RDCs but also from the CDCs. The first choice was made due to the fact that delivering the medical devices service parts has substantial importance in maintaining the healthcare service provided in medical centers. The second choice was because deliveries from the CDC in the current distribution network design is very common and useful in centralizing the inventory and enabling in time deliveries by air transport when there is no RDC reachable within the maximum acceptable order to delivery travel duration.

In scope of this study, evaluating alternative designs is essential since distribution network design consists of strategic decisions with long-term impacts. For instance, a contract with a logistics service provider to rent the facilities and to outsource transportation can last sometimes more than 10 years. In this horizon, challenging the current network structure choices could be beneficial to think of a network design that meets the business needs in the long term to a larger extend. This could be principally achieved by cutting redundant costs and providing even faster services to healthcare providers. Therefore, two major alternative designs have been studied.

In the first alternative design, late deliveries are allowed so that a cheaper distribution network design alternative is examined. In the second one, network structure is changed so that the customers are delivered only from the RDCs. This design alternative is of help to investigate the optimal distribution center locations in case domestic supply or neighbouring country shipments is preferred more than the shipments from the CDC. This could be due to two reasons: (1) it is cheaper to ship from the RDCs via road transport rather than air shipments from the CDC, and (2) serving from the RDCs increases the confidence to deliver in time, and from the service level perspective, it enhances the customer satisfaction in the long run by increasing the number of in time deliveries.

For the aim of investigating cheaper network designs, the original model with the cost minimization objective has been used. For the alternative designs in order to enhance the customer satisfaction, the post-validation model with the objective of minimizing maximum travel duration from a DC to a customer has been implemented. This way, an improved decision-making is allowed by presenting alternative outcomes with respect to these network designs.

These alternative designs are created by consulting the academic and company supervisors. The results are discussed and concluded based on the discussion with the supervisors.

5.1. Alternative Design 1: No penalty costs for late deliveries

In the original model, by using a very high penalty cost, late deliveries were avoided. This way, sufficient number of DCs were opened in the locations from which all customers could be delivered within the maximum acceptable order to delivery travel duration.

As the first alternative design, the penalty costs for late deliveries (M) is eliminated, which implies that it is no longer a must to deliver in time. In the current mathematical model, the travel duration of the deliveries is pre-specified based on the current speed of the express services of the third party logistics companies. By allowing late deliveries, it could be possible to discover a cheaper distribution network design. Later on, by acknowledging the late deliveries, the speed of the express services can be revised by requesting extra direct connections or it could be possible to change the departure to an earlier time.

In this model run, the objective function minimizes the facility rental costs and transportation costs so this optimization is purely from the costs perspective. The total costs slightly decrease and this is due to the decrease in the transportation costs as a result of a new allocation of customers to the distribution centers. However, because XX of the total costs belongs to the rental of the distribution centers, overall there is not a big difference in terms of costs.

While XX out of XX customer groups receive the service parts in time, XX groups face with delays.

5.2. Alternative Design 2: Delivery only from the regional distribution centers

In the original mathematical model, the service parts are sent either from one of the RDCs or the CDC. In this alternative design, the possibility of deliveries only from the RDCs have been examined. This alternative design is of help to investigate the optimal DC locations in case domestic supply or neighbouring country shipments is preferred more than the shipments from the CDC. Doing so potentially has two benefits: decreasing transportation costs and enhancing customer satisfaction.

Moreover, from the marketing and sales perspective, the customers prefer the products with locally stored service parts because they perceive it as a guarantee for less waiting time in case of malfunction. In countries with a large installed base, the customers have a convincing power for opening an RDC in the country, which implies that the distribution network design can sometimes become a multi-stakeholder issue and political decisions are made even though they lead to a sub-optimal design.

Running original model and post-validation model to minimize the costs and maximize customer service level respectively, the following results have been obtained.

5.2.1. Alternative design 2.1: Cost minimization

In alternative design 2.1, since there is no such a large capacity CDC anymore and the capacity of the RDCs is much lower, the results suggest XX RDC locations. Because XX are the countries with the highest demands, multiple DCs are opened in these countries to satisfy the entire demand in these countries. The initial original model results were not in favour of opening a DC in XX but in this design, RDCs in these countries are of use to delivery in time with minimum costs.

Overall there is a decrease in both rental costs and transportation costs, which may imply that from now on, the service parts deliveries should be managed without a CDC. However, from the operations perspective, managing XX DCs instead of XX DCs could be a major challenge in daily work flow, especially because of extra complexities in communication flow and inventory management.

Because of these undesirable complexities due to large number of DCs, in alternative design 2.1(b), the capacity of the DCs are increased from XX units to XX units, which is roughly the double. When the capacity is XX units, the yearly rental cost of the RDCs increase from XX to XX and this cost is approximated based on the billing information from the logistics service providers.

In design 2.1 (b), because the capacities of the RDCs are larger, eight distribution centers in total are sufficient to meet the entire demand. In fact, the total capacity of some of the RDCs is not fully utilized, which are namely XX. The reason why they are opened is ensuring in time delivery. The capacity of the RDCs in XX are fully utilized and this is due to the high demand in XX. Indeed, opening three RDCs in the same country is solely because of the high demand, as well.

The comparison of the original model and design 2.1(b) customer allocation to DCs shows that in design 2.1(b), international shipments are still happening such as from XX to XX, and so on and so forth. However, while the customers in XX are all supplied from XX in the original model, in design 2.1(b), because a DC is opened in XX can be supplied domestically. Following this, the optimal location of an RDC in XX is suggested to be XX. Also, the optimal location for XX seems to be XX.

Interestingly, although both the original model and design 2.1(b) suggest opening DCs in XX and XX, the cities are different. In XX, it is because the DCs capacity is too limited and the demand is high. So, next to XX, there are two more facilities in XX. In XX, the original model suggests XX while design 2.1(b) suggests XX. This has to do with the DC capacities as well. Because the capacity in design 2.1(b) for RDCs is much larger, the optimal number of DCs in Germany is decreased to one and the location became the middle of the formerly suggested locations. This implies if the decision maker only has a limited DC capacity due to some external reasons, then two facilities are needed in XX. However, if the decision maker opts for a single facility, its location should be neither of the former ones, but the middle of them, XX.

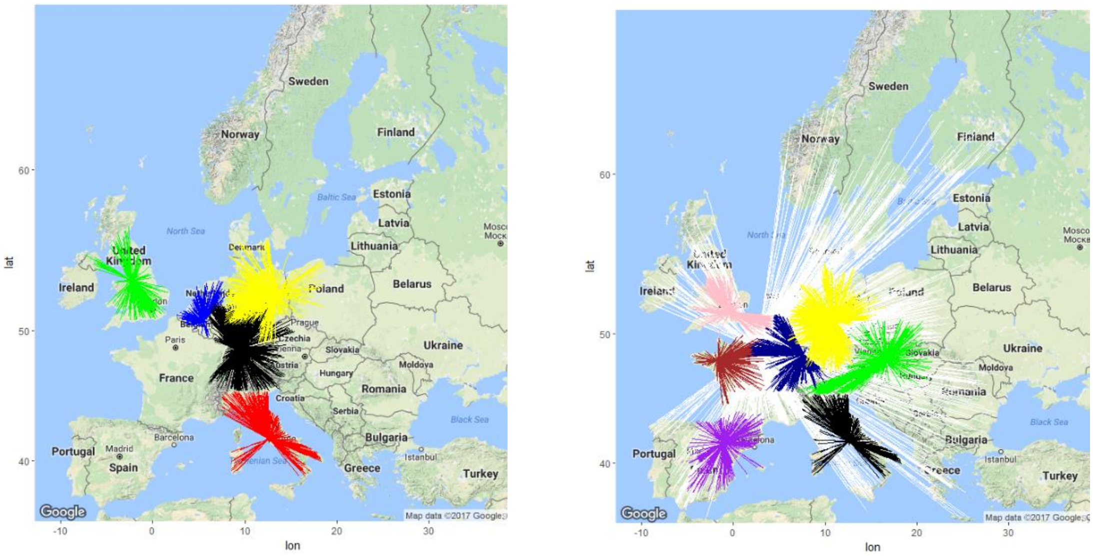


Figure 14. Demand allocation to DCs in the original model and alternative design 2.1(b)

5.2.2. Alternative design 2.2: Service level maximization

In this alternative design, the post-validation model with the objective of service level maximization is applied. This post-validation model is formulated as a p-center problem, where *P* is the total number of DCs and it is pre-specified. This way, different delivery duration options with respect to different number and set of open RDCs have been explored in detail.

In this model run, the capacity of all of the RDCs is specified as XX units, as in design 2.1 (b). The *P* value is determined based on the previous runs. More specifically, the original model and post-validation model run suggested XX DCs to be opened. In design 2.1 (b), with XX RDC capacity and without any CDC, the model suggested XX DCs. Considering these, the capacitated p-center problem is solved three times with *P*=8, *P*=7 and *P*=6.

In this design, the total costs decrease as number of DCs (*P*) gets smaller because the total costs are highly influenced by rental costs and less rent is paid when less DCs are opened. Looking only at the transportation costs, it is observed that the lowest costs is when *P*=6 and this is because the customer service level is at its lowest with XX in time delivery performance. From this result, the trade-off between low costs and high service level can be seen clearly. To achieve in time delivery, the costs are high and the costs only decrease when the service level is sacrificed.

In both design 2.1(b) and design 2.2 *P*=8, the capacity of the XX DCs are the same. In design 2.1(b) the objective was cost minimization while in design 2.2 *P*=8, the objective is service level maximization. In design 2.1(b), due to its objective function, the total transportation costs are less, as expected. The selected candidate locations for the DCs are different as well. In XX, according to design 2.1(b), the RDC is located in XX while according to service level maximizing design 2.2 *P*=8, it is situated in XX. Likewise XX, the RDC locations vary in XX as well depending on the objective function.

Alternative design 2.2(b) is devoted to the uncapacitated p-center problem to figure out the optimal RDC locations when DC capacity is not a constraint. Following this idea, firstly the capacity constraint is eliminated for all the candidate DCs but in this case all the items are delivered to the customers from the DC in XX. This is due to the fact that the shipments from XX are sent via air transportation and all customers are reachable within 15 hours, which is the minimum maximum delivery time that can be obtained.

In practice, sending all items from XX has several pitfalls. The confidence of delivery in time is lower since the shipment flexibility is less than road transportation in terms of number and time of departures and there can be serious transportation capacity problems. Besides, air transportation for all shipments is quite costly. Because of these reasons, in this design 2.2(b), the capacity of the DC in Paris is kept XX units per year while all other DC capacity constraints are eliminated. Similar to design 2.2 and with the same reasoning, the problem is solved for three instances, which are namely P=8, P=7 and P=6.

To calculate the rental costs of the uncapacitated DCs, number of items that are delivered from each facility has been checked.

In cases when P=8 and P=7, in time delivery can be achieved so from the service level perspective, their performances are equal. From the cost perspective, design 2.2(b) P=7 has less total cost. Hence, the set of DC locations in design 2.2(b) P=7 is preferable both in terms of costs and service level.

In design 2.2(b), P =6 although the number of DCs is the smallest, the rental costs are higher than in the case P=7 due to pricing depending on the capacity, as shown in Table 17. Total costs in design 2.2(b), P=7 is lower than design 2.2(b), P=6, which was initially unexpected. Comparing all the instances of design 2.2(b) among each other, the set of DCs in design 2.2(b), P=7 seems to provide both the lowest cost and highest service level.

5.3. Discussion of Alternative Designs

Throughout this chapter, nine distribution network configurations under two main alternative designs were investigated, which are summarized in Table 19 below. This table provides an overview of the features of all alternatives and could be used as a guide to follow the discussions in this and conclusion chapters.

Alternative design 1 explained the outcomes when late deliveries are allowed. Although the total number of DCs remained the same, their locations have changed. Following this, transportation costs decreased because of using less air transportation and more road transportation. But after all these changes, the service level decreased significantly to XX.

In alternative design 2, the CDC was eliminated and the distribution network design was investigated when there are only RDCs. In design 2.1, the RDC capacities remained the same (XX units delivery per year) and because of this, the model suggested opening of XX facilities, which could possibly cause operational complexities. Therefore, in design 2.1(b), the RDC capacities were increased (XX items delivery per year) and as a result, eight DCs were opened. Compared to the original model, the total costs in design 2.1 and design 2.1(b) were lower and in time delivery could be achieved.

Comparing design 2.1 and design 2.1(b), the transportation costs in design 2.1 was lower since with larger number of RDCs, distance between RDCs and customers were lower on average, which decreased the use of air transportation and international road shipments, thus the shipment fees. However, due to economies of scale, increasing the capacity of a DC was cheaper than opening a new facility. This was the reason why the rental costs were lower in design 2.1(b) than in design 2.1, despite the fact that the total number of deliveries in both design alternatives were the same.

In alternative design 2.2, the objective was changed into service level maximization by minimizing the maximum delivery time. The p-center problem formulation in post-validation model, with *P* values of 6, 7, 8 was used. In design 2.2, the capacity of the RDCs were XX items delivery per day, which was the same as in design 2.1(b) and there was no CDC with a massive capacity. In time delivery could be achieved only when *P*=8 and in this design, the total costs were higher than in design 2.1(b). This is because of the different objective functions. When service level is prioritized, the distribution is costlier.

In design 2.2(b), the RDCs were uncapacitated except the RDC in XX. When *P*=8 or *P*=7, in time delivery could be achieved and *P*=7 managed this with less total costs. The rental costs of the uncapacitated DCs were calculated based on the number of deliveries per DC in the model results, which was a more flexible pricing scheme than the previous design alternatives. This is the reason why the rental costs in design 2.2(b) *P*=8 was lower than in design 2.2 *P*=8. In design 2.2 *P*=8, no matter how much a DC is utilized a fixed rent was charged while in design 2.2(b) *P*=8, there were three price categories.

Table 7. Summary of the alternative network design results

	Design features				**Model run results**				
	Objective function	**Penalty cost for late deliveries**	**Network structure: CDC?**	**RDC capacities**	**Rental costs**	**Transportation costs**	**Total costs**	**In time delivery**	**Total number of DCs**
Original model	Cost minimization	Yes	Yes						
Alternative design 1	Cost minimization	No	Yes						
Alternative design 2.1	Cost minimization	Yes	No						
Alternative design 2.1(b)	Cost minimization	Yes	No						
Alternative design 2.2, *P*=8	Service level maximization	No	No						
Alternative design 2.2, *P*=7	Service level maximization	No	No						
Alternative design 2.2, *P*=6	Service level maximization	No	No						
Alternative design 2.2(b) , *P*=8	Service level maximization	No	No						
Alternative design 2.2(b) , *P*=7	Service level maximization	No	No						
Alternative design 2.2(b) , *P*=6	Service level maximization	No	No						

Until now the alternative designs were discussed on the basis of cost and in time delivery, in line with the literature in this field. Discussing these results with the practitioners in the XX team at GEHC, other factors underlying in the service parts distribution network design choices in terms of number, capacity and location of the facilities as well as the structure of the network have been recognized.

Considering the structure of the network, the decision of delivering either from the CDC and RDCs or only from the RDCs is critical. As the alternative design results suggest, it can be less costly if the deliveries are only sent from the RDCs since the air transportation from the CDC is very costly. Also, the RDCs increase the confidence of in time delivery since road transportation is more flexible in terms of frequency and time of departure. However, there is a global target for keeping the XX of the service parts inventory in the CDC and XX in the RDCs. This target is of use to centralize the control over the inventory for the entire Europe in a single location. Furthermore, it is argued that the shipping lanes from the CDC are better in terms of frequency and speed, compared to the shipping lanes between the RDCs and this is a major advantage to deliver in time, in case a requested service part is out of stock in the closest RDC to the customer.

Another important factor is domestic supply. Having a domestic DC in a country increases the competitiveness of the company to sell the medical devices and service maintenance agreements to the healthcare providers. These customers recognize domestic supply of service parts as crucial since they perceive it as a guarantee to have less waiting time in case of malfunction. In countries with a large installed base, opening a DC can be a strategic decision to maintain the installed base. In this empirical study, as France, Germany, Italy, UK and Spain have the largest installed base, opening at least one DC per country could be crucial. In light of this, while determining the facility locations, even if a set of DCs is not the optimal design in terms of time and cost, it can be still preferred.

Last but not least, the level of operational complexity affects the distribution network design choices and it could be identified based on the total number of DCs in the network. For instance, alternative design 2.1 suggested XX DCs to be opened so that the service parts can be delivered from the domestic DCs in the maximum level. However, this introduces complexities in terms of communication flow and inventory management, which could increase the costs significantly or risk in time deliveries. Therefore, total number of DCs is recognized as a factor in designing the distribution network.

Eventually, to be able to assess the performance of the alternative designs and to decide on the optimal distribution network design, five factors are determined and these are: (1) total costs, (2) in time delivery, (3) network structure, (4) operational complexity, (5) domestic supply. Considering all these factors, the decision maker is guided in the design of the distribution network choices with the score table in Table 21 below. The green colour implies a desirable outcome, while yellow and red stand for moderate and undesirable, respectively.

Table 8. Score table summarizing the alternative designs and five factors

	Total costs	**In time delivery**	**Operational complexity (Number of DCs)**	**Domestic supply (DC in top 5 countries)**	**Network structure (Is there a CDC?)**
Original model	[redacted]	[redacted]	[redacted]	No	Yes
Alternative design 1	[redacted]	[redacted]	[redacted]	Yes	Yes
Alternative design 2.1	[redacted]	[redacted]	[redacted]	Yes	No
Alternative design 2.1(b)	[redacted]	[redacted]	[redacted]	Yes	No
Alternative design 2.2, *P*=8	[redacted]	[redacted]	[redacted]	Yes	No
Alternative design 2.2, *P*=7	[redacted]	[redacted]	[redacted]	No	No
Alternative design 2.2, *P*=6	[redacted]	[redacted]	[redacted]	No	No
Alternative design 2.2(b), *P*=8	[redacted]	[redacted]	[redacted]	Yes	No
Alternative design 2.2(b), *P*=7	[redacted]	[redacted]	[redacted]	No	No
Alternative design 2.2(b), *P*=6	[redacted]	[redacted]	[redacted]	Yes	No

Looking at this score table, each design has its own advantages and disadvantages considering the five factors. If all these five factors are taken equally important, there is no single best design. However, the weights of the five factors can vary specific to the empirical study and as a result, depending on these weights an optimal distribution network design could be chosen.

Because this study is focused on medical devices service parts delivery next day 9 am, the emergency level is high, as explained in Chapter 3. Therefore, in time delivery has a higher weight than cost. Revenue gain from the maintenance service agreements are considered significant for companies and customer satisfaction is the key to maintain this revenue. Following this insight, in time delivery as well as domestic supply factors should receive higher weights. Comparing costs and operational complexity factors, a more complex distribution network could be still manageable when there is a major cost saving. Comparing network structure with other factors within the scope of this study is rather tricky because the trade-offs between a single and a multi-echelon network are usually related to the inventory management, which is out of scope of this study. Nevertheless, because this factor still affects the optimal distribution network design, the recommendations will be presented for both choosing to combine CDC and RDCs and only RDCs in the conclusion chapter.

6 Conclusion

The objective of this study was to explore how a medical devices service parts distribution network can be designed. This chapter aims to answer the research questions formulated in the beginning of this study. The practical and scientific contribution are demonstrated as well, which are followed by the discussion of limitations of this study and future research.

Question 1. What are the decisions involved in designing a distribution network?

This question was answered based on the literature review. Based on 16 scientific articles, a comprehensive list of decisions was prepared. The decisions in this list are: (1) location of distribution facilities, (2) number of distribution facilities, (3) throughput and storage capacity, (4) routing, (5) transport modes, (6) number of layers/echelons, (7) inventory stocking policy, (8) demand allocation to warehouses, and (9) production allocation to manufacturing facilities.

According to the literature, these decisions can be categorized in three levels, which are namely strategic, tactical, and operational. This categorization is based on the time frame that a decision is effective. Typically, strategic decisions require large amount of investments and implementation time so once these decisions are made, it will take several years until a change is made. Hence, the time frame that a strategic decision is effective is very long. The tactical decisions can change more frequently than the strategic decisions. The operational decisions are typically made on a daily basis so they require the least amount of resources. Among these 9 decisions, (1), (2), (3), (6) are considered strategic level decisions. (7), (8) and (9) are the tactical and (4) and (5) are recognized as the operational decisions.

The literature study also showed that these decisions are interactive and their interaction is two-ways. By nature, strategic decisions affect operational and tactical decisions. But at the same time, operational and tactical decisions have an impact on strategic decisions as well. As an example, if a particular mode of transportation is preferred in the operational level based on available shipping lanes of the third-party distributor companies, then it has a significant impact on decisions regarding the location of warehouses. These interactions result as some trade-offs, such as between time and costs. Considering these trade-offs as well as the nature of the business, competition in the market, customer expectations, product value and product variety, the distribution network choices are made.

Question 2. What are the current state-of-the-art distribution network design mathematical modelling algorithms?

The answer to this question was obtained from the literature review as well. An overview of the most common modelling approaches and decisions in the literature about distribution network design have been obtained. More specifically, some of the classic algorithms are median problem, covering problem, p-center problem, uncapacitated fixed charge facility location problem, and single-source capacitated facility location problem. Besides these, (mixed) integer programming, Lagrangian heuristics, stochastic programming, (non)linear programming, multi-objective problems, and composite-variables are some other algorithms, that are generalized to address more decisions.

These algorithms can be divided into exact algorithms and heuristics. Exact algorithms guarantee to find optimal solutions in a finite time while heuristics algorithms do not guarantee optimality but find a solution in a reasonable run time. When the problem at hand is NP-hard, due to the computational power limitations, exact algorithms cannot find a solution in a reasonable time and in this case, heuristics is of use to at least obtain a result.

The researchers, who conducted these studies, have chosen the appropriate algorithm based on the decisions that the problem at hand contains and the objective function. There is no single study that addresses all of the nine distribution network design decisions at once.

Four studies have been identified that particularly address service parts distribution network design. The design decisions have been made using integer programming, composite variables, and Lagrangian heuristics and in all of these studies, inventory stocking policy was a core decision. Putting this particular decision aside, a knowledge gap about using mixed integer programming to make strategic decisions regarding the design of the service parts distribution network was identified. Adapting an existing exact mixed integer programming algorithm to solve this problem was thought to be an important contribution to the existing literature.

Question 3. What are the alternative distribution network designs with regards to the decisions involved?

In line with the research objective and the scope of this study, four distribution network design decisions are addressed, which are namely (1) number of distribution centers, (2) location of distribution centers, (3) size of the distribution centers, (4) customer demand allocation to the distribution centers. Corresponding to these decisions, a mathematical model has been built and an optimal solution is found. Later, this mathematical model has been used to build two main alternative designs. These designs were discussed to facilitate informed decision-making process and by reflecting on major business needs in the long-term horizon.

In the first alternative design, late deliveries are allowed. By allowing late deliveries, it could be possible to discover a cheaper distribution network design. Later, by acknowledging the late deliveries, the speed of the express services can be revised by requesting extra direct connections or it could be possible to change the departure to an earlier time. As a result, the transportation costs could significantly decrease.

In the second alternative design, network structure is changed so that the customers are delivered only from the RDCs. This design alternative is of help to investigate the optimal distribution center locations in case domestic supply or neighbouring country shipments is preferred more than the shipments from the CDC. This could be due to two reasons: (1) it is cheaper to ship from the RDCs via road transport rather than air shipments from the CDC, and (2) serving from the RDCs increases the confidence to deliver in time, and from the service level perspective, it enhances the customer satisfaction in the long run by increasing the number of in time deliveries. In fact, two variants of this design alternative were analysed by adopting the cost minimization objective in the original model (alternative design 2.1) and the service maximization objective in the post-validation model (alternative design 2.2), respectively.

Design 2.1 and 2.2 were further investigated by alternating the DC capacities and number of DCs. In design 2.1, firstly the DC capacity remained the same but then, XX RDCs were needed to cover the entire customer demand. Because of potential operational complexity due to large number of DCs, the RDC capacity was increased to XX units from XX units in design 2.1(b), which is roughly the double capacity. In design 2.2, firstly the DC capacities were XX units and the variations in cost and in time delivery have been examined when the total number of RDCs (*P*) was 6, 7, and 8. In design 2.2(b), the RDCs were uncapacitated except the RDC in Paris. If the RDC in Paris was also uncapacitated, then all the service parts are delivered from there because all customers are delivered in time from there thanks to air transportation. However, this is not realistic in practice as explained in Chapter 5.3.2 and therefore it remained capacitated. Similar to design 2.2, the variations in cost, in time delivery have been examined when the total number of RDCs (*P*) was 6, 7, and 8 and the results are compared.

Question 4. Which of these distribution network design alternatives minimize the costs while meeting the customer service level requirements?

In this study, the customer service level requirement is regarded the next day 9 am delivery, which is also referred as in time delivery. If there are some customers, who are not delivered in time, then the customer service level requirements are not met. Considering this, alternative design 1, design 2.2 *P*=7, design 2.2 *P*=6, and design 2.2(b) *P*=6 do not meet the customer service level requirements. Regarding the cost, among the other alternative designs, the minimum total cost was obtained in design 2.2(b) *P*=7. The details related to comparison of the alternative designs can be found in Table 19 in Chapter 5.5.

Design 2.2(b) *P*=7 suggests that the service parts should be shipped only from RDCs. The total number of RDCs is XX and they are located in XX.

The allocation of customer demand to the RDCs is presented in Appendix 11. Interestingly, even though XX is one of the countries with highest demand, there is no RDC located there. These customers receive the service parts from XX, either from XX or XX. Another interesting fact about this result is that even though there is no capacity limitation expect the RDC in Paris, three out of seven RDCs are located in XX. This implies the in time delivery accessibility to the customers from XX is reasonably well. This has to do with the fact that XX has the highest customer demand and it is in a central location to serve the neighboring countries.

As this design suggests, to reach this low cost level compared to other alternative designs, it is a prerequisite to adopt a flexible pricing scheme in consultation with the logistics service providers for the RDCs' rents. For instance, this design suggests that the number of service parts delivered from XX is XX units so its rent is XX while from XX service parts are delivered. Because it falls to a lower capacity interval, its rent decreases to XX. The minimum capacity requirement for each RDC and the estimated rents are shown in Table 21 below.

From the billing data collected from the company, this flexible pricing scheme is possible in practice but because the capacity use estimates in the beginning are not the same with the actual use, the company is charged more for extra capacity use or certain DCs are underutilized despite their rent is paid for higher capacity use. In short, this flexible pricing scheme should be better benefited by making better-informed estimates as a result of this study.

Main Research Question: How can a medical devices service parts distribution network be designed to minimize the costs while meeting the customer service level requirements?

Question 4 asks the alternative design that minimize the costs while meeting the customer service level requirements and the design 2.2(b) P=7 was the answer to this question. But the main research question of this study was finding out the optimal design and in this sense, the optimality of the design 2.2(b) P=7 is questionable because time and customer service level are not the only factors affecting the distribution network design choices.

As discussed earlier in Chapter 5.5, while discussing the alternative design results with the practitioners in the XX team at GEHC, other factors underlying in the service parts distribution network design choices have been recognized. Eventually, to be able to assess the performance of all the alternatives and to decide on the optimal distribution network design, five factors were determined and these were: (1) total costs, (2) in time delivery, (3) network structure, (4) operational complexity, (5) domestic supply. Network structure implies the choice of delivering either from the CDC and RDCs or only from the RDCs. The operational complexity stands for the decision about the total number of DCs in the network, as managing more facilities mean more complexity. Domestic supply indicates the preference of service parts delivery from a domestic DC rather than an international shipment in the XX countries with the highest demand. Customers are likely to recognize domestic supply of service parts crucial since they perceive it as a guarantee to have less waiting time in case of malfunction.

It was also explained that the weight of these five factors are different. Although the weights were not quantitatively determined, a pairwise comparison gave an indication about their ranking from the most important to the least important. As a result of this pairwise comparison in the end of Chapter 5.5, in time delivery was recognized the most important factor, which was followed by domestic supply, costs, and operational complexity, respectively. Comparing network structure with other factors was found tricky because the trade-offs between a single and a multi-echelon network are usually related to the inventory management, which was out of scope of this study. Nevertheless, because this factor still affects the optimal distribution network design, the recommendations are presented for both choosing to combine CDC and RDCs and only RDCs.

The performance of all the alternative designs in terms of these five factors were summarized in the score table in Table 21 in Chapter 5.5. Prioritizing in time delivery and domestic supply, five alternative designs are eliminated and four alternative designs remained for further evaluation. These are (1) design 2.1, (2) design 2.1(b), (3) design 2.2, *P*=8 and (4) design 2.2(b), *P*=8. In terms of costs, the score table shows that all these four designs are in moderate level but the total costs of design 2.1(b), design 2.2 *P*=8, and design 2.2(b) *P*=8 are at least XX lower than the design 2.1. Because design 2.2 *P*=8 and design 2.2(b) *P*=8 have the same objective, network structure, operational complexity, they can be easily compared and as a result, design 2.2(b) *P*=8 is preferable since the total costs is roughly XX lower.

It is important to note that the objective function in design 2.1(b) was cost minimization and in design 2.2(b), *P*=8, it was minimization of the maximum delivery time. In both alternative designs, the optimal DC location in the XX is XX and in XX, it is XX. Because the shipments from XX can be sent via air transportation, in both designs the DC in XX serves to customers including but not limited to XX.

The optimal DC locations in XX could be decided based on whether a certain percentage of service parts will continue to be delivered to customers from a CDC as it is done in the current system. If yes, then XX seems to be the optimal location for a CDC and the shipments from XX can be all supplied from the CDC in XX. This way, rental costs and operational complexity will decrease. The transportation costs may increase since the road shipments from XX have the possibility to be delivered via air transportation to be in time.

In XX, the trade-offs between costs, service level and operational complexity is critical for the decision. On one hand, if the DCs will be situated in XX, service level is maximized. In fact, even earlier deliveries than next day 9 am could be managed. On the other hand, if there is a single DC in XX, costs and operational complexity are lower while in time delivery is still possible.

In XX, both of the DCs in XX are able to deliver in time. From the costs perspective, XX will be a better choice and from the service level perspective, XX will perform better since earlier than next day 9 am deliveries can be achieved.

Last but not least, design 2.1(b) suggests a DC in XX to serve some customers in X and in XX due to the capacity limitations of the DCs. In design 2.2(b), *P*=8 because all DCs are uncapacitated expect XX, these customers could be served from XX. Following this explanation, a DC in XX does not seem to be necessary as long as the capacity of other DCs are sufficient to satisfy the entire demand.

It is important to emphasize that design 2.1(b) minimizes the costs while design 2.2(b), *P*=8 maximizes the service level. Both alternative designs are able to deliver to all of the customers next day before 9 am but in design 2.2(b), *P*=8, the possibility to deliver earlier to the customers is maximized.

In both designs, there is no central distribution center. Incorporating the network structure factor, if deliveries from a central distribution center, having a massive capacity, is preferred as an outcome of inventory decisions, then XX seems to be the best location for it with the advantage of in time air deliveries to all customer locations. In this case, all the demands allocated to the RDCs in XX can be aggregated in XX. With the involvement of network structure factor, in total, four alternative distribution network designs can be derived from design 2.1(b) and design 2.2(b), P=8 as shown in the decision tree in Figure 35.

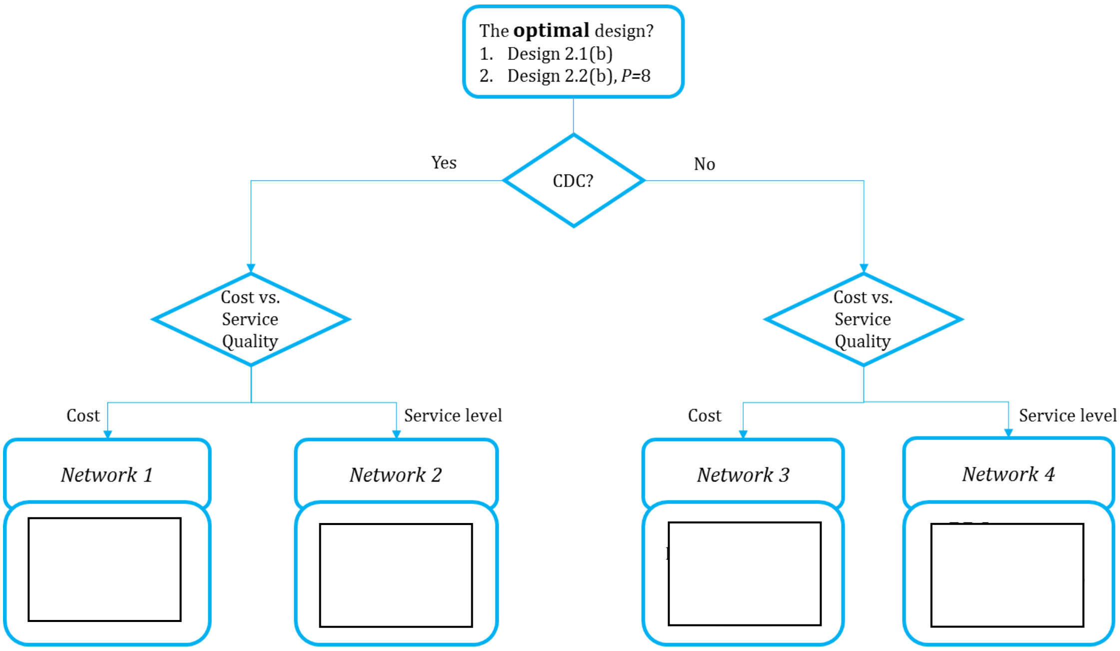


Figure 15. Decision tree to choose the optimal distribution network design

In this figure, choosing service level over cost implies that strategically, the company wants to strive for earlier deliveries than next day 9 am to some customers to further improve its competitiveness in the market.

If a CDC is desired, choosing network 1 instead of network 2 implies cost savings up to XX since there will be one less RDC. However, network 2 promises deliveries within 12-13 hours to the customers around the very east and very west parts of XX, around XX, and central part of XX. If it is of interest to improve the service quality in these locations, choosing network 2 would be a good choice.

In case there is no CDC, there are significant cost savings up to XX because a massive CDC costs much more than an RDC. Comparison between network 3 and network 4 shows that the transportation costs in network 4 are roughly XX higher. However, network 4 enhances the customer satisfaction by delivering to more customers within 12-13 hours in the very west and very east parts of XX, southern XX, central and southern XX, and central part of X. From the perspective of sales and marketing, choosing this network could give GE Healthcare an advantage and contribute in increasing revenues in these locations.

Based on the researcher's understanding of the industry, prioritizing service level over costs is more promising in the long term. Especially, considering the healthcare initiatives regarding extending the visiting hours of hospitals to 24/7 such as in Canada (Crawley, 2017), earlier deliveries than next day 9 am (i.e. faster than 15 hours) could become a common request from the customers in the near future. Considering this, the optimal distribution network design would be network 4. This alternative is chosen because it prioritizes service level and delivers only from the regional distribution center, which increases the confidence to deliver in time.

Scientific & Practical Contribution

As it was seen in the literature review, summarized in Table 2, service parts mathematical modelling is focused mostly on the inventory management aspect of the distribution network design but there are many more decisions involved, which are namely number of facilities, facility locations, allocation of customer demand, and storage capacities. Considering this set of decisions, the literature review has shown that Bramer & Simchi-Levi (1997) and Cohn & Barnhart (2006) previously conducted studies. However, elaborating on inventory stocking policies besides this set of decisions, Cohn & Barnhart (2006) developed a heuristics algorithm, which does not solve the problem to optimality. The single-source capacitated facility location problem algorithm by Bramer & Simchi-Levi (1997) solves the problem at optimality but the algorithm cannot be directly applied in service parts distribution network design without adaptations because characteristics of the service parts logistics are not incorporated in the model formulation. In addition to these, the holistic studies about the managerial aspects of the service parts distribution but they are all based on electronic, automotive or aviation industries.

Introducing a general cost minimizing mixed integer mathematical model and service level maximizing p-center problem, which optimize a medical devices distribution network in terms of number, location and capacity of distribution centers and the customer demand allocation to the distribution centers, both from cost and service level perspectives, are considered as significant contributions to the literature.

Service level maximizing p-center problem formulation is of help to minimize the downtime of the technical systems by faster deliveries than the maximum acceptable delivery duration. Both cost minimizing and service level maximizing formulations introduce the constraints that ensure in time delivery in all shipments. In addition to this, the DC capacities are defined in terms of handling capacities to determine the optimal number of facilities. These were the major adaptations in the single-source capacitated facility location problem algorithm. Furthermore, healthcare industry specific characteristics for the management of service parts logistics are determined and discussed as the factors in choosing the optimal design. These factors are total costs, in time delivery, network structure, operational complexity, and domestic supply.

The practical relevance of this study in the macro level is enhancing the quality of healthcare services in the healthcare providers. An optimal service parts distribution network reduces the downtime of the medical devices and therefore avoid possible negative impacts on patients because of delays in image diagnosis. In the company level, an optimal distribution network design is of help to achieve higher customer satisfaction and cost-effectiveness. The results of this distribution network design study present a guidance for practitioners regarding how an optimal medical devices service parts distribution network can be designed.

The empirical study part of this thesis is based on the General Electric Healthcare service parts distribution in Europe but it is important to emphasize that the approach to the problem at hand, the mathematical model developed and the five factors that have been identified to choose the optimal network design are general and therefore, applicable for not only for General Electric Healthcare but also for making strategic decisions for other medical devices service parts logistics planning as well. Following this study, healthcare providers can find out distribution network designs that help in reducing costs and improving their service quality by delivering in time and if desired, within a shorter time.

Limitations & Future Research

The results of the mathematical model, followed by the discussion about alternative designs and the conclusions are limited with the quality and accuracy of the available data. In unit shipment costs calculations, some critical assumptions have been made due to unavailability of data. Especially if a major inaccuracy in demand, costs, and delivery time data is recognized, the validity of the results should be checked by rerunning the model.

In this study, the sensitivity analysis was conducted using the original model for two parameters, which are customer demand and costs (unit shipment costs and fixed yearly rental costs). However, it was also acknowledged that all parameters could be subject to sources of uncertainty. Therefore, conducting sensitivity analysis for (1) DC capacities, (2) mean travel duration time between DC and customers, (3) maximum acceptable order to delivery duration and (4) penalty costs in case of deliveries could be of interest in future research. Regarding parameter (1), sensitivity analysis could be of use in investigating the trade-off between fixed rental costs and operational complexity. Increased DC capacity would mean less number of DCs but higher rental costs per DC while smaller DC capacity would imply larger number of DCs and lower rental costs per DC. Sensitivity analysis for parameter (2) and (3) could be of interest to explore further the allocation of customer demand to DCs. If the travel duration between customers and DCs change, for instance due to occasional changes of transportation mode, then the travel duration may fall below or above the initial maximum acceptable duration. Also, if the company wants to learn more about the distribution network design when the parameter (3) changes to for instance, XX hours, it is of use to conduct the sensitivity analysis to see the changes in total costs, total number and location of DCs, and allocation of customer demand to DCs. Considering parameter (4), it is important to note that within the scope of this study, a very high penalty cost is applied with the aim of avoiding customer-DC coupling which would lead to late deliveries. This penalty cost was not realistic since a realistic cost for late deliveries was not available at hand. Despite this, if a penalty cost could be obtained for customer dissatisfaction due to late deliveries in future studies, the current very high penalty cost in the model could be replaced and by applying sensitivity analysis, trade-offs related to cost and service level could be further investigated, especially reduction in costs is prioritized over in time delivery.

In addition to these, another future research could be showing the robustness of the original model with a different approach. This can be done by performing sensitivity analysis using the post-validation model i.e. p-center formulation and compare the results with respect to changes in the parameters.

It is also important to mention that the problem is complex because of the involvement of multiple decisions, geographical scope and the size of the dataset. To be able to obtain a result with an exact algorithm under these conditions, the model was run with the 500 most frequently ordered items and later, these items are grouped into three categories, based on their pay weight. Doing so, there is loss of information, which brings about further limitations. These limitations are about inaccuracies in flow of service parts from the DCs to customers and calculation of transportation costs. Acknowledging this limitation, to be able to run the model with the entire set of service parts, developing a heuristic algorithm could be of use in the future research. Although it will not guarantee an optimal result, an outcome could be obtained in a finite time.

Last but not least, the alternatives were evaluated based on five factors, determined in consultation with the practitioners while discussing possible variations in the network design. A deep dive research about identifying more factors, if there is any, and weighting them from the most important to the least important could be a future research. Later, the problem could be addressed with a combination of mathematical modelling and multi-criteria decision making and this approach will lead to a new scientific contribution.

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Appendices

Some parts are removed due to confidentiality!

Appendix 3. Details of the statistical tests

For data processing and modelling choices, statistical tests have been performed for the purpose of representativeness and distribution checks. The details of these tests are presented in this appendix.

Appendix 3.1. Demand distribution test for total demand over months

Total customer demand per month is presented previously in Figure 10 in Chapter 3.4. To decide whether there should be a time index for months in the mathematical model, it has been checked if there is a significant difference in demand among the months. While doing so, a Kolmogorov-Smirnov Test is performed to see if the demand over months is like a uniform distribution or not.

The hypothesis of the statistical test and the results are shown in Table 23. It has been concluded that the demand distribution over months follows a uniform distribution, which implies that there is no seasonality recognized. Thus, a time index is not required to model the demand.

Table 9. Kolmogorov-Smirnov test results

Null Hypothesis	Alternative Hypothesis	2-tailed sig.	Z	Decision
The demand follows a uniform distribution.	The demand does not follow a uniform distribution.	0.864	0.600	Retain the null hypothesis.

Appendix 3.2. Representativeness test for the modalities in the demand data

The frequency of modalities in the original and subset demand data is presented in Figure 36 below. To check whether the selected sample data is representative of the original data, a Chi-Square test was performed.

Before doing so, it has been ensured that the two conditions of Chi-Square Test (Table 24) have been satisfied. To make sure that the modalities with small frequencies do not violate the conditions, they are grouped under “Others” and then the Chi-square test is applied.

Table 10. Conditions to perform a Chi-Square test, from Heijnen (2016)

Conditions of Chi-Square Statistical Test:
1. If both variables have only two categories than all expected counts should be equal or larger than 5. In other cases, not more than 20% of all expected counts should be smaller than 5. 2. All expected counts should be larger than zero.

The hypothesis for the test and the result is presented in Table 25 below. It is concluded that the modality distribution in the subset data is not significantly different than the modality distribution in the original demand data.

Table 11. Hypothesis formulation and Chi-Square test results

Null Hypothesis	Alternative Hypothesis	p-value	Decision
The modality distribution in the subset data is representative of modality distribution in the original demand data.	The modality distribution in the subset data is not representative of modality distribution in the original demand data.	0.3155	Retain the null hypothesis.

Appendix 3.3. Representativeness test for the demand from countries

The frequency of demand among countries in the original and subset demand data is as shown in Figure 37. To check whether the selected sample data is representative of the original data, a Chi-Square test was performed.

Once again, it has been ensured that the two conditions of Chi-Square Test (Table 23) have been satisfied. Even though the demand frequencies in some countries such as Serbia and Bulgaria seem to be too low, the frequencies of all countries in the subset and original data satisfy the conditions so there is no need for grouping for low frequency countries. The hypothesis for the test and the result is presented in Table 26 below. It is concluded that the demand distribution over countries in the subset data is not significantly different than the demand distribution over countries in the original demand data.

Table 12. Chi-square test results

Null Hypothesis	Alternative Hypothesis	p-value	Decision
The demand distribution over countries in the subset data is representative of the demand distribution over countries in the original demand data.	The demand distribution over countries in the subset data is not representative of the demand distribution over countries in the original demand data.	0.2739	Retain the null hypothesis.

Appendix 4. Verification test details and results

A small arbitrary dataset has been used to perform these tests. These tests are conducted independently, which means that the changes in the parameters are made one by one on the basis set of parameters, which is shown below.

Indices:

i	index for service parts	$i \in \{1, \dots, I\}$
j	index for distribution centers	$j \in \{1, \dots, m+1\}$
k	index for customer locations	$k \in \{1, \dots, K\}$
t	index for type of distribution centers	$t \in \{1, \dots, s+1\}$

Indices sets (the values are given arbitrarily):

$I = 1$	There is 1 type of service part.
$m + 1 = 3$	There are 3 candidate distribution center locations.
$K = 5$	There are 5 customer locations.
$s + 1 = 3$	There are 3 types of distribution centers.

Parameters:

D_{ik}	amount of service parts *i* demanded by customer *k* (unit)
$\mathrm{e}_{\mathrm{ijk}}$	unit cost of shipment of item *i* from distribution center *j* to customer *k* (€/unit)
f_t	fixed yearly rental cost of a distribution center type *t* (€)
g_t	total number of deliveries that can be handled in a distribution center type *t* (unit)
p_{jk}	mean travel duration between distribution center *j* and customer *k* (hour)
PT	maximum acceptable order to delivery travel duration (hour)
M	penalty cost in case of delayed deliveries (€)

Parameter values (the values are given arbitrarily):

D_{ik} : $D_{11} = 10$, $D_{12} = 10$ $D_{13} = 10$, $D_{14} = 10$, $D_{15} = 10$

e_{ijk} : $e_{111} = 3$, $e_{112} = 3$, $e_{113} = 3$, $e_{114} = 3$, $e_{115} = 3$, $e_{121} = 2$, $e_{122} = 2$, $e_{123} = 2$, $e_{124} = 2$, $e_{125} = 2$, $e_{131} = 1$, $e_{132} = 1$, $e_{133} = 1$, $e_{134} = 1$, $e_{135} = 1$

f_t : $f_1 = 3000$, $f_2 = 20$, $f_3 = 5$

g_t : $g_1 = 30$, $g_2 = 15$, $g_3 = 1$

p_{jk} : $p_{11} = 10$, $p_{12} = 12$, $p_{13} = 13$, $p_{14} = 14$, $p_{15} = 15$, $p_{21} = 10$, $p_{22} = 10$, $p_{23} = 11$, $p_{24} = 11$, $p_{25} = 11$, $P_{31} = 10$, $p_{32} = 1$, $p_{33} = 1$, $p_{34} = 1$, $p_{35} = 1$

PT : 15

M : 9999999

Test 1. Demand is zero.

- D_{ik} : $D_{11} = 0$, $D_{12} = 0$ $D_{13} = 0$, $D_{14} = 0$, $D_{15} = 0$

Test 1 Results:

- No RDC is opened.
- Only the CDC is opened, due to the constraint: $\sum_{j=1}^{m+1} Y_{j1} = 1$, $\forall j \in \{1, \dots, m+1\}$.
- Objective function value: 3000, which is the cost for the open CDC.

Test 2. Unit cost of shipment is zero.

- $e_{111} = 0$, $e_{112} = 0$, $e_{113} = 0$, $e_{114} = 0$, $e_{115} = 0$, $e_{121} = 0$, $e_{122} = 0$, $e_{123} = 0$, $e_{124} = 0$, $e_{125} = 0$, $e_{131} = 0$, $e_{132} = 0$, $e_{133} = 0$, $e_{134} = 0$, $e_{135} = 0$

Test 2 Results:

- 2 RDCs and 1 CDC are opened to be able to satisfy the whole demand.
- Objective function value: 3040 , which is the total cost of opening these distribution centers.
- No costs incurred for shipment.

Test 3. Fixed yearly rental cost of the distribution centers is zero.

- $f_1 = 0$, $f_2 = 0$, $f_3 = 0$

Test 3 Results:

- In each candidate location (in total 3), a distribution center is opened. In total there are 1 CDC and 2 RDCs.
- Objective function value: 75. This is only the summation of shipment costs.

Test 4. Total number of deliveries that can be handled in the distribution centers is zero.

- $g_1 = 0$, $g_2 = 0$, $g_3 = 0$

Test 4 Results:

- No solution found. The model constraint $\sum_{j=1}^{m+1} d_{ijk} = D_{ik}$, $\forall i \in \{1, \dots, I\}, \forall k \in \{1, \dots, K\}$ imply that all customer demand has to be satisfied. In case of zero capacity of distribution centers, this constraint is violated and therefore, the solution space is empty.

Test 5. Total number of deliveries that can be handled in the central distribution center is 100, which is bigger than the total demand.

- $g_1 = 100$, $g_2 = 15$, $g_3 = 1$

Test 5 Results:

- Only 1 CDC is opened. No RDC is opened. This is because of the fact that the objective function minimizes the costs. CDC is always opened for sure and if it is possible to satisfy the whole demand from there, there is no need for an RDC.
- Objective function value: 3050. It is the total cost of the CDC and the shipments.

Test 6. Total number of deliveries that can be handled in the central distribution center is zero.

- $g_1 = 0$, $g_2 = 15$, $g_3 = 1$

Test 6 Results:

- No solution found. $\sum_{t=1}^{s+1} Y_{jt} \le 1, \forall j \in \{1, \dots, m+1\}$ constraint states that in each candidate location, there can only be a single distribtuion center. Because there are 3 candidate locations and opening 1 CDC and 2 RDC is not sufficient to meet the whole demand, the solution space is empty. Because the constraint $\sum_{j=1}^{m+1} d_{ijk} = D_{ik}, \forall i \in \{1, \dots, I\}, \forall k \in \{1, \dots, K\}$ implies that the entire customer demand has to be supplied.

Test 7. All mean travel duration between distribution centers and customers are zero.

- $p_{11} = 0$, $p_{12} = 0$, $p_{13} = 0$, $p_{14} = 0$, $p_{15} = 0$, $p_{21} = 0$, $p_{22} = 0$, $p_{23} = 0$, $p_{24} = 0$, $p_{25} = 0$, $P_{31} = 0$, $p_{32} = 0$, $p_{33} = 0$, $p_{34} = 0$, $p_{35} = 0$

Test 7 Results:

- 2 RDCs and 1 CDC are opened to be able to satisfy the whole demand.
- Objective function value: 3115. It is the sum of distribtuion center costs and shipment costs.
- There is no difference between the initial travel durations and zero travel durations because the initial travel duration values were all smaller or equal to the PT (maximum acceptable order to delivery travel duration).

Test 8. Maximum acceptable order to delivery travel duration is zero.

- PT = 0

Test 8 Results:

- In the constraint $p_{jk} - PT - u_{jk}^{+} + u_{jk}^{-} = 0, \forall j \in \{1, \dots, m+1\}, \forall k \in \{1, \dots, K\}$, u_{jk}^{+} keeps track of the delivery delays. If PT = 0, all deliveries are automatically delayed.
- Delay causes penalty costs in the objective function due to the expression $\sum_{j=1}^{m+1} \sum_{k=1}^{K} u_{jk}^{+} M$, implying that for each hour of delay M penalty cost will be incurred.
- Due to the high penalty cost M, the objective function value is roughly 230x1015, which is expected.

Test 9. Penalty cost in case of delayed deliveries is zero.

- M = 0

Test 9 Results:

- 2 RDCs and 1 CDC are opened to be able to satisfy the whole demand.
- Objective function value: 3115. It is the sum of distribtuion center costs and shipment costs.
- There is no difference between 0 and 9999999 because the initial travel duration values were all smaller or equal to the PT (maximum acceptable order to delivery travel duration). So there is no impact on the results if M is 0 or another value.

Appendix 5. Run time experiments

In this problem, number of items has been chosen to rescale the problem. The items could be aggregated based on their pay weight values. A number of experiments has been conducted to decide the number of groups that the items will be aggregated into. These experiments test the run time of the model in the IBM ILOG CPLEX Optimizer Version 12.7 in a Intel® Core (TM) i5-6500 processor, 3.20 GHz CPU, 8 GB RAM and 64-bit operating system computer with respect to different number of item groups. Table 25 below shows the results of the run time experiments for a variety of problem sizes. The number of customer locations, candidate DC locations and DC types were the same in each experiment since these parameters were not found adequate to rescale the problem in Chapter 3.6.1.

In case the number of item groups was 500, 250, 100 or 50, the computer ran out of memory within a run time of roughly 10 hours. In this case, no optimal result could be found. The large number of iterations and nodes consumed the available memory and did not allow further iterations that could lead to the optimal result. When the number of item groups was 10 or 5, the computer did not run out of memory within a run time of 10 hours, but it also could not obtain an optimal result. The difference between the upper and lower bounds of branch-and-bound, the so-called *gap*, was 100% after 10 hours, which should be 0% in optimality. Because there was no improvement in the *gap* after 10 hours run time, the model was terminated manually to avoid unfavourable long run time and the high possibility of running out of memory. It is important to note that the term favourable/unfavourable depends on the particular problem at hand and in modelling exercises, it is usually up to the modeller's judgement. When the number of item groups has been decreased to 4, similar to run number 5 and 6, no result could be obtained within 6 hours. In another computer with a more advanced processor and RAM, an optimal result could be presumably obtained but with the resources at hand, it was not possible.

Finally, the number of item groups has been decreased to 3 and an optimal result could be obtained within 70 minutes run time, which is much shorter than the previous runs. As a result, the items are grouped into 3 for the modelling purposes within the scope of this study. A summary of these run time experiments is shown in Table 27 below.

Table 13. Run time experiments to rescale the problem

Run number	Number of item groups	Number of customer locations	Number of candidate DC locations	Number of DC types	Run time	Result
1	500	166	70	3	~10 hrs.	Out of memory
2	250	166	70	3	~10 hrs.	Out of memory
3	100	166	70	3	~10 hrs.	Out of memory
4	50	166	70	3	~10 hrs.	Out of memory
5	10	166	70	3	~10 hrs.	No result
6	5	166	70	3	~10 hrs.	No result
7	4	166	70	3	~6 hrs.	No result
8	3	166	70	3	70 min.	Result obtained