TÉCNICO LISBOA

Supply Chain Optimization

The case of Civiparts Spain

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Abstract

Due to increased competitiveness, companies need to make a difference. Managing efficiently the supply chain is one of the factors that can make a difference in a company's costs. Civiparts, a company that sells parts for heavy vehicles and buses, is no exception. The company is trying to improve their supply chain in Spain. There are two distribution centres for the Spanish supply chain, one in Lisbon and one in Madrid. Nowadays, both of them supply the stores in Madrid, Mérida, Barcelona and Valencia. The company wants to improve their supply chain performance by reducing transportation costs and inventory holding costs, without decreasing the service level. Therefore, this dissertation intent to answer to two main questions: 1. What is the optimal delivery frequency to each store, taking into account the trade-off between holding costs and transportation cost for each store? 2. From which DC (Lisbon, Madrid or both) each store should be served, taking into account the trade-off between holding costs at each distribution centre and the transportation costs from each distribution centre to each store? To answer to the previous questions, the company's supply chain, suppliers', customers' and the delivery policies needed to be understood and analysed. A literature review was also made with the major concepts. Similar models to the one that was developed were also studied and analysed to create a new model suited for the company. A mixed integer nonlinear programming model was developed and implemented in GAMS software. The results showed that the best solution was to centralize the distribution operation in Madrid and serve all stores from Madrid. The recommended delivery frequency between the Lisbon and Madrid distribution centre was three times a week. For the stores, daily deliveries were recommend departing from Madrid. In the end, some suggestions are made to Civiparts and some future research topics are raised.

Keywords: supply chain optimization; transportation costs, inventory holding costs, network design, mixed integer nonlinear programming.

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1 Introduction

The purpose of this chapter is to present the dissertation. Throughout this chapter the reader will understand the motivation, the objectives and structure of this work.

1.1 Problem Background and Motivation

Most sectors of the global economies are operating in an environment much more complex and competitive than it was in the past. This situation is enhanced by a rapid rate of change which is being driven by external forces that have changed the economic perspective. Organizations are striving to be more efficient (reducing their cost of doing business) and to be more effective (improving customer service) to survive in this new environment. A critical element for achieving these two objectives simultaneously is the supply chain organization. It can be argued that transportation, a critical ingredient for overall supply chain performance, is the glue that holds the supply chain together (Coyle et al., 2011).

Over the years, technology has evolved. The internet, technological developments, the individual use of information and communication devices, the widespread availability of massive amounts of data have created new challenges and opportunities to transportation and logistics systems (Speranza, 2018).

The network design of a supply chain significantly affects the supply chain performance for a long period of time. Since each industry has a unique set of characteristics which evidently drive the network design of the supply chain, a number of various models have been formulated to meet the needs of such business contexts (Pham et al, 2017).

Civiparts is a company that sells parts for heavy vehicles and buses and it is present in five countries and two continents. As the company is constantly trying to improve the efficiency of its operations and is increasing their sales and winning market share in Spain, this master's thesis arises. Currently, Civiparts operate two distribution centres, one in Lisbon and one in Madrid and both of them are supplying the Spanish stores. The company thinks that it is better to improve the supply chain now, when they are entering the Spanish market than later, when they are stabilized with the company already running well. With a more efficient supply chain, they can make greater margins with the same price, or sell it by less and make the same margins. Therefore, the challenge proposed by the company is to analyse if the current distribution strategy is the best option or if there is a better solution for supplying the Spanish market, which can bring the most benefits to the company taking into account a trade-off between transportation costs, inventory holding costs and service level.

To provide a better solution, it is important to study the transportation system and the logistics activities in order to achieve better logistics efficiency, to reduce operation costs, and to promote service quality (Tseng et al, 2005). Furthermore, transportation impacts other areas of the company, since usually transportation costs are diminished by increasing the quantity being shipped, so the company needs to build up inventory, which also represents costs (Rodrigues, 2016).

1.2 Thesis Objectives

The focus of this study is on the supply chain of Civiparts Spain. The dissertation will be developed under real data (with a coefficient to respect confidentiality).

The goal is to answer to two main questions about logistics optimization:

1. What is the optimal delivery frequency to each store (Madrid, Merida, Valencia and Barcelona), taking into account the trade-off between holding costs and transportation cost for each store?

2.From which distribution centre (Lisbon, Madrid or both) each store should be served, taking into account the trade-off between holding costs at each distribution centre and the transportation costs from each distribution centre to each store?

1.3 Thesis Methodology

The methodology adopted is divided into three main stages: information gathering, development of a mathematical model and results discussion.

Initially, all the processes of the company were studied in order to characterize in detail the current situation. This allows to identify and understand the link between the entities of the supply chain, as well as all its rules and policies, seeking an integrated view of the entire supply chain. A detailed analysis of each of the themes in focus was also carried out: distribution and storage. This analysis was carried out collecting data to perform a reasoned analysis in the next stages.

In order to collect relevant data, several meetings were held to request information. The meetings took place in the distribution centres of Madrid and Lisbon. In the distribution centres was understood how Civiparts work. The company provided a computer with access to a software called SGIX, which controls inventory. Through this software it is possible to verify the inventory that circulated between all the facilities of the company and the existing stock in each store. Civiparts also provided access to the platform of the outsourced company that makes the deliveries, company T. In this platform, it is possible to verify the weight that was transported in each day and for what location. Access to SAP software was also used to withdraw invoices and inventory holding costs.

The second stage was the development of a mathematical model that translated the information acquired in the previous stage and in the literature review, and where the main opportunities for improvement were identified. The model was implemented in GAMS programming language. Three scenarios were studied: the baseline scenario, the optimal scenario and the centralization scenario.

In the last step, the results will be presented. In addition to the quantitative analysis, a qualitative analysis will also be made for other aspects that the mathematical solution does not contemplate as the environmental impact, the service level and the human resources availability.

1.4 Project Outline

This dissection is structured into four chapters:

Chapter 1: Introduction - In the present chapter is provided the contextualization of the problem, the motivation, the objectives, the methodology and the outline of the master thesis.

Chapter 2: Problem Description – In the second chapter, the problem to study will be characterized, detailing the company and the company's supply chain, operations, methods and policies.

Chapter 3: State of the Art - In this chapter, the main concepts, definitions, methodologies and results of previous research related to the case under study are clarified and discussed in light of the relevant scientific literature.

Chapter 4: Model Development – in the fourth chapter, the methodologies used in the development of the model describe in detail. A validation of the model is also done.

Chapter 5: Model Implementation – In the fifth chapter the data to be used is presented and its imlementation in the model is explained.

Chapter 6: Results and Discussion –This is the chapter where the results are presented, where a sensitivity analysis is made and where the advantages and disadvantages are discussed.

Chapter 7: Conclusions and Future Work – In the last chapter is where the results are presented, where a sensitivity analysis is made and where the advantages and disadvantages are discussed.

2 Problem Description

With the aim of helping to understand how the company operates, this chapter describes the procedures and the network design of the company as well as the purchasing and distribution policies.

First, the group Nors will be characterized, the group to which Civiparts belongs. Then the operation of the company is detailed. At the end, the problem that we want to improve is characterized.

2.1 Group NORS

The NORS group is a Portuguese group whose vision is to be one of the world leaders in transportation solutions and construction equipment. It has in its genesis 84 years of history and activity in Portugal, which began with the representation of the Volvo brand in 1933. Currently the NORS Group is present in 23 countries spread over 4 continents, with over 3,895 employees and a turnover of 1.4 billion Euros (Volvo, 2016).

The group has four business areas as showed in figure 1. In Red, the “Integrated Aftermarket Solutions”, in dark blue the “Original Equipment Solutions”, in green the “Recycling Solutions” and in light blue the “Safekeeping Solutions”.

Figure 1 - Nors Business Areas (Source: Nors, 2016)

Civiparts is in the "Integrated Aftermarket Solutions" along with AS Parts and One Drive. While AS Parts and One Drive sell parts for light vehicles, Civiparts sell parts for heavy vehicles and buses.

The business area "Original Equipment Solution" comprises the brands AutoSueco, Galius, Ascendum, Auto-Maquinaria, AutoSueco Automoveis and Agronew. AutoSueco is focused on the sale of Volvo Trucks and SDMO - a brand of generators. Galius is the distributor of Renault Trucks in Portugal. Ascendum and Self-Machinery sell industrial equipment for use in construction and excavation. The AutoSueco Automóveis sells light vehicles of the brands Volvo, Mazda, Land Rover and Honda. Agronew commercializes agricultural vehicles.

In "Safekeeping Solutions" business unit there are Mastertest and Amplitude Seguros companies. Mastertest is a vehicle inspection company and Amplitude Seguros is an insurance company.

In "Recycling Solutions" the group is present with two brands. Sotkon is the market leader in Iberia in underground waste containers. Biosafe is a company that is dedicated to providing solutions with rubber granules recycled from used tires.

2.2 The Civiparts

Civiparts is a company established in 1982. Their main business is the distribution of parts for trucks, buses and “car shop” equipment. Civiparts had a turnover of more than 60 million Euros in 2015. Globally Civiparts has around 200 employees.

The company vision and mission are:

"To provide products for the maintenance and repair of our clients’ vehicles, seeking to identify and meet their needs, suggesting the most rational solution from a technical and economical point of view, driven by energy, passion, humility and respect" (Civiparts, 2016).

The NORS Group is trying to reduce to the maximum his ecological footprint. Not being an exception, Civiparts has the following environmental commitment:

“As a company importing parts and accessories for heavy vehicles and therefore responsible for introducing the packaging waste for the products it sells on the domestic market.(...) As a strategic partner for most of our customers, in providing Grease and Lubricants, Civiparts does not forget its responsibility in collecting and recovering waste oils” (Civiparts, 2016).

The headquarters are located in Lisbon but is present throughout the Portuguese territory and in 4 other countries. Abroad the company is present in Spain, Angola, Morocco and Cape Verde. The sales from 2007 to 2011 and the contribution in percentage of sales of each country are showed in figure 2.

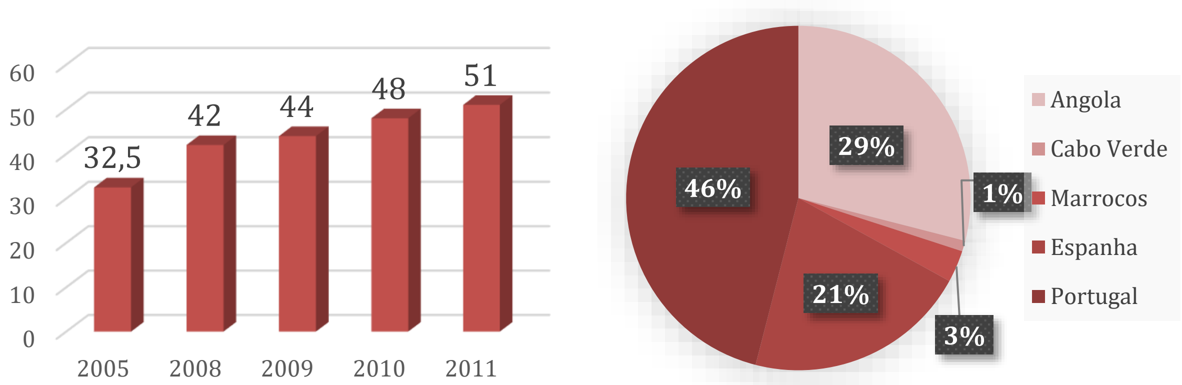

Figure 2 – Civiparts growth and sales around the world (source: Civiparts, 2016)

In Portugal there are eight points of sale: Braga, Leça da Palmeira, Albergaria, Leiria, Carregado, Lisbon, Faro and Seixal as it is possible to see in figure 3. Portugal is the country where Civiparts sales are higher. The warehouse in Lisbon is the biggest warehouse of the company. It also works as a distribution centre for the other countries.

Figure 3 - Civiparts Portugal (Source: Civiparts, 2016)

In Spain (figure 4), there are an agent in Vigo and four stores (that also works as warehouses): Barcelona, Madrid, Valencia and Merida. The agent in Vigo rents a warehouse (when necessary) to store his "little" stock since it is considered that it doesn't represent a large volume of sales and demand to open a store (196 705€ of sales in 2015). In figure 5, the sales of each Spanish store are discriminated. The focus of our project will be the supply chain of Civiparts Spain.

Figure 4 - Civiparts Spain (Source: Civiparts, 2016; modified)

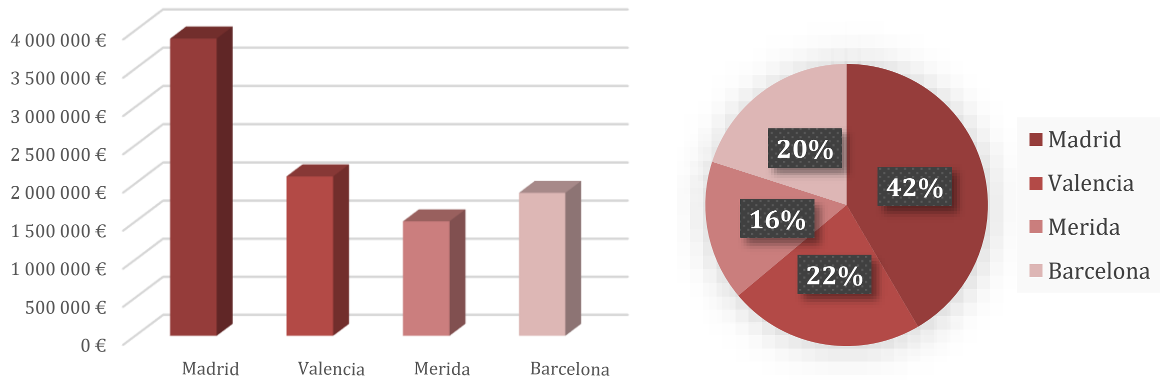

Figure 5 - Sales of Spain in 2015

In Angola, Civiparts has two stores in Luanda (Mulemba and Viana) and one in Benguela as shown in figure 6.

Figure 6 - Civiparts Angola (Source: Civiparts, 2016)

Morocco and Cape Verde have a store each, in Casablanca and Cidade da Praia respectively. Figure 7 is the map of Marrocos and figure 8 is the map of Cape Verde.

Figure 7 - Civiparts Marrocco (Source: Civiparts, 2016)

Figure 8 - Civiparts Cape Verde (Source: Civiparts, 2016)

2.3 The Civiparts Spain' Supply Chain

The supply chain consists of four main components: suppliers, distributors centres, retailers and customers. Civiparts only controls the distribution centres and the retailers in their supply chain. They don't have production or factories.

Civiparts Spain has different flows depending on the supplier. There are four different ways to get the products to Civiparts Spain customers. The different ways are represented by different colours in figure 9.

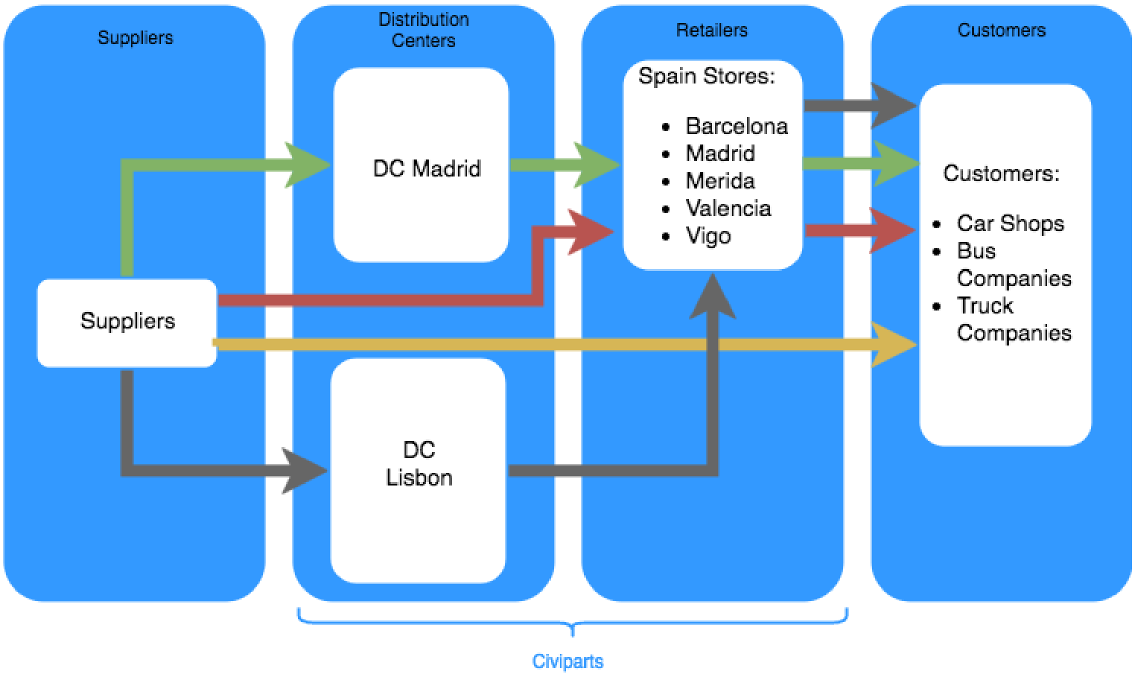

Figure 9 - Civiparts Supply Chain Structure

The simplest structure is represented by the yellow arrow. It represents the direct delivery to customers. Clients buy the products in stores, Civiparts informs the supplier and then the supplier delivers the items in the customer's address. This kind of delivery happens mostly to a product called AdBlue. Adblue is a liquid required to satisfy an European norm regarding the emission of gases. The liquid is sold in bulk or in small containers, but mostly in bulk. AdBlue represents around 3% of Civiparts sales. It would take a lot of space to have the amount of liquid needed to sell in a week (also, liquids are very heavy, so it would be very expensive to transport it). Civiparts don't have stock but has a quantity reserved in the supplier stock. This supplier, Greenchem takes care of all the transportation to the customer.

A different way of delivering the items is represented by the red arrows. These arrows represent direct delivery to stores without passing in any distribution centre. This kind of delivery is used in batteries, for instance. One of the suppliers, Varta for example, has a lot of stores around the country. Varta's store of Madrid delivers in the Civiparts warehouse of Madrid; Varta's store of Barcelona delivers in the Civiparts warehouse of Barcelona; and so on.

Another structure of the company supply chain is represented by the green arrows and occurs when the supplier delivers the items at only one place, in this case in Madrid. The warehouse in Madrid acts as a distribution centre (figure 10) and store simultaneously. Madrid is the central warehouse of the supply chain, so it is expected to have a higher stock of these kind of products to distribute by the Spanish stores.

Figure 10 - Madrid's warehouse distribution (Source: Civiparts, 2016; modified)

The grey arrows (on figures 9 and 11) represent the products that arrive in the distribution centre of Lisbon and then are distributed by the Spanish stores directly without passing through the distribution centre of Madrid. This is the scenario that will be analysed and study in this thesis. This distribution method is used in a significant number of items. Civiparts Spain buys this items to Civiparts Portugal (Civiparts Portugal is the "favourite supplier" for this kind of items). In Lisbon it is stored stock to provide the Portuguese and Spanish stores. The Spanish stores place orders to the Lisbon warehouse depending on their need. Figure 11 shows this supply chain structure.

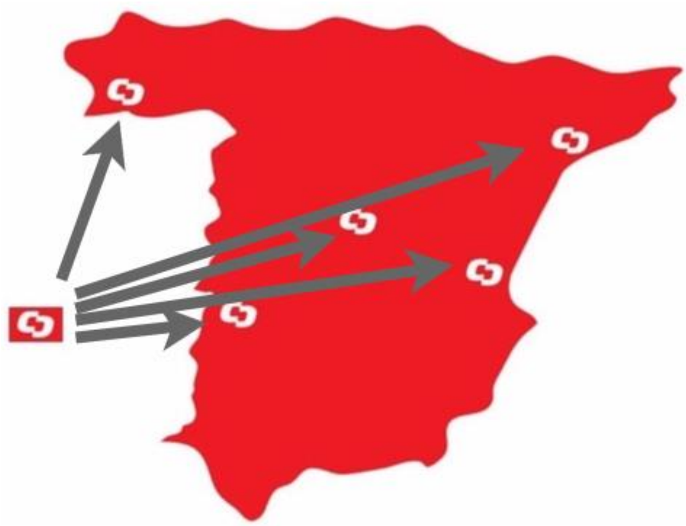

Figure 11 – Lisbon's warehouse distribution (Source: Civiparts, 2016; modified)

2.3.1 Civiparts' Suppliers

Civiparts has more than 10 000 stock keeping Units for more than 100 suppliers. The majority of the items have more than one possible supplier. When there is no stock in the first provider, the parts are requested to following supplier. The inventory system used by Civiparts, SGIX Auto, allows to sort the suppliers in order of preference. The supplier that appears in the first place for a SKU is called "favourite supplier". The software also shows the other possible SKU for the same item – same product but different brand or substitute products.

Civiparts has several types of contracts with suppliers. Some of them are capacity reservation contracts. Civiparts pays to reserve a certain number of items ensuring that stock is available for a certain date. Civiparts has this kind of agreement with the AdBlue supplier, for example.

There are buy-back contracts (Returns) for parts that are ordered by customers but then they end up quitting the purchase. However, not all suppliers accept to get back their items. These contracts allow to pass the risk to the vendor and encourage the company to buy more quantities. It is important to note that who pays the shipping cost of returns is Civiparts.

Civiparts always tries to get the best possible price from their suppliers. They often get lower prices if the purchase exceeds a certain amount. If the order does not reach certain levels, it is possible that Civiparts changes the supplier for that order or that the price charged for each item gets higher. It often happens that, to get quantity discounts (but not only)[1], who buys the pieces is Civiparts Portugal (since it is the country where sales are higher). The parts are then sold to Civiparts Spain – this is the reason why there is a distribution to the Spanish stores from the Lisbon warehouse. There are suppliers that require products to be sourced locally, i.e., Civiparts Spain buys to the company based in Spain and Civiparts Portugal buys to the same company but the one in Portugal. The batteries explained in the previous section are one of those cases. This is one of the reasons why some of the products are delivery directly to each store.

It is also often to happen returns between Civiparts' companies. If a given SKU has no stock in Portugal, but has stock in Spain (although it was sold by Civiparts Portugal in an earlier transaction) then this SKU is returned to Civiparts Portugal instead of being sold again between Civiparts'.

The focus of the study of this thesis are the products whose favourite supplier is Civiparts Portugal, i.e., products that Civiparts Portugal buy from the suppliers and then sells to the all the Civiparts stores in Spain.

The purchases of Civiparts Spain to Civiparts Portugal represented in 2015 a sales volume of 1 503 498 € for a total of 73 535 items. This supplier (Civiparts Portugal) alone represents 17% of the sales of Civiparts Spain.

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[1] In a various number of items, Civiparts Portugal can get better deals than Civiparts Spain.

2.3.2 Civiparts' Distribution Centres and Retailers

Civiparts has a central warehouse where they perform activities that have effect in all their retailers over the world. This central warehouse is the distribution centre of Lisbon. Located on the outskirts of the Portuguese capital, this distribution centre is not only the distribution centre of the Portuguese supply chain but also the distribution centre for all the Civiparts companies around the world. The warehouse has 2500 m^2 and there are around 5 000 000 € in stock stored in this warehouse. The warehouse also has a store and a lot of offices in the building.

The distribution centre of Madrid only supplies the stores in Spain. The warehouse is relatively smaller than the Lisbon warehouse (1000m^2). Inside, there are about 3 000 000 € in stock stored. This warehouse, like all the retailer's warehouse in Spain, also has a store where clients can buy and pick up their items. The retailers of Barcelona, Merida and Valencia have smaller warehouses than the one in Madrid.

The agent in Galicia tries not to store stock and only orders to Madrid or Lisbon when it has orders - pull strategy. For this reason and because Galicia only works with urgent shipments, this representation of Civiparts will not appear in this study. It does not make sense to study the relationship between holding costs and transportation costs of a "store" that should not have stock. So, for this route, there are only the alternative of low stock and frequent deliveries.

2.3.3 Civiparts' Customers

Most of the Civiparts clients are workshops (car shops), bus companies - passenger transport - and truck companies - freight transport. The army is also a customer of the company. Civiparts is part of the business area of the Integrated Aftermarket Solutions of the Group Nors, so they do not sell parts to new trucks or busses but to their repair and maintenance.

It is not very common to have private individuals with heavy vehicles but if it is the case, Civiparts will not reject the customers.

Civiparts is growing in sales year after year. They are gaining new customers all over the countries. Civiparts can maintain good relations with customers and they end up returning and buying more products because the company can practice competitive prices when compared to the prices of the competition.

2.3.4 Civiparts' Delivery Policy and System

Civiparts Portugal divides their purchase orders from the Spanish warehouse/stores into 3 types: Urgent, Overstock and Normal.

Urgent deliveries are sent on the same day and match the final customers' urgent needs that cannot be met by the existent stock in the warehouse, but the customer want to buy and will collect later (Civiparts do not ask for any type of deposit, which may imply some risks). There are urgent orders almost every day for every location departing from Lisbon.

Overstock orders are rare. They are the orders between warehouses - transhipment - where products that do not have sales at a particular location are transferred to another warehouse.

Normal orders are orders placed to replenish each warehouse or store stock. The normal deliveries are weekly scheduled. There are orders leaving Lisbon to Mérida (every Monday), Valencia (every Tuesday), Madrid (every Wednesday) and Barcelona (every Thursday). There are also normal orders leaving Madrid: daily to Valencia and Barcelona and weekly to Merida.

Currently, there are about five orders leaving Lisbon to each location per week (except Vigo, that doesn't have a store), which means, one every working day. This happens because of the urgent orders, that happens almost every day. When there are urgent orders in the same day as the normal orders they are dispatched together. Sometimes it is shipped only one product to satisfy the need of one client.

In the internal policy of Civiparts is stated that the store that receives the order are the one who pays for the transportation. The monthly cost of transportation between the distribution centre of Madrid, and the stores of Civiparts Spain is around 15 000€. Table 1 shows the approximate transport costs for each location.

Table 1 – Monthly cost of transportation per store

Stores	Cost of transportation / Month
Madrid	4000 €
Barcelona	4100 €
Valencia	3500 €
Merida	3400 €

2.4 The Civiparts' Problem

Civiparts is a company that is always pursuing a better strategy for the supply chain of every country they are operating. With that in mind, some problems keeping arising. The transportation and the level of stock are two important factors that are in continuous improving. Civiparts aims to find the best relationship between the cost of transportation, the cost of holding stock and service level.

This work is motivated by the desire of reduce costs and improve the supply chain in Spain. The increase of products coming from Civiparts Portugal also contributes to the rise of this work (Grey arrows from figures 9 and 11). The company wants to conclude whether the company benefits more in having more stock and less deliveries or if the company should have less stock with more frequent deliveries.

Another problem in hand is related with the transportation flows. The company does not want to reduce the service level but wants to optimize its supply chain routes of distribution since there are doubts arising regarding the two distribution centres (Lisbon and Madrid) sending orders to the same place (each store/retailer: Madrid, Merida, Barcelona and Valencia) instead of doing transhipment between them and assign one of them to replenish each retailer.

One of the hypotheses to study is to “eliminate” the routes from Lisbon to Barcelona, Merida and Valencia. Since the urgent orders exist and will always exist from Lisbon to all the stores, we cannot eliminate the routes but we can eliminate the normal deliveries. Normal deliveries departing from Lisbon would just answer to the needs of Madrid. Madrid would than answer to the needs of the others Spanish stores centralizing the distribution in Madrid.

In case of centralization, the orders from the stores would be requested to Madrid instead of Lisbon, therefore, the stock in Madrid would have to increase (or not if the delivery frequency from Lisbon increased). In order to reduce all orders from Lisbon as much as possible (including the urgent ones), Madrid would need to store stock that were previously stored in Lisbon. It is necessary to study whether this is an advantage or not and, if so, to define the stock level in Madrid.

Summing up, there are two questions to be answered:

1. What is the optimal delivery frequency to each store (Madrid, Merida, Valencia and Barcelona), taking into account the trade-off between holding costs and transportation cost for each store?

2.From which distribution centre (Lisbon, Madrid or both) each store should be served, taking into account the trade-off between holding costs at each distribution centre and the transportation costs from each distribution centre to each store? (figure 12).

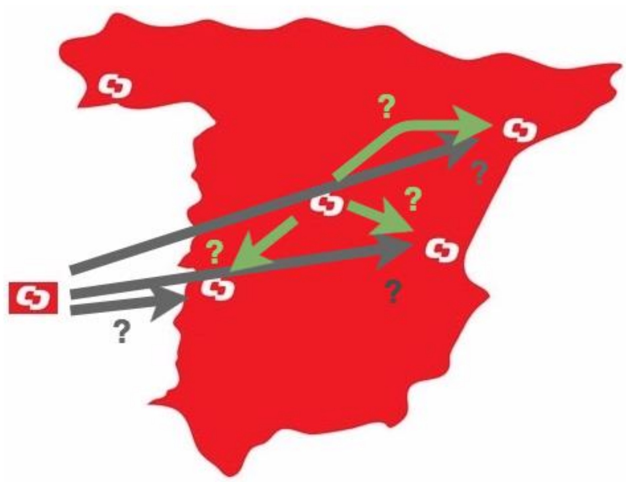


Figure 12 - From which DC (Lisbon, Madrid or both) each store should be served?

3 State of the Art

In order to better understand the problem described and develop the framework to achieve the better solution for this problem, it is necessary to make a scientific research. In this chapter it is intended to carry out a literature review of supply chain concepts and methodologies that are being used to help companies optimize their supply chain.

It is necessary to analyse the existing literature to comprehend how and why supply chains are in a continuous change and in what mathematical models the companies are basing their research in order to improve and reduce costs. The concepts of transportation and inventory will be explored in the next sub-chapters.

The sources for the literature review include books, articles in journals and web pages. The books were consulted in the libraries of the universities of Instituto Superior Técnico in Tagus Park, Porto Salvo and Escuela Técnica Superior de Ingenieros Industrial in Madrid. The majority of the documents were obtained using search engines like Google, Google Scholar, ScienceDirect, B-on and Researchgate with the concepts of supply chain management, network design, transportation and inventory (with some variations) as key words.

3.1 Supply Chain Management

According to Chopra & Meindl (2007), a **Supply Chain** consists in all parties involved in fulfilling a customer request, as well as all the functions necessary in this task. The supply chain includes not only the manufacturer and the suppliers, but also transporters, warehouses, retailers, and even shoppers (or customers) themselves (figure 13). Within each organization, the supply chain includes all functions involved in receiving and filling a customer request. These functions include, but are not limited to, new product development, marketing, operations, distribution, finance, and customer service.

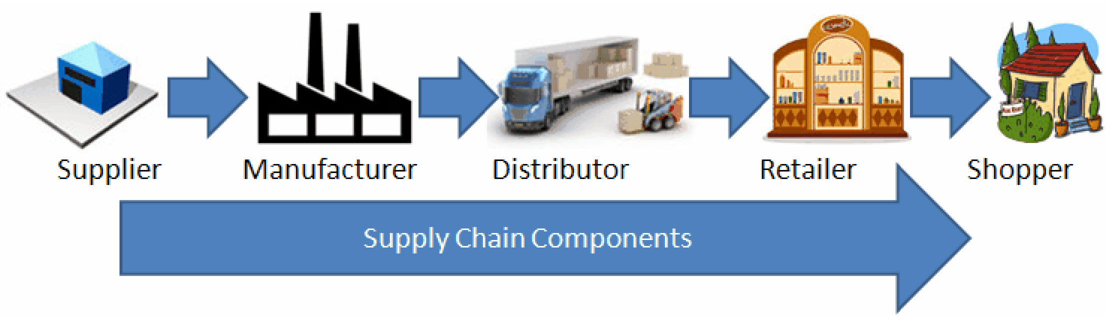


Figure 13 - Supply Chain Components (source: Biz-devolpment, 2011)

The first component of the supply chain is the **Supplier**. Suppliers are responsible for providing the raw materials. They can also provide component parts, unfinished or non-consumable products. After the suppliers, the manufacturers. **Manufacturers** do the production or the final assembly of the product. **Distributors** are responsible for storing and handling the products at the warehouse and distributing them to the retailers. **Retailers** are the intermediate step between the consumers and the suppliers. They buy and resell the product. **Consumers** buy and use the product (biz-development, 2011).

Supply Chain Management is the set of approaches utilized to efficiently integrate suppliers, manufacturers, warehouses, distributors, and retailers, so that goods are produced and distributed at the right quantities, to the right locations, and at the right time, in order to minimize system wide costs while satisfying service level requirements (Simchi-Levi et al., 2008).

Different explanations can be found in the literature, however all definitions seem to pinpoint that **Supply Chain Management** refers to the integration of key business processes, both internal and external to the firm, from end-users through original suppliers that provide products, services, and information and add value for customers and other stakeholders (Rodrigues, 2016).

Shapiro (2006) states that the **Objective of the Supply Chain Management** is to minimize total supply chain cost to meet fixed and given demand. This total cost may include a number of terms such as:

- raw material and other acquisition costs;
- inbound transportation costs;
- facility investment costs;
- direct and indirect manufacturing costs;
- direct and indirect distribution centre costs;
- inventory holding costs;
- inter-facility transportation costs;
- outbound transportation costs;

One can argue that total cost minimization is an inappropriate objective for the firm to pursue when analysing strategic and tactical supply chain plans. Instead, the firm should seek to maximize the net revenues.

Although Shapirro doesn't refer to customer satisfaction, other definitions also include the importance of customer satisfaction. Napolitano, (2015) states that the objective is to optimize total cost but also to maintain or improve customer service levels: Order lead time, on-time delivery and fill rate. For Sukati, Hamid, Baharun, & Yusoff (2012) the principle of supply chain activity is receiving input from suppliers, add value and deliver it to customers. A supply chain encompasses all the parties that are involved, directly or indirectly, in fulfilling a customer request. For Carvalho (2010), the supply chain aims to create value for the customer. In this sense, a set of activities are produced in order to provide the customer with the right product, in the right place, at the right time, in the right quantity, at the lowest cost.

Although the phrase 'supply chain management' is now widely used, it could be argued that it should really be termed 'demand chain management' to reflect the fact that the chain should be driven by the market, not by suppliers. Equally the word 'chain' should be replaced by 'network' since there will be multiple suppliers and, indeed, suppliers to suppliers as well as multiple customers and customers' customers to be included in the total system (Christopher, 2011).

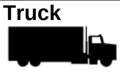
3.2 Transportation

Transportation refers to the movement of product from one location to another as it makes its way from the beginning of a supply chain to the customer. Transportation is an important supply chain driver because products are rarely produced and consumed in the same location. Transportation is a significant component of the costs incurred by most supply chains. In fact, transportation activity represented more than 10 percent of the GDP of the United States (Simchi-Levi et al., 2008).

Coyle et al. (2011) stated that **Transportation** is the glue that holds the supply chain together and is a critical ingredient for overall supply chain performance.

The five basic modes of transportation are listed and characterized in table 2.

Table 2 - The five basic modes of transportation (source: Rodrigues, 2016)

Mode	Strengths	Limitations	Primary Role	Primary product characteristics	Example products
Truck 	Accessibility Fast and versatile Customer service	Limited capacity High cost	Move smaller shipments in local, regional and national markets	High value finished goods Low volume	Food Clothing Electronics Furniture
Rail 	High capacity Low cost	Accessibility Inconsistent service Damage rates	Move large shipments of domestic freight long distances	Raw material High volume	Coal Paper Grain Chemicals
Air 	Speed Freight protection Flexibility	Accessibility High Cost Low capacity	Move urgent shipments of domestic freight and smaller shipments of international freight	High value finished goods Low volume Time sensitive	Computers Periodicals Pharmaceuticals B2C deliveries
Water 	High capacity Low cost International capabilities	Slow Accessibility	Move large domestic shipments via rivers, canals and large shipments of international freight	Low value Raw materials Bulk commodities Containerized finished goods	Crude oil Minerals Farm products Clothing Toys
Pipeline 	In –transit storage Efficiency Low cost	Slow Limited network	Move large volumes of domestic freight long distances	Low value Liquid commodities Not time sensitive	Crude oil Petroleum Gasoline Natural gas

3.2.1 Transportation Problem

The definition of the **transport network**, establishing the set of nodes and routes along which the flow of goods is processed, has a major impact on the performance of the Supply Chain. An optimal network allows for a high level of service at the lowest cost but requires a complex approach that integrates several dimensions, such as transportation costs and inventory holding costs (Carvalho, 2010).

There are a lot of ways to address a transportation problem and all of them implicates a great complexity and analyse and therefore it is common to use mathematical models. Some developments in the area of operations research helped in the achievement of great solutions, some of them are:

- Shortest path
- Transportation - Milk Run
- Transportation with intermediary warehouses
- Traveling salesman problem
- VRP – Vehicle Routing Problem

The transportation problem is related to direct shipments between multiple origins and multiple destinations. Given a network with multiple origins and multiple destinations, it aims to define the flows between each origin and each destination. An extension of this model incorporates the use of "milk-run" systems in which there is a possibility of transhipment between the various origins to supply a particular destination, opposing to direct supply from various sources (Figure 14). This system is widely used for just-in-time supplies (Carvalho, 2010).

Transport networks involving direct shipments have some advantages: the absence of a central warehouse usually requires less coordination effort but increases the inventory holding costs resulting from the sending of larger orders. The use of a “milk-run” system reduces inventory, transported loads are smaller, but increase the complexity in terms of coordination.

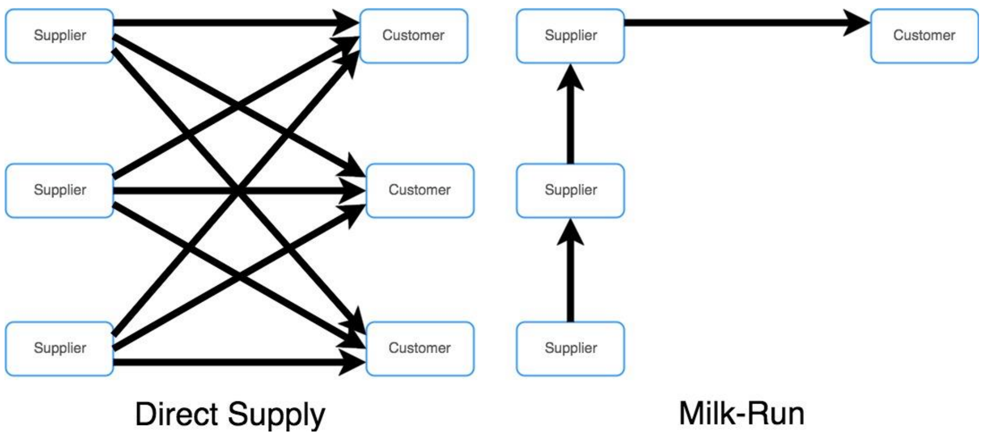


Figure 14 - Direct Supply and Milk Run Schemes

The transportation with intermediate warehouses problem is related with the centralization or decentralization of the supply chain (Figure 15). Centralized inventory control is a common cooperative strategy, where the stock control activities of the whole system become concentrated at a particular member (or a group of members), which takes full control of the inventory replenishment of the supply chain, and uses available demand and cost information in planning the operations. Centralizing inventory management provides cost reductions and improved service levels by decreasing uncertainty and providing better utilization of resources for production and transportation (Çelebi, 2015).

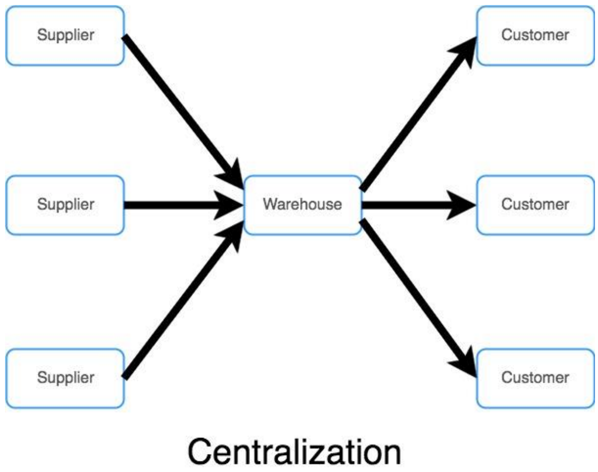


Figure 15 - Centralization Scheme

Tseng et al., (2005) stated that only a good coordination between each component would bring the benefits to the maximum. Chopra & Meindl (2007), said that, first, it is crucial to align transportation strategy with competitive strategy. Secondly, managers should consider both in-house and outsourced transportation, at the appropriate combination to meet their needs.

3.2.2 Transportation Risks

There are three general types of **transportation risks**: risk that the shipment is delayed, risk that the shipment does not reach its destination because intermediate nodes or links are disrupted by external forces and the risk of hazardous material (Chopra & Meindl, 2007).

Rodrigues (2016), pointed out some mitigation measures that managers can implement in order to diminish transportation risks impacts, like moving inventories closer to destination, using alternative lanes, building a lead time buffer, designing a network with multiple routes to the destination (and changing according to their needs), minimizing probability of exposure and damage by using modified containers and low-risk transportation modes, providing proper handling training and increased security conditions.

Risk is a never-ending challenge. Organizations must establish a repetitive, measurable, verifiable risk monitoring process to remain focused on existing and emerging transportation disruptions (Coyle et al., 2011).

3.2.3 Transportation Costs

A transportation service incurs in various costs, such as labour, fuel, maintenance, terminals, roads, administration and others. The costs can be divided into those that vary with services or volume (variable costs) and those that do not (fixed costs). Of course, all costs are variable if one considers a sufficiently long time and a sufficiently large volume. However, for transportation pricing purposes, it is useful to consider the costs that are constant during the carrier's "normal" volume of operation as fixed. All other costs are treated as variables (Ballou, 2008).

Variable Costs are function of the level of activity in a given period and include the direct costs associated with transportation of each cargo. They include, for instance:

- Fuel;
- Tires;
- Maintenance and repair;
- Labour, collection and delivery.

Fixed Costs are costs that doesn't change with the level of activity. Some examples of fixed costs are:

- Cost of ownership
- Annual sales tax (purchase price, useful life, etc)
- Licenses fees and taxes
- Management and overhead cost
- Insurance costs

The costs that have the biggest impact are the fuel, the labour and the cost of ownership. Fuel and labour are directly related with the distance travelled. Other factors that influence directly the transportation costs are: the density, the type of cargo, the demand, the responsibility, and the backhaul (Marufuzzaman et al., 2015).

Transportation is one of the most structuring activities of logistics and it's responsible for a big share of the logistics costs, around one to two thirds of the logistics costs. In fact, it is not uncommon for transports to account for 10 percent of the total cost of a product (Rodrigues, 2016).

3.2.4 Transportation trade-offs

The efficient management of a supply chain requires a systemic and integrated approach. In another words, the various activities should be seen as elements of a system and should not be studied, analysed and optimized individually, but in the context in which they are inserted in and, taking into account the interactions with the other elements that form the system. In transportation management, the dependency relationships in the various processes that are associated with it are particularly relevant on the impact that some decisions have, for example, on inventory holding costs, operations effort and coordination in customer responsiveness, among others.

Time vs Space

The frequency of a transport system is also a factor with great impact on the costs of a transport system. For example, a high frequency of supply reveals a large capacity of response by the supplier (for example, deliveries in 24 hours after the request), that leads to higher cost of transportation (lower vehicle occupations and therefore higher cost / unit). If, on the other hand, the frequency decreases, the loads can be consolidated over time until they become fully charged, maximizing the occupancy of the vehicle space, and lowering the transport costs. Thus, a lower response capacity would allow significant reductions in transport costs as a result of the economies of scale obtained in transport (Carvalho, 2010).

Transportation vs Inventory

In general, the trade-offs between inventory and transportation costs come from the facts that: transportation influences the time that inventories remain in transit and on the premises; and the fact that configuration of the logistics network (which maintains inventories) influences transportation. Fast transportation allows inventory to remain for a short time in the vehicles and offers certainty conditions that allow the reduction of safety stocks in the warehouses. In this way, they provide the compensation between high transport costs and low inventory holding costs. Slow transportation shows the opposite situation and, although they present lower costs, they induce the need of maintenance of inventories for long time in transit and demand a greater quantity of safety stocks (Amaral & Guerreiro, 2014).

Table 3 summarizes the main trade-offs between inventory and transportation costs achieved by Amaral & Guerreiro (2014). The authors also stated that: “The impact on the operating income is composed by the difference in cost between transportations, by the cost difference between inventories held and by the difference in profit tax arising from these cost distinctions. In addition to operating income, the situation impacts the cost of capital, as it interferes with the amount of investments in inventories.”

Table 3 - Summary of the main trade-offs between inventory and transportation costs (Amaral & Guerreiro, 2014)

↑ Inventory Holding Costs		↓ Inventory Holding Costs	
↓Transportation Costs	- Delayed transportation - Contracting informal companies and individual carriers - Batch consolidation - Decentralized stocks - Policy of not prioritizing stock items - Push strategy	↑ Transportation Costs	- Appropriate transportation - Hiring formal and modern companies - Non-consolidation of lots - Centralized stocks - Policy of prioritizing stock items - Pull strategy

3.3 Inventory

An area that is also important in terms of logistics is storage and stock management. It promotes a trade-off with transport since inventory levels increase with the reduction of transport flows and decrease with the intensification of transport flows. Inventory has two major components: the storage component itself (which may include all handling of internal materials in the storage facilities) and the management of stocks. Pure storage does not add value to the product, the value of a product to the customer when entering and leaving the warehouse is exactly the same, or on the contrary, may even decrease (risk of obsolescence, breakage, deterioration, among other reasons). However, the whole process of making the product available to the customer is based, among other things, on a set of storage and transport activities that allow the fulfilment of the demand (Carvalho, 2010).

According to Chopra & Meindl (2007), inventory exists in the supply chain because of a mismatch between supply and demand. For instance, at a steel manufacturer, this mismatch is intentional because it is more economical to manufacture in large lots and store the excess for future sales. The mismatch is also intentional at a retail store where inventory is held in anticipation of future demand. An important role that inventory plays in the supply chain is to increase the amount of demand that can be satisfied by having the product ready and available when the customer wants it. Another significant role that inventory plays is to reduce cost by exploiting economies of scale that may exist during production and distribution. Inventory is held throughout the supply chain in the form of raw materials, work in process, and finished goods. Inventory is a major source of cost in a supply chain and has a huge impact on responsiveness.

The important issues in storage are the decisions on the location of stock points, points of consolidation and deconsolidation of cargos / materials, location and management of warehouses and installation of cross docking. In addition, the number of storage points, size and inventory policy are equally essential (Carvalho, 2010). Other aspects that need to be taken into account when managing inventory are the obsolescence, demand fluctuation, vendor-managed-inventory, learning and forgetting, deteriorating items, warehouse capacity, disposing of unsold items, retail space allocation, controllable lead-time, and financial-holding cost - when the money is tied up in inventory it cannot be used elsewhere (Zahran & Jaber, 2017).

Companies routinely increase product variety in order to enhance competitiveness and grow sales. Unfortunately, increasing product variety creates operational challenges and results in higher inventory levels. Increases in product variety result in higher inventory levels due to larger numbers of stock keeping units, each with their own lot sizes, safety stock levels, and order quantity levels. Product variety has been documented to increase the complexity and uncertainty in the operating environment deteriorating decision quality (Wan & Sanders, 2017).

3.3.1 Inventory Risks

Too much supply leads to inefficient capital investment, expensive markdowns and needless handling costs, while too much demand generates the opportunity cost of lost margins. Each situation is the consequence of one of two types of inventory risk: the former is the risk of excessive inventory (inventory risk) while the latter is the risk of insufficient supply (supply risk). Because most supply chains are incapable of perfectly matching supply and demand, all of the firms in a supply chain bear at least some supply risk. But some firms may be able to avoid inventory risk completely (Cachon, 2004).

Demand uncertainty incurs a risk cost to the supplier and price volatility incurs a risk cost to the buyer. Such uncertainty means that supply chains askes for additional risk mitigation measures through the use of different control mechanisms such as contracts or legal agreements. Contractual negotiations with supply chain partners are vital to establish visibility and risk control through agreed contractual processes to manage fluctuations in demand and price volatility. Some of those **Supply Chain Contracts** that address demand uncertainty are buyback, quantity flexibility, revenue sharing, profit sharing and full return. The supply chain contractual processes listed earlier address the improvement in the efficiency of the supply chain network, but do not usually actively address the risk mitigation. Supply chain contracts could offer robust strategies to increase supply chain resilience through mitigating uncertainties or risks in addition to making a supply chain more efficient (Cachon, 2004).

3.3.2 Inventory Holding Costs

To decrease inventory holding costs, firms try to consolidate and limit the number of facilities in their supply chain network. For example, with fewer facilities, Amazon is able to turn its inventory about 12 times a year, whereas Borders, with about 400 facilities, achieves only about two turns per year. (Chopra & Meindl, 2007).

Torkul et al. (2016), stated that the **Inventory Holding Costs** are equal to the product of the area in the chart (figure 16) and unit variable cost, with multiplication of the unit constant cost of warehousing and the cycle time. Q is the initial inventory amount; Qs represents the safety stock; L and L_0 are the cycle times for re-order point model and real-time model respectively; ROT means reorder time and ROP means reorder point.

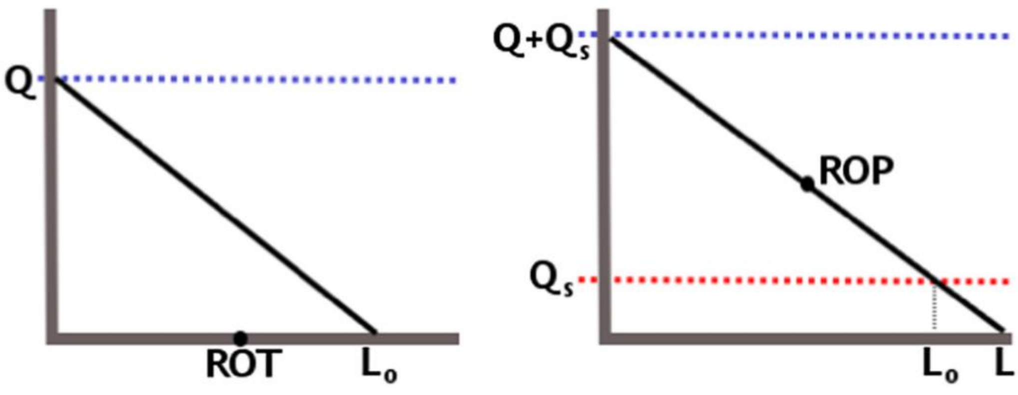


Figure 16 - Amount of inventory per cycle time (Torkul et al, 2016)

According to Chopra & Meindl (2007), **Inventory Holding Cost** is estimated as a percentage of the cost of a product and is the sum of the following major components:

• **Obsolescence (**or spoilage) cost: The obsolescence cost estimates the rate at which the value of the stored product drops because its market value or quality falls. This cost can range dramatically, from rates of many thousand percent to virtually zero, depending on the type of product. Perishable products have high obsolescence rates. Even non-perishables can have high obsolescence rates if they have short life cycles. A product with a life cycle of six months has an effective obsolescence cost of 200 percent. At the other end of the spectrum are products such as crude oil that take a long time to become obsolete or spoil. For such products a very low obsolescence rate may be applied.

• **Handling cost:** Handling cost should include only incremental receiving and storage costs that vary with the quantity of product received. Quantity-independent handling costs that vary with the number of orders should be included in the order cost. The quantity-dependent handling cost often does not change if quantity varies within a range. If the quantity is within this range (e.g., the range of inventory a crew of four people can unload per period of time), incremental handling cost added to the holding cost is zero. If the quantity handled requires more people, an incremental handling cost is added to the holding cost.

• **Occupancy cost**: The occupancy cost reflects the incremental change in space cost due to changing cycle inventory. If the firm is being charged based on the actual number of units held in storage, we have the direct occupancy cost. Firms often lease or purchase a fixed amount of space. As long as a marginal change in cycle inventory does not change the space requirements, the incremental occupancy cost is zero. Occupancy costs often take the form of a step function, with a sudden increase in cost when capacity is fully utilized and new space must be acquired.

• **Miscellaneous costs**: This component of the holding cost deals with a number of other relatively small costs. These costs include theft, security, damage, tax, and additional insurance charges that are incurred. Once again, it is important to estimate the incremental change in these costs on changing cycle inventory.

• **Cost of capital**: Amaral & Guerreiro (2014) and Zahran & Jaber (2017) stated that we should also consider the cost of capital or opportunity cost. The value kept in inventory can be considered as a logistic investment. The value used in inventory prevent its application in a more attractive and profitable application.

3.4 Supply Chain Optimization

Wiles & Van Brunt (2001) developed two basic linear freight rate models a model to achieve reduction in fright costs and increase the economic benefits in some agriculture commodities by concentrating the commodities at the depot. One or more deposits could be located optimally within the harvesting region to reduce overall transportation costs by doing the transhipment at a lower freight rate. For a circular harvesting region, it was found that the economic benefit varied as the cube of the radius of the production region and linearly with the production intensity. The authors considered the different freight rates according to the route rates, the collecting costs, the cost of operating a depot and the production intensity within the supply region.

According to Dhakry & Bangar (2013), there are two important issues in the supply chain area that contribute to the total cost of the supply chain network, namely, transportation and inventory holding costs. That being said, retail companies can achieve significant savings by considering these two costs at the same time rather than trying to minimize each separately. The authors developed a nonlinear integer programming problem solved by a heuristic to find an initial solution and an upper bound followed by a branch-and-bound algorithm based on the Lagrangian relaxation of the non-linear program. Three scenarios were analysed in their work: flow-through, single distribution centre and regional distribution centre. These scenarios were made to correspond with the ways that the suppliers ship their products. The suppliers ship products according to tree different paths. In the first path, product is shipped through a cross dock facility to a store, meaning that no inventory is held at the facility but only at the store. In the second path, product is shipped by the suppliers directly to the stores. In the third path, inventory is held at a distribution centre and then shipped to the stores. The goal is to identify distribution locations as well as quantities shipped between various points that minimize the total costs. The results obtained shows that the single and regional distribution centres are more cost-efficient when compared to the flow-through approach.

Monthatipkul & Yenradee (2008) proposed in their paper a new inventory control system called the inventory/distribution plan control system for a one-warehouse/multi-retailer supply chain. The aim is to determine the optimal product flow through the supply chain. In their control system, a proposed mixed integer linear programming model is solved to determine an optimal plan that controls the inventories of the supply chain. The model minimizes the order quantity, the holding costs, the quantity in transit, the transportation cost and the lost-sale costs. In their paper it is also proposed a practical way to determine appropriate safety stock ate the warehouse and at the retailers. The determination of the most suitable safety stock policy, is a major issue of using the inventory/distribution plan control system. The most suitable policy is determined by searching the safety stock policy that can give the desired fill rate and the lowest total cost.

Li et al. (2011) proposed a class of coordination policies for the split deliveries which can reduce the inventory holding costs of the retailers without increasing transportation costs in a non-linear programming model. They stated that the objective of the warehouse is to find a distribution strategy integrating inventory replenishment and transportation decisions, i.e., the delivery quantity, frequency and routing pattern of each vehicle, so that the long run average total transportation and inventory holding cost of the system per period is minimized while meeting each retailer’s demand over an infinite horizon.

In 2013, Cardoso et al. (2013) developed a mixed integer linear programming for the design and planning of supply chains with reverse flows while considering simultaneously production, distribution and reverse logistics activity. The main goal of this paper is the maximization of the net present value taking into account uncertainty in the products demand and the results provide details on sizing and locations of plants, warehouses and retailers, definition of processes to install, establishment of forward and reverse flows and inventory levels to attain. In the forward flow, it is possible to send the goods to the market from the plants, the warehouses and the retailers. New entities can be installed if necessary, or in case they already exist they may suffer a capacity expansion.

Varela et al. (2011) used multi-objective approach to the design and planning of supply chains. In this work, the author used symmetric fuzzy linear programming modelled to balance profit and environmental impact. The aim is to maximize the profit while considering environmental aspects. To improve the supply chain performance, a mixed integer linear programing optimization problem using Resource-Task-Network methodology was created.

Arampantzi & Minis (2017) propose a multi-objective mixed integer linear programming model, which captures significant decisions involved in the re-design of high performance supply chains. The tree objectives are: costs, social and environmental. The cost objective includes investment, operational and emission costs. The environmental objective captures emission quantities and waste generation at each link of the supply chain. The social objective considers employment opportunities, prioritizing societal community development and improved labour conditions. To solve the proposed model the authors used both goal programming and the ε-constraint method to achieve efficient trade-offs among the three objectives. They applied the proposed model to a global manufacturer. The goal programming method resulted in both economic and environmental cost improvements, while maintaining social costs under control. The ε-constraint method provided the opportunity to regulate the expenditures related to environmental and social strategies.

3.5 Chapter Conclusions

To a better understanding of the problem addressed, this chapter presented concepts regarding the state of the art about supply chain management, transportation and inventory with emphasis to the transportation costs, inventory holding costs, risks and trade-offs that arise.

Transportation is a very important part of the supply chain because products aren't produced and consume in the same place. With that in mind, the role of transportations is to take the goods from one point to another. There are risks in the transportation. The risk of arriving late, the risk of never arriving and the risk of damaging the good during the way. Another matter that was approached was the transportation problems. Transportation problems are now solved with the assistance of mathematical models. Managers have to evaluate different aspects and made trade-offs regarding time and space and regarding transportations and inventory.

Inventory is also a very important for the wellbeing of the supply chain. Keeping inventory stored allows to answer unexpected demand, allows to obtain economies of scale by storing the excesses and allows to keep stock for future demand. The inventory risks are related with having more stocked than needed or not having enough stock to answer the supply. The inventory holding costs are not easy to calculate but some authors have defined some ways of doing it.

Regarding the problem descripted in chapter 2, it is possible to make a connection with the trade-off between transportation costs and inventory holding costs, the transportation problem and the advantages and disadvantages that each decision will bring to the company.

4 Model Development

Given the literature reviewed, a mathematical model was developed to optimize the supply chain of Civiparts Spain and to answer to the research questions:

1. What is the optimal delivery frequency to each store (Madrid, Merida, Valencia and Barcelona), taking into account the trade-off between holding costs and transportation cost for each store?
2. From which distribution centre (Lisbon, Madrid or both) each store should be served, taking into account the trade-off between holding costs at each distribution centre and the transportation costs from each distribution centre to each store?

The steps used in the development of the model will be described in detail in this chapter with the intention of informing the reader of what are the characteristics of the model, the mathematical formulation and the model validation. Figure 17 illustrates the three steps described in this chapter that were used in the development of the optimization model.

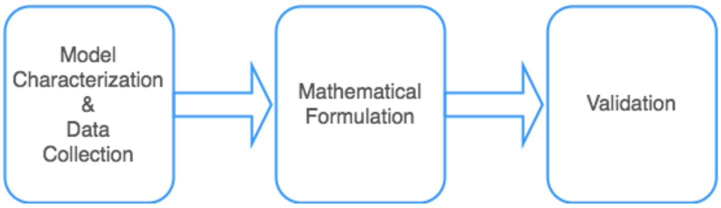


Figure 17 – Steps for the model development

After the mathematical formulation, the model was implemented in GAMS language - generic algebraic modelling system language - using the solver Knitro version 10.2.0 to solve the mixed integer nonlinear programming in the GAMS software version 24.8.

4.1 Model Characterisation and Data Collection

The problem at hand can be described as a generic problem of transportation from the suppliers to the stores passing through distribution centres (figure 18). Different products are delivered by different suppliers in different locations. The developed model, although taking into account the specific case of Civiparts, is a generic model and can be adapted to different distribution networks with similar operations.

This problem can be described in the following form:

Given:

- Transportation cost function;
- Retailers/stores demand for each day;
- Distribution centres capacities;
- Distribution centres expenses;
- Inventory opportunity cost;

Determine:

- Optimum delivery frequencies
- Which distribution centre (or both) should serve each store

With the goal of minimizing transportation and inventory holding costs.

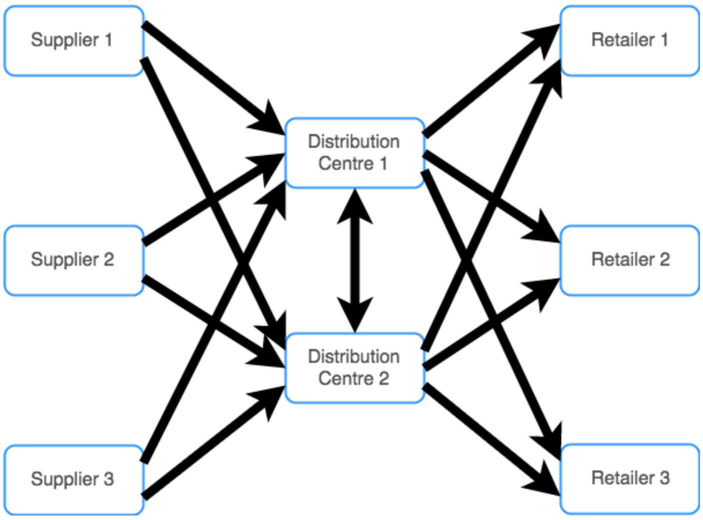


Figure 18 – Generic Transportation Model

The optimization model aims to minimize the logistics total cost, which includes transportation cost and inventory holding costs, improving the distribution strategy used by Civiparts. The transportation costs can be reduced in several ways, such as:

- transporting more quantity at the same time leads to fewer trips at a lower cost per kilogram;
- Ordering the products from the nearest distribution centre is cheaper than ordering them from further distribution centre;
- It may be cheaper, when ordering from one supplier, to do a transhipment / cross docking operation between distribution centres to reach a specific retailer.

It also must be considered that reducing transportation cost usually means lower gas emission and fewer pollution, so it is also good for the environment to develop studies like this one.

However, reducing the transportation cost will lead to an increase in inventory holding cost, so a trade-off must be solved. To reduce the inventory holding cost per unit it is necessary to reduce:

- Cost of obsolescence;
- Handling cost;
- Occupancy cost;
- Miscellaneous costs;
- Opportunity Cost;

Because inventory costs are accounted by item, reducing items in the distribution centre reduces inventory holding costs.

In the development of the model, different issues had to be considered such as the relevant entities, the distribution centre capacities, the demand, the time period, the transportation costs per unit and the inventory costs per unit.

Entities

In this study case, the only entities relevant in Civiparts' supply chain are the distribution centres and the stores, as the focus of this work is the improvement of Civiparts' internal supply chain. The stores in Spain work as the retailers from figure 18.

Regarding the distribution centres, two locations were considered: Madrid and Lisbon. It is important to note that there is no distribution centre that supplies a predefined set of stores, and normally, stores in Spain are supplied by both distribution centres. Regarding the stores, all stores located in Spain were considered with the exception of Vigo. Vigo was excluded due to its minor importance and also because it is not a "true" store, it is an agent. The stores that the company intends to open will also not be considered for the present study because there are no relevant data that allow to calculate a standard behaviour of their demand and their cost of distribution. However, they will be taken into account in the discussion of results, when relevant.

As the focus are in the operations that only depend on Civiparts, a plant has been set up for each distribution centre to simulate the existence of a supplier (the transportation cost between the plants and the distribution centres in the same location is 0€). The Madrid's Plant works as supplier for Madrid's distribution centre and doesn't interact with Lisbon's distribution centre. The Lisbon's plant acts as a supplier for both distribution centres, but in practice, the Lisbon's distribution centre is the one that ships the orders to the distribution centre of Madrid. In the model the flow goes from the plants to the distribution centres and later to the Stores. This was the way used to represent the flow that arrives in Madrid's distribution centre from Lisbon's distribution centre. This route has a cost function in the model and is not for free as the other flows between plants and distribution centres.

The structure of the network in the model includes only the paths represented by the green arrows and grey arrows from figure 9 in chapter 2. In addition to those arrows, a purple arrow was created to represent the transhipment between the distribution centres and subsequent delivery to the stores (figure 19). The connection from Lisbon to Madrid doesn't exist as a transhipment operation in the actual scenario, it exists in a normal transportation operation from the distribution centre of Lisbon to the store of Madrid. Meaning that the distribution centre of Madrid doesn't work as a distribution centre from the items that come from Lisbon.

Since the transportation from the suppliers to the distribution centre is not part of this study, we are only dealing with the logistics network represented in figure 19.

Recalling from chapter 2, the green arrows occurs when the supplier delivers the items at only one place, in this case in Madrid, and then distribute them by the stores. The grey arrows represent the products that arrive in the distribution centre of Lisbon and then are distributed to the Spanish stores directly without passing through the distribution centre of Madrid. The purple and grey arrows represent the same flows, but the purple ones do a transhipment between distribution centres, or, in another words, centralizing the Spanish distribution in Madrid instead of Lisbon.

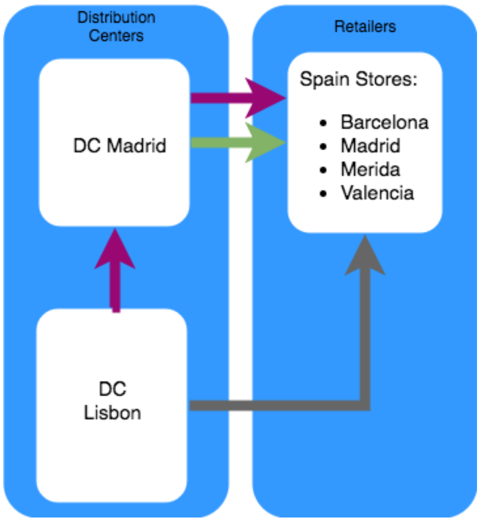


Figure 19 – Civiparts Supply Chain in analyses

The grey and green arrows represent four routes, one to each store from the respective distribution centre. The purple arrow from the distribution centre of Madrid to the stores also represent four routes, one to each store but from products that come from the distribution centre of Lisbon, or in another words, product which the favourite supplier is Civiparts Portugal. The green and the purple arrows that represent the Madrid's outbound flow are dispatched together to achieve economies of scale in the transportation costs.

The grey arrow that goes to the store of Madrid can be joined with the purple one between distribution centres since both arrows represent the route Lisbon-Madrid. In the model, only one arrow will be allowed. The outbound flow from the distribution centre of Lisbon to the store of Madrid won't "pay" inventory costs is Madrid, so the purple one will be the one allowed since the inventory costs of Madrid must be charged to that flow.

The green arrow from de distribution centre of Madrid to the store of Madrid is only theoretical since they share the same facilities, and, as said, it has a cost of 0€, so no disadvantages in terms of cost comes from the previous paragraph.

Summing up, the network considered in the model is composed by the distribution centres of Lisbon and Madrid, the Civiparts Spain stores and involves the flows that goes from Lisbon to all the stores in Spain. The flow that arrives in Madrid directly from suppliers and are then distributed by the Spanish stores was also considered to include the economies of scale in the transportations costs in case of centralization. The reverse flow is not considered since it is almost non-existent. The company does not consider to open a new distribution centre.

Figure 20 summarizes the network design to be implemented in the model. To the flow represented by the grey arrow that arrives at the distribution centre of Madrid is charged the Madrid's inventory holding cost and not Lisbon's inventory holding cost. This means that inventory holding cost from Lisbon is never charged to the flow that goes from Lisbon to Madrid. To this flow only the inventory holding cost of the Madrid distribution centre is charged. The reason why this happens is because, in case of centralization, the company may not be doing cross docking (situation in which both inventory holding costs should be charged). It is considered that in Madrid there would exist more stock. Since there is more stock, it means that the inventory holding cost from Lisbon should not be charged, because the demand that was asked previously to Lisbon will be now answered by the distribution centre of Madrid.

The flow that goes from Lisbon to Madrid and "can go for free" to the store, since the cost of transport between the distribution centre and the Madrid's store is 0 € / kg. In case of centralization, the inventory holding cost is only charged to Madrid. In case of decentralized distribution, that flow will also pay inventory costs in Madrid but this will not influence the result of the study because this cost will always have to be paid to satisfy the demand of the Madrid store.

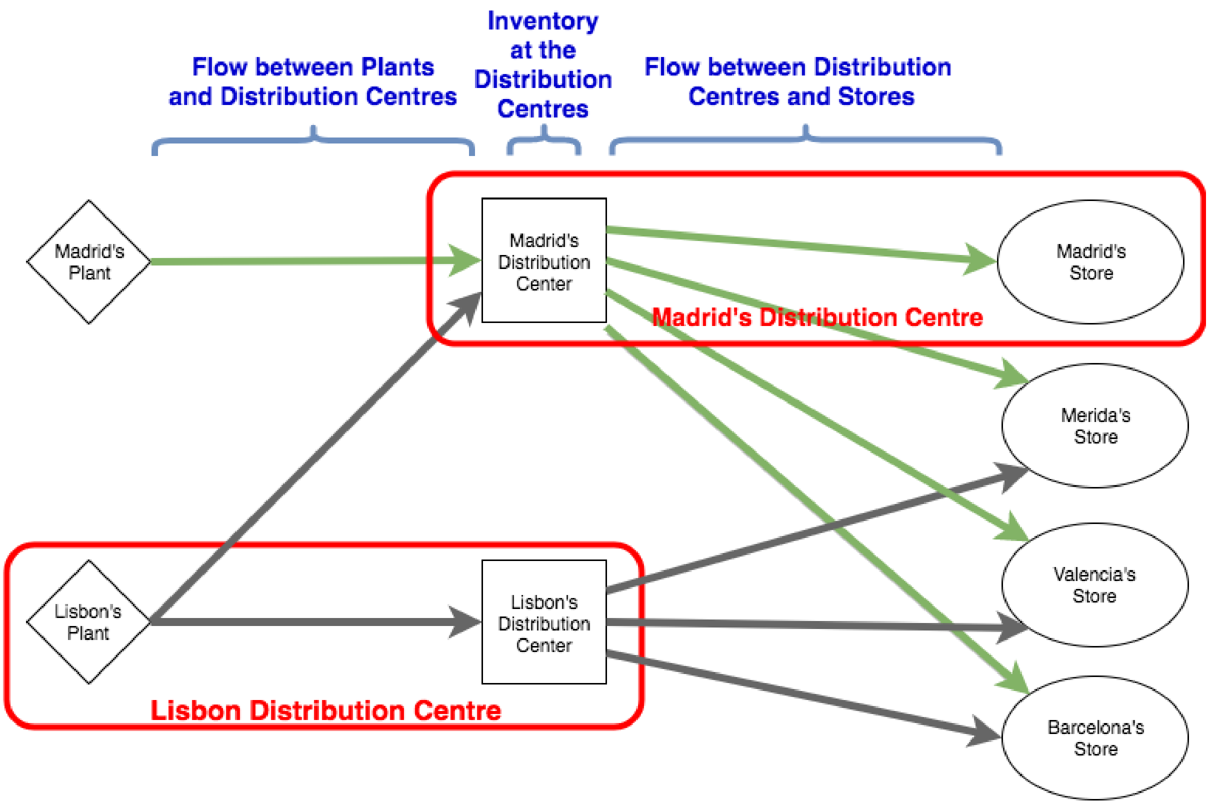


Figure 20 – Civiparts network design to be implemented in the model

Demand

Civiparts offers a wide range of products to its customers. Enumerate the quantities of products transported to each store for each item would make the computational model very heavy due to the high number of items. As such, demand has been set in kilograms globally, not discerning the differences that could exist for product or family of product. This simplification was made, since the use of flows by product would imply the collection of information on the weight of each product or average weight of each family of products. The complexity that this analysis would bring to the computational model would be greater than the advantage in terms of precision of the results since the focus of the work is the global transportation costs. Moreover, the transportation cost charged by company T is a function of the weight transported. Therefore, the demand can be set in kilograms.

As mentioned in chapter two, there are trucks departing once a week to each store from Lisbon. There are also trucks departing from Madrid to Valencia and Barcelona on a daily basis and from Madrid to Merida in a weekly basis. Nonetheless, by analysing historical data on this route (Madrid-Merida), it was found that the majority of the weeks have daily deliveries, so the weakly-delivery to Merida was transformed in a daily-delivery. The main reason for this to happen are the urgent orders that have to be satisfied. The demand of the urgent orders was also considered and included in the demand of all the stores.

The flows between entities are determined by the demand of the stores, that also set the demand for each distribution centre. It is considered that there is only a maximum of one shipment per day of items between entities.

Two types of demand were defined: the one that must be supplied by the Madrid's distribution centre ($demand\_madrid_{s,t}$) and total demand ($demand_s$). $Demand\_madrid_{s,t}$ is a daily demand for each store and is defined for one week from Monday to Friday (t1 to t5). The total $demand_s$, is a weekly demand for each store and includes the previous demand plus a demand from Lisbon. The demand from Lisbon can go directly to each store or can go through a centralization in the Distribution centre of Madrid.

Tables 5 and 6 show the values that were considered for weekly $demand_s$ and daily $demand\_madrid_{s,t}$. respectively. The demand values were calculated trough a study period of 20 weeks and obtained in visits, meetings or with access to the SGIX software. To calculate the demand of each store, an average weight was considered based on the information of both companies (Civiparts and company T) regarding the transportation.

The values contain a coefficient to guarantee the confidentiality of the results without changing the outcome of the results.

Table 4 - Demand

Store	$demand_s$ $[Kg/week]$
s_madrid	14000
s_merida	6400
s_valencia	6600
s_barcelona	6900

Table 5 – Demand from Madrid

	t1 $[Kg/day]$	t2 $[Kg/day]$	t3 $[Kg/day]$	t4 $[Kg/day]$	t5 $[Kg/day]$
s_madrid	1900	1800	2000	2200	2100
s_merida	1200	1600	500	800	700
s_valencia	600	100	2800	1000	400
s_barcelona	1300	1000	600	1500	800

Capacity

Regarding the vehicles used in the distribution, their capacity is not considered because that responsibility is transferred to the transportation company T. Usually, there is a cell phone conversation before the truck leaves to collect the products at Civiparts to find out the truck size required.

Regarding the distribution centre capacities, the average inventory was considered to represent 90% of the storage capacity. Although the capacity of the Madrid warehouse to receive more inventory was not unanimous within the company, it was considered that this should not be an obstacle to the study. Although it should not be considered as an obstacle, it must exist. Capacity is one of the biggest limitation to a centralization model. The storage capacities were considered for distribution centres only. The capacities of the stores were not considered since the daily demand of the stores is the factor that leads the simulation (it must be fulfilled) and the stores will not order more than they can handle. Also, the demand is based on historical data, so it should not overload the store capacity.

As part of the assumption that the average inventory is in stock, so its capacity is 90% full, when the model informs that there are 0 kg in stock, it means that the warehouse has its average inventory in stock, so the capacity that appears in the model is only the 10% remaining (Table 4). The remaining capacity of the Madrid's distribution centre (20 000 kg) will be the capacity for the flow studied in the model. This values were obtained in the SGIX software in units and then transformed in kilograms and contain a confidentiality coefficient.

Table 6 – Remaining Capacity (10% of full capacity)

Distribution centre	Remaining Capacity $[Kg]$
dc_madrid	20 000
dc_lisbon	180 000

Time Period

The time period considered for the model was two weeks. Each store is supplied on a weekly and on a daily basis, depending on the origin. The demand of products that leave Portugal is weekly for each store. The demand for the products from Madrid is daily. Although the demand repeats itself every week, the two weeks' time interval was considered in order to study if the behaviour is the same for the two weeks or if it would keep inventory from one week to the other and thus have less frequent deliveries.

The lead-time is not taken into account since it does not influence the cost. However, it influences the service level and the response time that is not part of the model. All routes take about 24 hours, except the routes from Lisbon to Barcelona and Valencia which take 48 hours. The introduction of the lead-time would not bring significant results to the model but will be taken into account in the discussion of results when relevant.

Transportation costs

The transportation costs were calculated from a table given by company T (table 7). Transportation rates are tabulated according to the weight carried and the route - origin and destination, according to the distance between origin and destination. The rates are tabulated in kilogram intervals for each route in piece wise functions. The values have an associated coefficient to guarantee confidentiality. Table 8 shows the correspondent column to each route.

Table 7 – Compnay T's rates (in Euros)

Kgs	A [€]	B [€]	PT1 [€]	PT2 [€]
<= 5	3,51	4,93	5,72	7,77
[5-10]	3,83	5,46	6,35	8,61
[10-20]	5,49	8,32	7,60	13,10
[20-30]	6,84	10,36	8,86	16,36
[30-40]	8,16	12,34	10,12	19,53
[40-50]	9,38	14,16	11,38	22,45
[50-60]	10,50	15,80	12,63	25,11
[60-70]	11,92	18,03	15,15	28,68
[70-80]	12,85	19,42	15,15	30,95
[80-90]	14,02	21,15	17,66	33,75
[90-100]	15,15	22,83	17,66	36,48
[100-125]	18,66	28,92	20,81	46,37
[125-150]	20,43	31,61	23,95	50,78
[150-175]	23,07	35,99	27,09	57,98
[175-200]	24,60	38,32	30,24	61,83
[200-250]	29,61	46,08	36,52	74,45
[250-300]	34,01	53,46	42,81	86,48
[300-350]	38,00	60,17	49,10	96,61
[350-400]	41,43	65,92	55,38	105,32
[400-450]	44,50	71,15	61,67	127,24
[450-500]	46,87	75,31	67,96	134,04
[500-600]	54,45	87,48	80,53	154,99
[600-700]	61,75	99,00	93,11	174,91
[700-800]	69,01	110,17	105,68	194,57
[800-900]	74,16	117,88	118,25	208,08
[900-1000]	80,63	127,58	130,83	225,08
[1000-2000]	0,0752 /kg	0,1187 /kg	0,1204 /kg	0,2092 /kg
>2000	0,0708 /kg	0,1116 /kg	0,1204 /kg	0,1968 /kg

Table 8 - Correspondence between columns and routes

Column	Routes
PT1	Lisbon - Madrid
	Lisbon - Merida
PT2	Lisbon – Valencia
	Lisbon - Barcelona
A	Madrid - Valencia
	Madrid - Merida
B	Madrid - Barcelona

A power regression of table 7 was made to reach the transportation costs function per kilogram. The upper limit of each interval was used to calculate the cost per kilogram and to do the regression. Figure 21 shows the power function regression on the cost function per kilogram for column PT1. The same procedure was done to the other columns (appendix 8.1).

Initially, it was considered that a mixed-integer linear program would be performed (using the linear function, on the left), but, in the course of the development of the model, it quickly came to conclusion that it would have to be a non-linear function. The reason for this change is due to the tabulated values in transportation costs. In a linear function we have $y = a\,x + b$, it could be seen as a fixed cost "a" per which kilogram "x" plus a fixed cost of opening the route "b". The advantage in transporting more items at the same time is only "b", that is divided by more kilograms "x". In a power function $y = x * (a * x^b)$, the expression between parentheses is the cost per kilogram when transporting "x" kilograms, paying less per kilogram when transporting more. This value is then multiplied by the number of kilograms "x" transported. It is important to notice that "b" will be a negative number and the power function (x^b) is not defined when "x" is zero and "b" is negative.

As the cost per kilogram is variable, a power function was used so that the cost per kg depends on the weight shipped with no fixed cost, which is what happens.

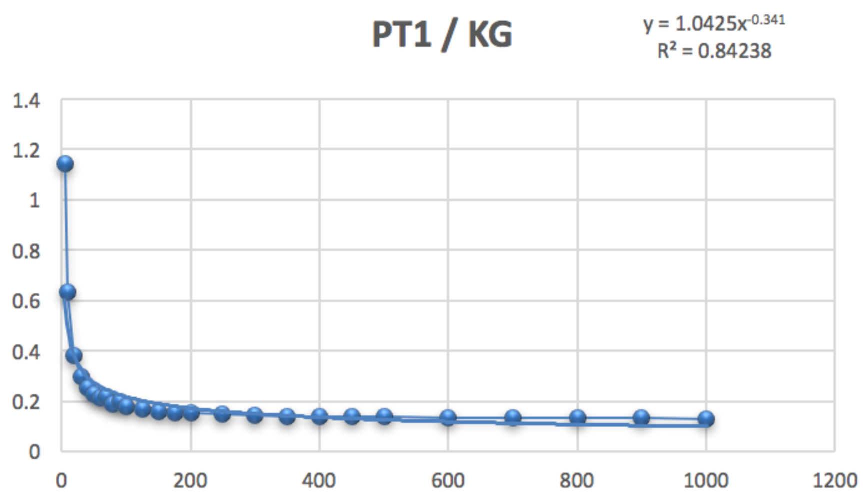


Figure 21 – PT1's power regression

Considering that a power function expression is $y = a\,x^b$ the values of a and b for each route between plants and distribution centres ($aa\_t\_p\_dc_{p,dc}$, $bb\_t\_p\_dc_{p,dc}$), and between distribution centres and stores ($aa\_t\_dc\_s_{dc,s}$ and $bb\_t\_dc\_s_{dc,s}$) are given in table 9. The result of the power function must be multiplied by the kilograms transported (a decision variable) in order to achieve the total cost of the shipment.

Table 9 – Transportation cost from distribution centres to stores – Function values

From p_madrid		
To	$aa\_t\_p\_dc_{p,dc}$	$bb\_t\_p\_dc_{p,dc}$
dc_madrid	0	0
dc_lisbon	1.0425	-0.341
From p_lisbon		
To	$aa\_t\_p\_dc_{p,dc}$	$bb\_t\_p\_dc_{p,dc}$
dc_madrid	1.0425	-0.341
dc_lisbon	0	0
From dc_madrid		
To	$aa\_t\_dc\_s_{dc,s}$	$bb\_t\_dc\_s_{dc,s}$
dc_madrid	0	0
s_merida	0.821	-0.35
s_valencia	0.821	-0.35
s_barcelona	1.1286	-0.327
From dc_lisbon		
To	$aa\_t\_dc\_s_{dc,s}$	$bb\_t\_dc\_s_{dc,s}$
dc_madrid	1.0425	-0.341
s_merida	1.0425	-0.341
s_valencia	1.6256	-0.301
s_barcelona	1.6256	-0.301

Inventory holding Costs

The inventory holding costs were calculated according to Chopra & Meindl (2007) and Amaral & Guerreiro (2014) indicated in chapter 3. Table 10 shows the values obtained from SAP Software. It is important to remember that the values were changed with a coefficient to protect Civiparts' confidentiality agreement.

Table 10 – Inventory Holding Costs

Inventory Holding Costs				
			Lisbon	Madrid
[1]	Obsolescence		~0 €	~0 €
[2]	Handling Cost		602 069 €	522 526 €
[3]	Occupancy Cost		61 480 €	52 090 €
[4]	Miscellaneous Costs		14 878 €	11 727 €
[5]	Total Cost	[1] + [2] + [3] + [4]	678 427 €	586 343 €
[6]	Average inventory value		7 057 179€	1 301 008 €
[7]	Rate warehouse cost per average inventory	[5]/[6]	10%	45%
[8]	Opportunity cost		5%	5%
[9]	Average Cost of item		19.67€	20.22€
[10]	Average inventory holding cost/year	[9] * ([7] + [8])	2,95 €/year	10,11 €/year
[11]	Average inventory holding cost/day	[10] / 261	0,0114 €/day	0,0389 €/day
[12]	Average inventory holding cost/day.Kg		0,0048€/kg day	0,0166€/kg day

The cost of obsolescence [1] is approximately zero and will be considered null because the risk of the items becoming obsolete is very low, or in another words, the items have a long expiration date.

The handling cost [2], the occupancy cost [3] and the miscellaneous cost [4] were collected from SAP software. The total cost [5] is the sum of the previous costs ([1] + [2] + [3] + [4]). It can be observed that the total costs is higher in Lisbon when compared to Madrid. However, the difference in total costs is not significant when compared to the value that each distribution centre stores: Lisbon stores almost six more times in value than Madrid. The average inventory value [6] was retrieved from SGIX software.

The warehouse cost per average inventory [7] is the ratio from the total cost [5] per the average inventory value [6].

The opportunity cost [8] considered for calculating the cost of inventory was given by the company (5%).

The average annual inventory holding cost [10] is calculated by the percentage (45% + 5%= 50% for Madrid; 15% for Lisbon) of the average cost of an item [9] ([9]* ([7] + [8]) = [10]). The average cost of an item between distribution centres had a small variation that can be accepted and has no significate.

The average inventory holding cost per day [11] is the annual cost [10] divided by the working days (365-[52*2]). Average inventory holding cost per day per kilogram is the average inventory holding cost per day [11] divided by the average weight (2.375 kg).

The sum of the percentages [7] and [8] is a very high value in Madrid when compared to Lisbon. The inventory holding cost used in the model is in the last line of table 10, since it is the cost of keeping one kilogram for each work day in the warehouse.

It is assumed that the products in the distribution centres are always ready to be loaded. Although the time required to pick and packaging may differ from location to location, the difference in handling cost [2] is not taken into account. In addition, and considering that the handling time that increases in one location, decreases in another, it would introduce a robustness in the model that does not bring significant results. As we are studying the possibility of centralization in Madrid, it would be possible that the handling cost (time available and human resource) would be higher. However, in case of centralization, the handling cost in Lisbon would be reduced, since the orders from Lisbon would be sent only to Madrid instead of sending them to all the locations. In the stores, the handling cost would also be lower because they would only receive an order from Madrid and would no longer receive the one from Lisbon.

The handling cost from both distribution centres are taken into account in the inventory holding cost as referred. Only the handling cost variations were not considered.

4.2 Mathematical Formulation

Mathematical formulation involves sets, parameters, variables, cost functions, objective function, and restrictions.

4.2.1 Sets

The model uses different sets. These represent groups of objects that belong to a predefined category and that allow to define the network structure, entities and time horizon of the model. Five types of sets and associated indexes are defined.

The “DC” set represents the different distribution centres. In the case of case of Civiparts this set included two elements, the distribution centre of Lisbon and the one in Madrid.

$$DC = \{dc_1, \dots, dc_n\}$$

The set "S" represents the set of stores. In this case we have the stores of Madrid, Merida, Valencia, and Barcelona. These stores are supplied by the distribution centres.

$$S = \{s_1, \dots, s_n\}$$

The “P” set is an auxiliary set. It represents the plants that supply the distributions centres. They don’t exist in reality but it was the entity created to represent the origin of the flow that arrives to the distribution centre.

$$P = \{p_1, \dots, p_n\}$$

The set “T” represents the days of a week. In this model, only the five working days of the week were considered.

$$T = \{t_1, \dots, t_5\}$$

The “W” set represents the weeks. Two weeks will be considered. Each week has five working days. The time scale could be measured only in days, however, representing it in weeks too, allows a better presentation of the results and a better understanding the frequency of deliveries per week more easily.

$$W = \{w_1, \dots, w_n\}$$

4.2.2 Parameters

The parameters represent the data known beforehand. The following parameters were considered in the model:

cap_dc_{dc} – Inventory capacity for distribution centre (dc) in kilograms.

ic_{dc} – Inventory holding cost for each distribution centre (dc) in euros.

$demand_{s}$ – Weekly demand for each store (s), that can be answered from both distribution centres (dc), in one week (w) in kilograms. It represents the sum of the grey and purple arrows from figure 19. This demand also includes the $demand\_madrid_{s,t}$.

$demand\_madrid_{s,t}$ – Demand for each store (s), that must be answered by the distribution centre of Madrid (dc_{Madrid}) in kilograms. It represents the demand from the green arrows in figure 19.

The following parameters are only used as auxiliary to calculate the values from the transportation cost functions (Equations 2 and 3).

$aa\_t\_p\_dc_{p,dc}$ – Values of A for each route from plant (p) to distribution centre (dc) in the equation ($y == A\,x^{B}$).

$bb\_t\_p\_dc_{p,dc}$ – Values of B for each route from plant (p) to distribution centre (dc) in the equation ($y == A\,x^{B}$).

$aa\_t\_dc\_s_{dc,s}$ – Values of A for each route from distribution centre (dc) to store (s) in the equation ($y == A\,x^{B}$).

$bb\_t\_dc\_s_{dc,s}$ – Values of B for each route from distribution centre (dc) to store (s) in the equation ($y == A\,x^{B}$).

4.2.3 Variables

All variables presented in this section are nonnegative variables.

$f\_dc\_s_{dc,s,w,t}$ – Flow between distribution centre (dc) and store (s) on week (w) and day (t), in kilograms.

$f\_p\_dc_{p,dc,w,t}$ –Flow that arrives at the distribution centre (dc) from plant (p) on week (w) and day (t), in kilograms.

$inv\_dc_{dc,w,t}$ – Inventory at the distribution centre (dc) in day (t) and week (w), in kilograms.

z – auxiliary variable to use in the objective function, in euros.

4.2.4 Objective Function

The objective function (1) minimizes the transportation costs and the inventory holding costs of Civiparts supply chain. The costs of transportation represented in the objective functions are derived from the kilograms transported between the Lisbon distribution centre and the Madrid distribution centre (2) and by the kilograms transported from both distribution centres to the stores (3). As explained, the transportation cost functions are power functions because in a linear function the gain of transporting more at the same time is not so evident as in a power function. A positive lower bound of 1e-5 was set for the $f\_dc\_s_{dc,s,w,t}$ and for $f\_p\_dc_{p,dc,w,t}$ in order to keep them in a real domain, otherwise the functions (2) and (3) wouldn't be define for $f\_dc\_s_{dc,s,w,t}$ and $f\_p\_dc_{p,dc,w,t}$ equal to zero. The value is very low and does not have influence in the results.

Inventory holding costs (4) results from the kilograms of items that were present in the distribution centre in that day (including cross docking items). The value is obtained by multiplying the quantity of kilograms by the cost of having one kilogram per day in a warehouse, value that was calculated previously.

The equations (1), (2), (3) and (4) are all in euros.

$$MIn\ Z = \sum_{p}\sum_{dc}\sum_{w}\sum_{t} Transportation\_Costs\_p\_dc_{\ p,dc,w,t} + \sum_{dc}\sum_{s}\sum_{w}\sum_{t} Transportation\_Costs\_dc\_s_{\ dc,s,w,t} + \sum_{dc}\sum_{w}\sum_{t} Inventory\_Costs_{\ dc,w,t} \quad (1)$$

$$Transportation\_Costs\_p\_dc_{\ p,dc,w,t} = f\_p\_dc_{p,dc,w,t} * aa\_t\_p\_dc_{p,dc} * (f\_p\_dc_{p,dc,w,t})^{\ bb\_t\_p\_dc_{p,dc}} \quad (2)$$

$$Transportation\_Costs\_dc\_s_{\ dc,s,w,t} = f\_dc\_s_{\ dc,s,w,t} * aa\_t\_dc\_s_{dc,s} * (f\_dc\_s_{dc,s,w,t})^{\ bb\_t\_dc\_s_{dc,s}} \quad (3)$$

$$Inventory\_Costs_{\ dc,w,t} = inv\_dc_{dc,w,t} * ic_{dc} \quad (4)$$

4.2.5 Constraints

Constraints (5) guarantees that the weekly demand of each store is not inferior to the sum of the flow that arrives at the store that week, which means that it is a constrain to make sure that the demand is fulfilled. Equation (6) is similar to the previous equation, but it is a demand that must be served daily from Madrid. While the weekly demand (5) can be served by any of the distribution centres, $demand\_madrid_{s,t}$ has to be served daily and only by the distribution centre of Madrid.

$$demand_s <= \sum_{dc} \sum_{t} f\_dc\_s_{dc,s,w,t} \ , \ \forall s \in S, \ \forall w \in W \tag{5}$$

$$demand\_madrid_{s,t} <= \sum_{dc} \sum_{t} f\_dc\_s_{dc\_Madrid,s,w,t} \ , \ \forall s \in S, \ \forall w \in W, \ \forall t \in T \tag{6}$$

Equation (7) ensures that the number of kilograms present in the distribution centres is not greater than their capacity. As said, the average inventory was considered to represent 90% of the storage capacity leaving 10% for the simulation flow.

$$inv\_dc_{dc,w,t} <= cap\_dc_{dc} \ , \qquad \forall dc \in DC, \ \forall w \in W, \ \forall t \in T \tag{7}$$

To keep the inventory level up to date, it is necessary to add the kilograms that arrive to the distribution centre - the inbound flow - and subtract the kilograms that leave the distribution centre - the outbound flow. Equation (8) updates the stock level on the 1st day (t) of the week (w), adding the entrances of the same day and subtracting the outbound flow of the previous day (t + 4) from the previous week (w-1). Equation (9) updates the stock on the remaining days of the week.

$$if\ t = 1; \ inv\_dc_{dc,w,t} = \ inv\_dc_{dc,w-1,t+4} + \sum_{p} f\_p\_dc_{p,dc,w,t} - \sum_{s} f\_dc\_s_{dc,s,w-1,t+4} \ , \ \forall dc \in DC, \ \forall w \in W, \ \forall t \in T \tag{8}$$

$$if\ t > 1; \ inv\_dc_{dc,w,t} = \ inv\_dc_{dc,w,t-1} + \sum_{p} f\_p\_dc_{p,dc,w,t} - \sum_{s} f\_dc\_s_{dc,s,w-1,t+4} \ , \ \forall dc \in DC, \ \forall w \in W, \ \forall t \in T \tag{9}$$

The following equations are constraints on the flow. Equation (10) does not allow more outbound flow than the one available in storage.

Equation (11) is related to the flow between the distribution centre of Lisbon and the store of Madrid. As previously said, geographically, the distribution centre of Madrid and the Madrid store are in the same place. So the shipping cost of the Madrid distribution centre to Madrid's store is zero euros. The shipping from Lisbon must be done through the distribution centre and not to the Madrid's store. The reasons that lead to such a decision is that the store in Madrid cannot send items to any other store and the distribution centre can, and can also move it to the Madrid store without any additional cost. So, if the shipment that is made from Lisbon to Madrid only answers the demand from the store in Madrid, there will be no losses in sending to the distribution centre first, however, if there is more flow travelling to Madrid, accumulating the flow is a big advantage in terms of transportation cost. Another reason for this restriction is because shipments to Madrid have to "pay" inventory holding cost in the distribution centre of Madrid, and the shipping to the Madrid's store would "pay" the inventory holding cost in the distribution centre of Lisbon (that is cheaper) since the flow always have to go through a distribution centre. For this reason, shipping from Lisbon to Madrid (distribution centre or store) will always be represented by the flow between the plant of Lisbon (that doesn't "pay" inventory holding cost) and the distribution centre of Madrid, and then, if necessary, will go to the store with no added cost, as said. This will also allow to simulate that the items were already there (the inventory holding cost in Lisbon is not charged, but the transportation cost is, simulating previous deliveries), allowing to study if the inventory level in Madrid should be increased to respond to the demand and not by just doing cross docking. The value of flow must be approximated to zero because equation (3) is not defined for flow null and $bb\_t\_dc\_s_{dc,s}$ negative, otherwise it would represent an error, so the flow must be equal to 1e-5.

The last equation (12) is related to the items represented by the green arrow, that are the ones that arrive at the distribution centre of Madrid sent by the suppliers. The flow from Madrid's plant to Madrid's distribution centre has to be equal to the demand of the items represented by the green arrows, which are only ordered from the Madrid's distribution centre.

$$f\_dc\_s_{\,dc,s,w,t} \;<=\; inv\_dc_{dc,w,t}\,, \forall dc \in DC,\ \forall w \in W,\ \forall t \in T \tag{10}$$

$$f\_dc\_s_{\,\text{dc\_madrid,s\_madrid},w,t} \;=\; 0.00001\,,\ \forall w \in W,\ \forall t \in T \tag{11}$$

$$f\_p\_dc_{\,\text{p\_madrid, dc\_madrid},w,t} \;=\; \sum_{s} demand\_madrid_{s,t},\ \forall w \in W,\ \forall t \in T \tag{12}$$

4.3 Model Validation

Once the model has been constructed, it should be validated through a simple example to guarantee the validity of the results returned by it.

In order to validate the model, for a time period of two weeks, the demand for every store was defined with 1000 kilograms per week, which means 8000 kg leaving and arriving at the distribution centres in two weeks. The $demand\_madrid_{s,t}$ was defined by table 11, which means that at least 100 kilograms will leave from Madrid's distribution centre to each store at the specific day. To test the inventory level, it was also imposed that the $f\_p\_dc_{p\_lisbon,dc\_madrid,w1,t5}$ was 1000 kilograms, in order to keep stock in inventory for one day to the other, in this case, also from week to the other. The inventory holding cost per kg and day was defined as 0.01€ for the Lisbon's distribution centre and 0.06€ for the distribution centre of Madrid.

Table 11 – Demand from Madrid (in kilograms)

	t1	t2	t3	t4	t5
s_madrid	0	100	0	0	0
s_merida	0	0	100	0	0
s_valencia	0	0	0	100	0
s_barcelona	0	0	0	0	100

The model returned an optimal solution z with the value of 1449,5 €. The model is also able to divide the total cost into inventory holding cost, 210 €; cost between the distribution centre of Lisbon and the distribution centre of Madrid, 184,3 €; and cost of transportation from both distribution centres to stores, 1055,2 €.

The flow between plants and DC are presented in table 12. The flow in the table is in accordance with the stipulated data. In these two weeks there are 8000kg arriving at the distribution centres, 4100 Kg in the first week [w1] (1000+2700 from p_lisbon and 400 + 0 from p_madrid) and 3900 Kg in the second week[w2] (800+2700 from p_lisbon and 400+0 from p_madrid). Which means that there are 100 kg that stay in stock from one week to the other, leading to a less demand from part of the distribution centres in the second week.

Table 12 – Flow from plant to distribution centre (in Euros)

From p_lisbon							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	0	0	1000	1000
	w2	0	0	0	0	800	800
dc_lisbon	w1	0	0	0	0	2700	2700
	w2	0	0	0	0	2700	2700
From p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	100	100	100	100	400
	w2	0	100	100	100	100	400
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

The transportation cost from the flow presented in table 12 can be validated in table 13. The cost from p_madrid is always 0 € because there aren't flow going from p_madrid to dc_lisbon or because the cost from p_madrid to dc_madrid is 0 €/kg. The flow from p_lisbon to dc_lisbon is also 0 €/kg. The flow from p_lisbon from dc_madrid only happened in t5, and the values are according to the cost function used.

Table 13 – Transportation cost from plant to distribution centres (in Euros)

Transportation costs from p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
Transportation costs from p_lisbon							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	0	0	98,9	98,9
	w2	0	0	0	0	85,4	85,4
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

Also an important thing to validate is the flow between distribution centres and stores (table 14). It is possible to verify that every store receives its weekly $demand_s$ and it's $demand\_madrid_{s,t}$. Now it is possible to validate the $demand\_madrid_{s,t}$. From table 12 and 14 it is possible to see that there are 1100 kgs arriving at the distribution centre of Madrid in (w1, t5); 1000kg from p_lisbon, the flow that was forced, and 100 from p_madrid, and that only 1000 kgs leave the distribution centre, 900 to s_madrid and 100 to s_barcelona, which means that there are 100 kgs in inventory, that are then send to s_madrid on (w2, t1).

Table 14 – Flow from distribution centre to stores (in kilograms)

Flow from dc_madrid							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	100	0	0	900	1000
	s_merida	0	0	100	0	0	100
	s_valencia	0	0	0	100	0	100
	s_barcelona	0	0	0	0	100	100
w2	s_madrid	100	100	0	0	800	1000
	s_merida	0	0	100	0	0	100
	s_valencia	0	0	0	100	0	100
	s_barcelona	0	0	0	0	100	100
Flow from dc_lisbon							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	900	900
	s_valencia	0	0	0	0	900	900
	s_barcelona	0	0	0	0	900	900
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	900	900
	s_valencia	0	0	0	0	900	900
	s_barcelona	0	0	0	0	900	900

The next table (table 15) shows the transportation cost incurred by the flow between distribution centres and stores. The values are also according to the cost functions. As said, the flow between the distribution centre of Madrid and the store of Madrid is 0€/kg since they share the same space. The cost to the store of Merida and to the store of Valencia has the same rate. The cost to Barcelona is more expensive. The cost from the distribution centre of Lisbon to the stores of Valencia and Barcelona has the same rate and to the store of Merida is cheaper.

Table 15 – Transportation cost from distribution centres to stores (in Euros)

From dc_madrid							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	0	16,4	0	0	16,4
	s_valencia	0	0	0	16,4	0	16,4
	s_barcelona	0	0	0	0	25	25
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	16,4	0	0	16,4
	s_valencia	0	0	0	16,4	0	16,4
	s_barcelona	0	0	0	0	25	25
From dc_lisbon							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	92,2	92,2
	s_valencia	0	0	0	0	188,8	188,8
	s_barcelona	0	0	0	0	188,8	188,8
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	92,2	92,2
	s_valencia	0	0	0	0	188,8	188,8
	s_barcelona	0	0	0	0	188,8	188,8

Table 16 shows the inventory level in both distribution centres, that are also according to the previous statements. Table 17 shows the inventory holding cost and it can be validated by the values in table 16.

Table 16 - Inventory level (in kilograms)

dc_madrid						
	t1	t2	t3	t4	t5	total
w1	0	100	100	100	1000	1300
w2	100	100	100	100	900	1300
dc_lisbon						
	t1	t2	t3	t4	t5	total
w1	0	0	0	0	2700	2700
w2	0	0	0	0	2700	2700

Table 17 – Inventory holding cost (in euros)

dc_madrid						
	t1	t2	t3	t4	t5	Total
w1	0	6	6	6	60	78
w2	6	6	6	6	54	78
dc_lisbon						
	t1	t2	t3	t4	t5	Total
w1	0	0	0	0	27	27
w2	0	0	0	0	27	27

4.4 Model Application

In the application of the mathematical model, tree scenarios will be studied. The first will be the baseline (Scenario 1) where the current solution is studied. The second scenario will be the optimal solution without any restrictions (Scenario 2). To answer to the two questions presented in chapter two, both scenarios will be compared and analysed to find a solution that optimizes the Civiparts supply chain. The two scenarios will be compared to find what might be the handicap that the solution of the second scenario may rise when implemented. After that analysis, a third scenario will be shortly analysed to support the answers to the questions from chapter two and to emphasise the advantages and disadvantages of the solutions from the tree scenarios.

In the first scenario, constraints were created to make the case as close as possible to what actually happens. Restrictions were created so that the stores' demand for each distribution centre be as close to reality as possible and regarding the frequency of delivery to the stores were also created - Constraints (13). Although the demand for all the stores remains the same, the distribution centre that supplies that demand may be different. This constraint state that only the demand from the store of Madrid will go through the distribution centre of Madrid. So, the demand that is not from Madrid's distribution centre, must be fulfilled by the distribution centre of Lisbon (grey arrows from figure 19). This way there will be no centralization in Madrid for products that come from Civiparts Portugal.

$$\sum_{t} f\_p\_dc_{p\_lisboa,dc\_madrid,w,t} \leq demand_{s\_madrid} - \sum_{t} demand\_madrid_{s\_madrid,t}, \forall w \in W \qquad (13)$$

With these constraints, the model did not have much to optimize but in this scenario, the purpose is to see what is being done to compare with the optimal solution (results from scenario 2).

In the second scenario, the model fulfils the weekly $demand_s$ and daily $demand\_madrid_{s,t}$ without any restrictions, either in terms of the distribution centre that supplies the stores or in terms of the frequency of delivery to each store.

The third scenario arises in order to study the total centralization of the distribution in Madrid and to compare it with the optimal solution, Constraint (14) was added only in the third scenario in order to force a total centralization. Initially only the two first scenarios were planned but with the outcome of the results a third scenario was created to test and validate (or not), the optimal solution. With this constraint, the outbound flow of the Lisbon's distribution centre to the stores is zero. However, the flow still go to the Madrid's distribution centre from Lisbon because in model, the flow to the distribution centre of Madrid leaves from the plant in Lisbon (p_lisbon) and not from the distribution centre.

$$f\_dc\_s_{dc\_lisboa,s,w,t} \leq 0.00001 \quad , \ \forall s \in S, \ \forall w \in W, \ \forall t \in T \tag{14}$$

With the aim of assessing the robustness of the solutions found, a sensitive analysis to some parameters will also be performed.

5 Results and Discussion

This chapter aims to reveal the quantitative results obtained by the mathematical model and the qualitative results from other aspects that the mathematical solution does not contemplate such as the environmental impact, the service level and the human resources availability.

Throughout this chapter, the routes and quantities of each delivery will be presented as well as their associated cost. The comparison between the baseline scenario (Scenario 1) and the optimal scenario (Scenario 2) are explained in detail. The comparison with the centralization scenario (Scenario 3) appears only at the end. Computational results are shown in Appendices 8.2, 8.3 and 8.4.

5.1 Results

Tables 18 and 19 show the flow that arrives at each distribution centre for Scenario 1 and 2, respectively, whether from suppliers (from p_lisbon to dc_lisbon, from p_madrid to dc_madrid and to dc_lisbon) or between distribution centres (from p_lisbon to dc_madrid).

Table 18 – Flow from plant to distribution centre (in kilograms) - Scenario 1

From p_lisbon							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	4000	0	0	4000
	w2	0	0	0	0	4000	4000
dc_lisbon	w1	0	5000	0	0	0	5000
	w2	3400	0	0	1600	0	5000
From p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	5000	4500	5900	5500	4000	24900
	w2	5000	4500	5900	5500	4000	24900
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

Table 19 - Flow from plant to distribution centre (in kilograms) - Scenario 2

From p_lisbon							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	5700	0	1700	0	0	7400
	w2	1700	0	1700	0	4000	7400
dc_lisbon	w1	0	0	0	0	1600	1600
	w2	0	0	0	0	1600	1600
From p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	5000	4500	5900	5500	4000	24900
	w2	5000	4500	5900	5500	4000	24900
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

It is possible to verify that the values arriving from p_lisbon are different in the two scenarios. As for what arrives from suppliers to Madrid (from p_madrid), the value remains the same. This equality was already expected since the demand remains the same. The flow that we are interested in studying is the one that leaves p_lisbon because it is the flow that comes from Civiparts Portugal. The values from p_madrid for dc_madrid are the values of the suppliers that deliver in the Madrid distribution centre to be distributed to the stores (green arrows from figure 9) and the local suppliers that only supply the Madrid's store (red arrows in figure 9).

In the baseline scenario, the flow arriving from p_lisbon is 4000 kg per week for dc_madrid and 5000 kg per week for dc_lisbon. In the optimal scenario these values change to 7400 kg per week for dc_madrid and 1600 kg per week for dc_lisbon. It is noticed that the value that arrives from p_lisbon to dc_lisbon is smaller in the optimal scenario. This indicates that there was a centralization but that it was not a total centralization. If it were, the value that arrived at dc_lisbon from p_lisbon would be 0.

Another point to note is that the frequencies from p_lisbon in the optimal scenario are two and three per week for dc_madrid and one per week for dc_lisbon. In the baseline scenario, the frequency of delivery in distribution centres is one per week for dc_madrid and one and two for dc_lisbon. This means that in the optimal scenario, there are a greater frequency of deliveries to Madrid from Lisbon.

Tables 20 and 21 show the costs associated with the inbound flow of the distribution centres. In the optimal scenario, it is possible to verify that the cost of transportation is higher. In this case, the transport values are not identical in both weeks although the demand is the same. The difference of cost between weeks is partly due to the fact that in one week there are three deliveries and in another week there are only two.

In terms of values, the optimal scenario has a transportation cost of 485.7 € higher in the total of the two weeks. The cost per kilograms was expected to be lower since the flow is higher, but in fact, on average, the cost is higher in the optimal scenario, 0.066 €/kg against 0.062 €/kg in the baseline scenario. The reason why this happens is due to the frequency of delivery.

The other values have a cost of 0 € because, in practice, there are no transport (p_lisbon and dc_lisbon share the same location; the same happens in Madrid) and there is no flow between p_madrid and dc_lisbon.

Table 20 - Transportation cost from plant to distribution centres (in Euros) - Scenario 1

Transportation costs from p_lisbon								
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	246.5	0	0	246.5
	w2	0	0	0	0	246.5	246.5
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
Transportation costs from p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

Table 21 - Transportation cost from plant to distribution centres (in Euros) - Scenario 2

Transportation costs from p_lisbon							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	311,3	0	140.3	0	0	451.6
	w2	140,3	0	140,3	0	246,5	527.1
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
Transportation costs from p_madrid							
		t1	t2	t3	t4	t5	Total
dc_madrid	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0
dc_lisbon	w1	0	0	0	0	0	0
	w2	0	0	0	0	0	0

The flows between the distribution centres and the stores are represented in tables 22 and 23. As for the stores in Madrid and Merida, flow is the same in both scenarios. Barcelona's and Valencia's stores are only served by the Madrid distribution centre in the optimal scenario. This means that the 1700 kg of the demand of Barcelona and Valencia, supplied by Lisbon in the baseline scenario, are being supplied from Madrid in the optimal scenario.

In table 23, it is also possible to verify that the centralization is not total because the store in Merida continues to be supplied by both distribution centres.

Table 22 – Flow Between distribution centres and stores (in kilograms) - Scenario 1

Flow from dc_madrid							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	1900	1800	6000	2200	2100	14000
	s_merida	1200	1600	500	800	700	4800
	s_valencia	600	100	2800	1000	400	4900
	s_barcelona	1300	1000	600	1500	800	5200
w2	s_madrid	1900	1800	2000	2200	6100	14000
	s_merida	1200	1600	500	800	700	4800
	s_valencia	600	100	2800	1000	400	4900
	s_barcelona	1300	1000	600	1500	800	5200
Flow cost from dc_lisbon							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	1600	0	0	0	1600
	s_valencia	0	1700	0	0	0	1700
	s_barcelona	0	1700	0	0	0	1700
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	1600	0	1600
	s_valencia	1700	0	0	0	0	1700
	s_barcelona	1700	0	0	0	0	1700

Table 23 - Flow Between distribution centres and stores (in kilograms) - Scenario 2

Flow from dc_madrid							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	5900	1800	2000	2200	2100	14000
	s_merida	1200	1600	500	800	700	4800
	s_valencia	600	100	4500	1000	400	6600
	s_barcelona	3000	1000	600	1500	800	6900
w2	s_madrid	1900	1800	2000	2200	6100	14000
	s_merida	1200	1600	500	800	700	4800
	s_valencia	600	100	4500	1000	400	6600
	s_barcelona	3000	1000	600	1500	800	6900
Flow from dc_lisbon							
		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	1600	1600
	s_valencia	0	0	0	0	0	0
	s_barcelona	0	0	0	0	0	0
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	1600	1600
	s_valencia	0	0	0	0	0	0
	s_barcelona	0	0	0	0	0	0

Tables 24 and 25 represent the cost associated with the transportation of flow represented in the previous tables. The transportation costs to Merida are the same for both scenarios, since the demand is distributed in the same way.

The transportation costs from Lisbon to Valencia are 0 € and 294.5 €/week, the transportation costs from Madrid to Valencia are 376.9 €/week and 325.3€/week in the optimal scenario and in the baseline scenario, respectively. This represents a saving of 242.9 €/week in the transportation from the distribution centres to Valencia. For Barcelona, the saving is 180.2 €/week to Barcelona.

Table 24 – Transportation cost from distribution centres to stores (in Euros) - Scenario 1

From dc_madrid							
To		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	82.4	99.3	46.6	63.3	58	349.6
	s_valencia	52.5	16.4	142.9	73.2	40.3	325.3
	s_barcelona	140.7	117.9	83.6	154.9	101.5	590.6
w2	s_madrid	0	0	0	0	0	0
	s_merida	82.4	99.3	46.6	63.3	58	349.6
	s_valencia	52.5	16.4	142.9	73.2	40.3	325.3
	s_barcelona	140.7	117.9	83.6	154.9	101.5	590.6
From dc_lisbon							
To		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	134.8	0	0	0	134.8
	s_valencia	0	294.5	0	0	0	294.5
	s_barcelona	0	294.5	0	0	0	294.5
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	134.8	0	134.8
	s_valencia	294.5	0	0	0	0	294.5
	s_barcelona	294.5	0	0	0	0	294.5

Table 25 – Transportation cost from distribution centres to stores (in Euros) - Scenario 2

From dc_madrid							
To		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	82.4	99.3	46,6	63.3	58	349.6
	s_valencia	52.5	16.4	194.5	73.2	40.3	376.9
	s_barcelona	247	117.9	83.6	154.9	101.5	704.9
w2	s_madrid	0	0	0	0	0	0
	s_merida	82.4	99.3	46,6	63.3	58	349.6
	s_valencia	52.5	16.4	194.5	73.2	40.3	376.9
	s_barcelona	247	117.9	83.6	154.9	101.5	704.9
From dc_lisbon							
To		t1	t2	t3	t4	t5	Total
w1	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	134.8	134.8
	s_valencia	0	0	0	0	0	0
	s_barcelona	0	0	0	0	0	0
w2	s_madrid	0	0	0	0	0	0
	s_merida	0	0	0	0	134.8	134.8
	s_valencia	0	0	0	0	0	0
	s_barcelona	0	0	0	0	0	0

Tables 26 and 27 shows the inventory present at the distribution centres each day. It can be verified that the presence of inventory in the distribution centre of Madrid is higher in optimal scenario, which is in accordance with the centralization discussed in the previous tables. It is also possible to note that the Lisbon distribution centre is only used once per week (at day t5) in the optimal scenario. The 1600 kilograms represent the demand of Merida, which does not have its distribution centralized.

Table 26 - Inventory at the distribution centre (in kilograms) - Scenario 1

dc_madrid						
	t1	t2	t3	t4	t5	total
w1	5000	4500	9900	5500	4000	28900
w2	5000	4500	5900	5500	8000	28900
dc_lisbon						
	t1	t2	t3	t4	t5	total
w1	0	5000	0	0	0	5000
w2	3400	0	0	1600	0	5000

Table 27 - Inventory at the distribution centre (in kilograms) – Scenario 2

dc_madrid						
	t1	t2	t3	t4	t5	total
w1	10700	4500	7600	5500	4000	32300
w2	6700	4500	7600	5500	8000	32300
dc_lisbon						
	t1	t2	t3	t4	t5	total
w1	0	0	0	0	1600	1600
w2	0	0	0	0	1600	1600

The inventory holding costs are shown in tables 28 and 29. The total cost of holding inventory in Lisbon is lower in the optimal scenario in 16.3 € per week. The cost of holding inventory in Madrid is higher in the optimal scenario in 56.5 € per week, which results in an inventory holding cost higher in 40.2 € per week in the optimal scenario.

Table 28 - Inventory holding costs (in Euros) - Scenario 1

dc_madrid						
	t1	t2	t3	t4	t5	Total
w1	83	74.7	164.3	91.3	66.4	479.7
w2	83	74.7	97.9	91.3	132.8	479.7
dc_lisbon						
	t1	t2	t3	t4	t5	Total
w1	0	24	0	0	0	24
w2	16.3	0	0	7.7	0	24

Table 29 - Inventory holding costs (in Euros) - Scenario 2

dc_madrid						
	t1	t2	t3	t4	t5	Total
w1	177.6	74.7	126.2	91.3	66.4	536.2
w2	111.2	74.7	126.2	91.3	132.8	536.2
dc_lisbon						
	t1	t2	t3	t4	t5	Total
w1	0	0	0	0	7.7	7.7
w2	0	0	0	0	7.7	7.7

5.2 Scenarios Comparison

5.2.1 Baseline Scenario *versus* Optimal Scenario

Table 30 shows the total costs given by the mathematical model. It is possible to verify that the inventory holding costs and the transportation cost from Lisbon to Madrid increase from the baseline scenario to the optimal scenario but the benefit in the distribution to the stores compensates that loss in about 150 € per week, which means around 600 € per month.

Table 30 – Total costs comparison

Total Costs				
	Scenario 1 - Baseline	Scenario 2 - Optimal	Difference	%
Inventory holding costs	1007.48 €	1087.72 €	**+80.24 €**	**+7.96%**
Transportation Costs (Total)	4487.55	4110.93 €	**-376.62 €**	**-8.39%**
Transportation cost from Lisbon to Madrid	493.02 €	978.61 €	**+485.59 €**	**+98.49%**
Transportation costs from both DCs to stores	3994.53 €	3132.32 €	**-862.21 €**	**-21.58%**
Total Costs (z)	5495.03 €	5198.65 €	**-296.38 €**	**-5.39%**

It is possible to verify that the operation where the optimal scenario saves the most is in the deliveries to the stores. If we only consider the transportation costs, the savings are 376.62 € per week, which means around 1500 € per month, representing an 8.39% reduction.

In terms of inventory holding costs, using the distribution centre of Madrid as a centralized warehouse would become more expensive. In addition to being supplied by the Lisbon distribution centre, which causes the products to pass through two distribution centres, the Madrid's distribution centre has a lower inventory turnover in the current scenario (baseline scenario), so, the inventory holding cost allocated to each item is slightly higher. The fact of increasing the turnover or the stock level in Madrid, will also increase the costs of handling in Madrid. This increase in costs could be compensate by the decrease in handling costs in Valencia's and Barcelona's stores, for instance.

The store of Merida is an ambiguous situation because the model doesn't not centralize its distribution route. The store would continue to receive orders from both distribution centres. This would not bring as much benefit as a total centralization because it doesn't simplify the work in Lisbon, that would still have to prepare orders for Madrid and for Merida, instead of dealing with the Madrid demand only (in case of full centralization). In the next subchapter, this situation will be study in more detail.

5.2.2 Optimal Scenario *versus* Forced Centralization Scenario

The third scenario, the scenario where total centralization is forced through the use of constraint (14) is not studied in detail in the previous subchapter because its results are very similar to the results of the optimal scenario, except for the Merida store, that have its distribution of products from Civiparts Portugal centralized in Madrid.

The Merida's store, geographically located in the middle of both distribution centres is the store that raises the most obstacles to centralization. Therefore, the constraint added to the optimal scenario obliged Merida store to be supplied by Madrid distribution centre (Forced Centralization Scenario). The results obtained are shown in table 31.

Table 31 – Total costs comparison

Total Costs				
	Scenario 2 - Optimal	Scenario 3 - Forced centralization	Difference	%
Inventory holding costs	1087.72 €	1125.48 €	**+37.76**	**+3.47%**
Transportation Costs (Total)	4110.93 €	4082.68 €	**-28.25**	**-0.69%**
Transportation cost from Lisbon to Madrid	978.61 €	1094.94 €	**+116.33**	**+11.89%**
Transportation costs from both dc to stores	3132.32 €	2987.74 €	**-144.58**	**-4.62%**
Total Costs (z)	5198.65 €	5208.16 €	**+9.51**	**-0.18%**

The total transportation cost when centralizing all the distribution are cheaper than the optimal scenario in 28.25 € in the two weeks. However, the inventory holding costs are higher, and the gain in transportation costs does not compensate for the increase in inventory holding costs, which provokes the model to "recommend" a not centralized distribution. It is important to remember that the inventory holding costs in Merida's store were not considered, which means that if the inventory holding costs in Merida (obsolescence cost, handling cost, occupancy cost, miscellaneous costs and cost of capital) decreased by 9.51€ in every two weeks, then the full centralization would be the optimal scenario. If we consider the inventory holding cost of Madrid (0,0389 €/day), 9.51€ means around 25 items per day during two weeks. To the stores of Barcelona and Valencia the model recommended the centralization of the distribution (in both scenarios) and didn't need to know the decrease in inventory holding costs in the stores. The delivery frequency between Lisbon and Madrid in the forced centralization scenario was the same as in the optimal scenario.

5.3 Sensitivity Analysis

A sensitivity analysis was made for some parameters to evaluate the robustness of the previously obtained solutions. The parameters chosen were the demand of each store, the transportation cost, the inventory holding costs and the distribution centres' capacity.

The demand is something that influences the transportation costs (due to the non-linear function) because with more demand, the lower the cost per kilogram is. In order to test the consistency of the solution in the optimal scenario, several tests were performed, where both demands ($demand_s$ and $demand\_madrid_{s,t}$) were increased and decreased. Tables 32 and 33 show the variations made on the demands. The column "0" is the optimal solution. The tests were done varying the demand by 5% in 5% but only the most relevant results are presented in the tables (the same method was used to all the parameters tested in this subchapter).

The reduction of the demand from Madrid (table 32) lead to two different results: For Valencia, the demand from Madrid could reduce 50% that the system would still recommend the centralization. For Barcelona a reduction lower than 5% in the demand would recommend a decentralized distribution. Although a reduction is not expected, it must be taken into account. A reduction of 5% may happen in some weeks due to variation of the demand. In a demand's reduction of 5%, the store of Barcelona and Merida would have their distribution decentralized and Valencia would have it centralize.

Increasing the demand of the stores from Madrid's distribution centre by 20% also led to a total centralization. According to the company, a demand increase is more likely to happen than a reduction of the demand.

Table 32 – Sensitivity analyses for the demand from Madrid (in Euros)

$demand\_madrid_{s,t}$	-50%	-5%	0	+10%	+20%
Inventory Holding Costs	941.22	1035.8	1087.72	1145.53	1138.76
Transportation Costs (Total)	3671.15	4140.26	4110.93	4171.71	4399.25
Transportation cost from Lisbon to Madrid	123.42	586.07	978.61	1014.57	1343.82
Transportation costs from both dc to stores	3547.73	3554.19	3132.32	3157.14	3055.43
Total Costs	4612.37	5176.06	5198.65	5317.24	5538.01
Centralized Stores	Valencia	Valencia	Valencia and Barcelona	Valencia and Barcelona	All

When decreasing the $demand_s$ by 25% the model also recommends a full centralization (table 33), but a reduction in the demand of that magnitude is not expected. The solution of the model for this situation makes sense because the ratio between flow from Lisbon and the flow from Madrid would reduce (same flow from Madrid and less flow from Lisbon) and point in the synergy from the flows of Madrid and subsequent centralization.

Increasing the $demand_s$ in a reasonable range (until 50%) did not change the distribution to Merida, leaving the centralized distribution only to the stores of Barcelona and Valencia (table 33).

Table 33 - Sensitivity analyses for the demand (in Euros)

$demand_s$	-25%	-20%	0	+50%
Inventory Holding Costs	845.77	892.83	1087.72	1574.94
Transportation Costs (Total)	2685.18	3032.03	4110.93	5765.53
Transportation cost from Lisbon to Madrid	133.36	301.86	978.61	1829.37
Transportation costs from both dc to stores	2551.82	2730.17	3132.32	3936.16
Total Costs	3530.95	3924.86	5198.65	7340.47
Centralized Stores	All	Valencia and Barcelona	Valencia and Barcelona	Valencia and Barcelona

Regarding the transportation costs to the stores ($Transportation\_Costs\_dc\_s_{\ dc,s,w,t}$), only by increasing the costs by 50% (more precisely 47%) could achieve a total centralization, otherwise, the optimal solution wouldn't change (table 34). On the other hand, a reduction of 55% would lead to a total decentralized solution. If the reduction in the transport costs between distribution centres and stores was only 45%, then the distribution to Merida and Barcelona would be decentralized (table 34).

Table 34 - Sensitivity analyses for the transportation costs to the stores (in Euros)

Transportation costs from both dc to stores	-55%	-45%	-40%	0	+45%	+50%
Inventory Holding Costs	1027.54	1047.60	1067.66	1087.72	1133.16	1153.70
Transportation Costs (Total)	2329.06	2567.05	2686.35	4110.93	5457.42	5544.83
Transportation cost from Lisbon to Madrid	640.82	622.63	681.06	978.61	1033.74	1090.86
Transportation costs from both dc to stores	1688.24	1944.42	2005.29	3132.32	4423.68	4453.97
Total Costs	3356.60	3614.65	3754.01	5198.65	6590.58	6698.53
Centralized Stores	None	Valencia	Valencia and Barcelona	Valencia and Barcelona	Valencia and Barcelona	All

Regarding the transportation costs from Lisbon to Madrid ($Transportation\_Costs\_p\_dc_{\ p,dc,w,t}$), decreasing the cost by 50% would lead to a total centralization but a reduction of cost with this value is not expected to happen. On the other hand, only an increase of 50% would decentralized the distribution to Barcelona (table 35). Increasing it by 100% would lead to a total decentralization.

Table 35 - Sensitivity analyses for the transportation costs between distribution centres (in Euros)

Transportation cost from Lisbon to Madrid	-50%	-45%	0	+50%	+100%
Inventory Holding Costs	1125.48	1106.60	1087.72	1067.66	1047.60
Transportation Costs (Total)	3555.66	4773.03	4110.93	4491.43	4817.55
Transportation cost from Lisbon to Madrid	586.34	612.36	978.61	1144.33	1232.51
Transportation costs from both dc to stores	2969.32	3054.07	3132.32	3347.10	3585.04
Total Costs	4681.14	4773.03	5198.65	5559.09	5865.15
Centralized Stores	All	Valencia and Barcelona	Valencia and Barcelona	Valencia	None

If the inventory holding costs ($Inventory\_Costs_{\ dc,w,t}$) in Lisbon increased or decreased by 100%, nothing would change in terms of distribution (table 36). The results were the same when applied to Madrid's distribution centre inventory holding costs (table 37). For the distribution to the stores of Barcelona and Valencia be supplied by both distribution centres in the optimal scenario, the inventory holding costs of Madrid would have to increase 740%. However, an inventory holding cost increase of 310% already indicated a decentralization of the distribution to Barcelona's store. To centralize the distribution to Merida only by increasing the inventory holding cost in Lisbon, it would have to increase in 570%.

Table 36 - Sensitivity analyses for the inventory holding costs in Lisbon (in Euros)

Inventory Holding Costs	-50% (only in Lisbon)	0	+100% (only in Lisbon)
Inventory Holding Costs	1080.04	1087.72	1103.08
Transportation Costs (Total)	4046.16	4110.93	5149.24
Transportation cost from Lisbon to Madrid	903.15	978.61	903.16
Transportation costs from both dc to stores	3143.01	3132.32	3143.00
Total Costs	5126.20	5198.65	5149.24
Centralized Stores	Valencia and Barcelona	Valencia and Barcelona	Valencia and Barcelona

Table 37 - Sensitivity analyses for the inventory holding costs in Madrid (in Euros)

Inventory Holding Costs	-50% (only in Madrid)	0	+100% (only in Madrid)
Inventory Holding Costs	579.76	1087.72	2160.08
Transportation Costs (Total)	4029.10	4110.93	4046.16
Transportation cost from Lisbon to Madrid	896.78	978.61	903.15
Transportation costs from both dc to stores	3132.32	3132.32	3143.01
Total Costs	4608.86	5198.65	6206.24
Centralized Stores	Valencia and Barcelona	Valencia and Barcelona	Valencia and Barcelona

Regarding the distribution centres capacity (cap_dc_{dc}), it is possible to observe that the days with most inventory in each distribution centre (table 26), 10700 kg in Madrid and 5000 kg in Lisbon, represent 53% and 3% of the remaining capacity (total capacity minus the level of average inventory). Although these values are in kilograms and should be in cubic meters, with these values, capacity problems are not expected. However, since we are using average inventory values, there are days when the inventory will be higher (than the average inventory) leaving the remaining capacity lower than the one used in the model. This situation can bring problems in Madrid. Unfortunately, the data available do not allow a study at this level.

5.4 Advantages and Disadvantages of the Centralization

As mentioned, this study was triggered due to a potential growth of the purchase of products to Civiparts Portugal by Civiparts Spain and to optimize the supply chain. The distribution cost is a considerable expense that must be taken into account when choosing the distribution routes and frequency. The decisions that Civiparts make regarding its distribution strategy will always influence the inventory holding costs, the profit margins, the inventory levels and the service levels. Therefore, it is necessary to study the impact on each factor of a change in the current supply chain, namely for products that leave the Portuguese distribution centre. However, part of the distribution that goes to the stores is from other suppliers, not being bought to Civiparts Portugal, which obliges to add the products that goes from the distribution centre in Madrid to the stores in order to take advantage of the synergies in joining orders.

Taking into account the company's inventory management system, the total centralization of distribution allows for better management of inventory because it leads to a concentration of safety stocks and an optimized purchase management (with the possibility for more frequent shipments) leading to a reduction of average stock in all Spanish locations, and also with a faster delivery, since Madrid can get to any location in 24 hours and, from Lisbon to Barcelona and Valencia the shipment takes 48 hours.

In Table 38 are presented some of the examples that represent the savings/losses of the total centralized solution when compared to the actual scenario regarding the inventory Holding Costs.

Table 38 – Advantages and disadvantages Of the inventory Holding Costs

Inventory Holding Costs		
Inventory Holding Costs [1]		↑
DC Madrid	Average Inventory [2]	↓
	Handling Cost [3]	↑
	Service level [4]	↑
Stores (except Madrid's)	Average Inventory [5]	↓
	Handling Cost [6]	↓
	Service level [7]	↑

In the previous subchapter, it was already discussed the inventory holding costs [1] and the transportation costs. At the Madrid's distribution centre, it could be kept the same level of inventory [2] or it could be reduced, but increase it, at least in quantity of each item will have no advantage. Keeping the same inventory will bring no change in relation to what is practiced now, but since we have a greater frequency of delivery from Lisbon, going from one time a week to three times a week, the safety stock no longer has to last for a week but for two days. Still regarding the increase of inventory, having more quantity of each item does not bring any advantage because there will be items with long periods of storage, using resources and opportunity cost. The advantage would be to increase the diversity of items (increasing the service level [4]), so that the stores request less and less to Lisbon and more to Madrid, although it is almost impossible to avoid urgent deliveries from Lisbon because Madrid will not be able to have as many diversity of items as Lisbon. As seen in the sensitivity analysis, the increase of demand from Madrid will lead to the advantages of centralization being even more pronounced (table 32). Where the stock level could increase, would be in the Lisbon distribution centre, but since Lisbon already has the safety stock for Spanish stores (and the rest of the Civiparts in the world) the level in Lisbon also would not have to increase. The stock level might even reduce since the distribution centre in Madrid will keep safety stock for the Spanish stores without increasing its stock due to the higher frequency of delivery from Lisbon (and indirectly because the delivery to the stores from Madrid is daily).

In relation to the stores' average inventory level [5], and since delivery to stores from Madrid is daily, we can lower the stock level in all stores by having a safety stock in Madrid, which will be in the stores 24h after being requested. In the worst scenario, the item will arrive in 48 hours if it has to be requested to Lisbon in an urgent order. 48 hours is what already happens in for Valencia and Barcelona, so the new solution will improve the service level in the stores [7] and in the worst scenarios, maintain it.

The big point against centralization will always be the cost of inventory where handling costs [3] are included. Whether the inventory level is maintained or lowered at the distribution centre of Madrid, handling costs will always be higher, either by receiving a larger volume that needs to be consolidated or by sending more volume to each store at a time. With regard to the handling cost in stores [6], it is expected that this cost will decrease since the stores will have less stock and also because the stores will receive only from Madrid, except for urgent orders, that will be small packages from Lisbon.

It will be up to the company to decide whether the increase in labour needs in Madrid justifies or not to centralize. The cost of hiring another person was not considered because it does not seem necessary (and also because there was not enough information to make such a decision) but this is not an unanimous decision within the company.

Centralization can also be considered as a strategy for the future. If there is a gain in centralizing the distribution for the current number of stores, then, this trend will be even more evident if the company wants to open more stores in other places in Spain. If one day the agent of Vigo happens to be turn into a store, the most probable scenario is that the centralization of the distribution is the most suitable and the most affordable.

The analysis of all the determining factors reinforce the fact that the centralization of the distribution contributes to the optimization of the supply chain, allowing to reduce distribution costs by around 650 € per month (22 business days). On the other hand, it turns out that centralizing the distribution to Merida is not the optimal solution but centralizing it has an extra cost of around 21 € per month. All these points go according to table 3 from chapter 3, given by Amaral & Guereiro (2014). The company won't have full control over the distribution since it is an outsourced service, but they can always avoid the delayed transportation, synchronizing the orders, which means that what arrives has to arrive in the morning, and what goes out has to leave at the end of the day, so that it gives time to do crossdocking in Madrid if necessary, otherwise it will take more than 48 hours to go from Lisbon to Barcelona and Valencia.

5.5 Conclusions

Overall, the mathematical model aimed to choose from which distribution centre (Lisbon, Madrid or both) each store should be served and to choose what is the optimal delivery frequency to each, taking advantage of transportation costs synergies. At the same time, the model also considered minimizing inventory holding costs. There was a challenge in trying to get the best combination to fulfil the demand from each store, having the ability to assess the trade-off between these two fundamental logistics costs.

In the following subchapters the answer to the two main questions presented in this dissertation will be given.

5.5.1 From which distribution centre each store should be served?

Regarding the distribution centre that should serve each store, although it is not the cheapest option (more expensive in 21 € per month, 22 business days), all stores in Spain should be supplied by the Madrid distribution centre. The Madrid store, which is in the same physical space as the distribution centre, is indirectly supplied by the Lisbon distribution centre but only because Madrid is a distribution centre too. Figure 22 show the supply chain structure recommended. The purple arrows were added to the supply chain structure. The grey and purple arrows represent the products that arrive in the distribution centre of Lisbon from the suppliers and are then distributed to the Spanish stores. The grey ones represent the urgent orders (keeping the same routes as before but only to urgent orders) and the purple ones represent the new normal orders (centralized distribution in Madrid). The normal orders do a transhipment between distribution centres, centralizing the distribution to Spain in Madrid. From the distribution centre to the stores, the green and purple arrows are dispatched together to achieve transportation costs synergies.

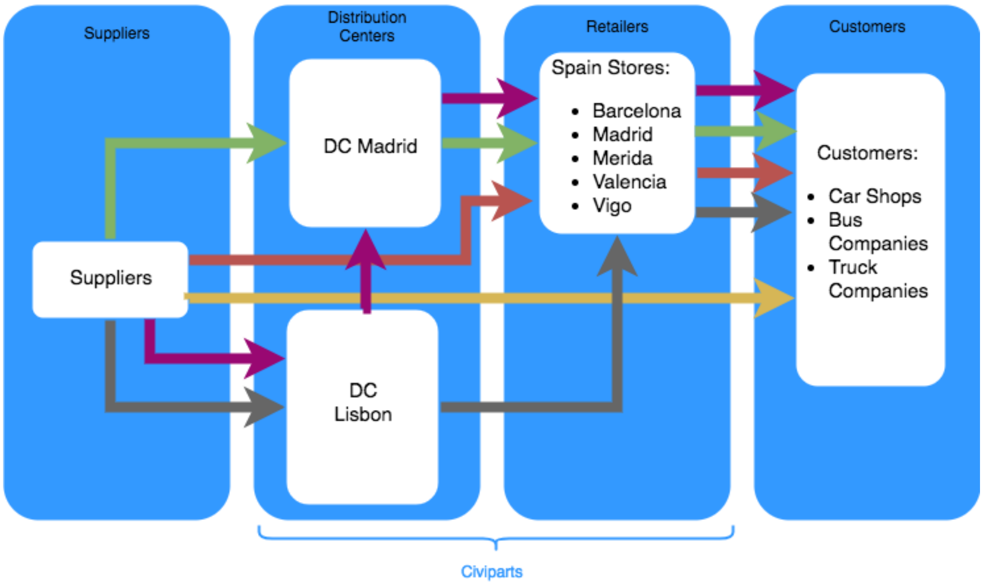


Figure 22 – Supply Chain Structure

Figure 23 shows the distribution from products that leave the distribution centre in Portugal and go to the stores. The green arrows represent both green and purple arrows from the distribution centre to the stores from the previous image.

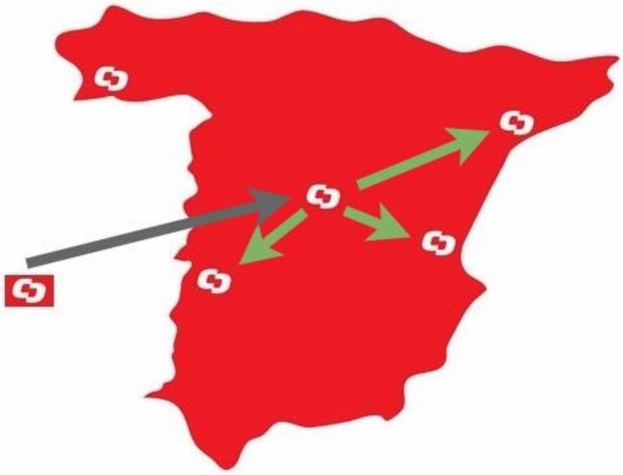


Figure 23 – Recommended Network Design

5.5.2 Delivery Frequency

Regarding the frequency of deliveries, the mathematical model tells us that the Lisbon-Madrid route should be done 2 or 3 times a week (result from the first and second week). More than one or two times than what is currently being done.

On the other hand, the mathematical model tells us not to do the Lisbon-Valencia and the Lisbon-Barcelona routes. Lisbon-Merida is a route that also disappears despite the opposite indication from the mathematical model, as said, 21 € per month more expensive with the centralization. The saving in kilometres is therefore considerable, it increases two times the distance between Lisbon and Madrid and withdraws once each of the routes from Lisbon to the stores of Merida, Valencia and Barcelona. This reduction in kilometres also points to a reduction of the emission of pollutant gases, being therefore a decision that also helps the environment.

Table 33 represents the new frequencies for each route departing from the distribution centres. From the distribution centres of Lisbon, the shipping's will leave only to Madrid, three times a week. From the distribution centre of Madrid, the shipping's will leave every day to each store, Merida, Valencia e Barcelona.

Table 39 – Route Frequency

Route Frequency							
From - To		Monday	Tuesday	Wednesday	Thursday	Friday	Total
DC Lisbon	s_madrid	X		X		X	3
	s_merida						0
	s_valencia						0
	s_barcelona						0
DC Madrid	s_merida	X	X	X	X	X	5
	s_valencia	X	X	X	X	X	5
	s_barcelona	X	X	X	X	X	5

6 Conclusions and Future Work

This chapter aims to present the conclusions of this thesis and to present the most important results from the developed analyses. In the end some suggestions will be given to be done in the future.

Civiparts is a company that resells heavy vehicles parts, being responsible for the purchase of products, storage and subsequent sale. The optimization of distribution processes is crucial in order to guarantee a high level of service without high levels of stock.

The work developed in this dissertation began by elaborating a description of the company and describing the points to be optimized in order to obtain a global view of the entire supply chain. The existence of multiple vendors with different delivery methods, with different rules for each country and a varied offer of products are some of the factors that make the entire network quite complex and challenging.

The focus of the dissertation was on the outbound flow from the distribution centre of Lisbon to Spain. The process of distribution from the distribution centre of Lisbon to the stores was described and the factors with the greatest impact for the current situation were characterized.

Civiparts Spain is a company that uses two distribution centres, one in Madrid and one in Lisbon, and both of them serve all the stores in Spain. It was intended to verify if this was the best solution for the supply chain or if it could be optimized. Civiparts hire an outsourced company, company T, to do the transportation. All stores in Spain receive weekly orders from the Lisbon distribution centre. From the Madrid distribution centre, there were daily orders to Valencia and Barcelona, and weekly to Merida (although urgent shipments were sent everyday). The monthly cost of transportation between the distribution centres and the stores in Spain was around 15 000€.

A literature review was developed to provide a good base of study and a lot of similar models to the one that was adapted to tackle the problem at stake. The importance of transportation and the breakdown of transportation costs were analysed in chapter 3. Chopra & Meindl (2007), clarified the benefits of the centralization. Carvalho (2010) stated the importance of the trade-off between time and space. Amaral & Guerreiro (2014), provided a summary of the main trade-offs between inventory holding costs and transportation costs and a model that also could be adapted in the thesis. Inventory holding costs and the importance of keeping inventory stored to answer unexpected demand and that allow to obtain economies of scale was also mentioned.

An analysis of the organization's global system, together with the scientific research were undertaken to identify potential opportunities for improvement derived from the overall flow across the supply chain instead of considering the gain from one particular warehouse. From this process, a study was carried out using a mathematical model that embeds the trade-off between inventory holding costs and transportation costs, and it concludes that centralization in Madrid was the best option for the distribution of products in Spain. On one hand, this decision saves on transportation costs, allows for an improvement in the service level by being able to put the products in stores faster and allows for a reduction of stock due to centralization. On the other hand, additional inventory holding cost emerge (only in Madrid). After analysing all these factors, it was possible to conclude that the option of centralizing the distribution to Spain in Madrid is valid and beneficial to the organization.

The future design of the organization was developed based on the transportation costs between each entity and the costs of inventories in the distribution centres. The challenge in this project was to combine a solution with a high impact on the performance of the supply chain at a low cost, i.e., without having to open new facilities, using only the existing facilities.

Initially, in order to answer the questions defined at the beginning, the idea was to develop a mixed integer linear programming model, but it quickly became clear that this model did not translate economies of scale into the transportation cost, so it was decided to develop a mixed integer nonlinear programming model where the gain in the cost for transporting more kilograms each time is more pronounced.

The model was constructed with data collected from a period of 20 weeks, at the Madrid and Lisbon distribution centres during visits, meetings or with access to the SGIX software. The data were changed with a coefficient to protect the confidentiality of the company data, but did not change the outcome of the results.

To calculate the demand of each store, an average weight was considered based on the records of the transportation done by the two companies, Civiparts and the transportation company contracted in outsource, company T. In terms of limitations, it is important to say that the demand considered is an average demand in Kilograms and not items or parts. The demand for each product would take a lot of time and wouldn't bring any further or more realistic results because the transportation cost is, most of the times, based on the weight of the shipment.

The model was solved with the help of GAMS software. Several scenarios were tested and analysed to validate the decisions. This led to the recommended solution not being the one provided by the model as the optimal solution. The model indicated that only the Valencia and Barcelona stores should have centralized distribution, but a total centralization scenario indicated that centralizing the Merida distribution was only 21 € per month more expensive than being supplied by both distribution centres. Other reasons such as organization, stock level, cost of transportation (which is cheaper in the centralization but inventory holding costs are higher leading to a decentralized solution) lead to full centralization being the option to recommend.

Also, in terms of environmental impact, it is believed that the results are better in the centralized distribution. Although the company that does the transportation is an outsourced company (so it may do the same routes), Civiparts will no longer require the travels from Lisbon to Barcelona, Valencia and Merida and will only increase the route from Lisbon to Madrid two times.

The previous paragraphs already revealed the answers to the questions for which it was intended to respond: From each distribution centre should each store be served and how many times a week. The answer is that the only shipment that leaves the Lisbon distribution centre is the one that goes to the other distribution centre, the one in Madrid, in a transhipment operation three times a week, Monday, Wednesday and Friday. The routes from the distribution centre of Madrid to the stores of Merida, Valencia and Barcelona are done every day.

With regard to the final solution of the optimization model, the results are substantially better when compared to the current scenario, with savings representing around 5% of total costs (8% if consider the transportation costs only), which is a very attractive situation that the company needs to study to later implement. With centralization it is possible to make bigger margins at the same price, or sell the items for less money and make the same margins, gaining competitive advantage either because it has lower operation costs or because it sells at a more affordable price, gaining the clients preference.

For the future work, it is highlighted the implementation of the centralization of the distribution to Spain, thus reducing the existing stock in stores. In this sense, a detailed analytical study of the number of each item that should be kept in the stores and in the Madrid distribution centre should be done to create an automatic tool (probably to implement in the SGIX software) able to manage this process.

In order to assess this potential, Civiparts should confront the results obtained in this dissertation with their current forecasting methods and capacities, as well as understanding if there are constraints that might not have been considered (for example, if hiring someone is needed, etc.) that could change the results or even achieving better ones. Overall, it seems to be an unexplored potential for more efficient decisions in terms of transportation, which could concretize into very favourable conditions.

The centralization of distribution will lead to a new supply chain dynamic, so it is crucial to study which internal limits should be adopted to optimize the process. Given the relationships among the various entities of the supply chain, it is essential that this analysis will be done with the focus of being implemented in a computer software. It is also essential to define all the necessary requirements to ensure all the proposed improvements and the maximum integrity and quality of information. The work to be developed could be integrated into the optimization of the inventory management strategy and the analysis of the transportation profitability, completing detailed study of the supply chain from an end-to-end perspective.

The environmental aspect could also be studied in more detail since it was an aspect that was only studied in a superficial way. This is a very sensitive and important topic that should be considered, therefore another idea for a future work should be to simultaneously model the transportation costs, the inventory holding cost and the environmental impact in one objective function. Perhaps it may be solved by a bi-objective mixed integer nonlinear programming that could show the best planning of orders to minimize those variables.

To conclude, there are aspects that can be improved in future stages, however, it is expected that this dissertation has a positive contribution to the academic community regarding the study of nonlinear transport cost functions using a real example and that the analysis and developed tools will be of great use to Civiparts decision-making process.

7 References

Amaral, J. V., & Guerreiro, R. (2014). Mensuração dos impactos econômico-financeiros dos trade-offs entre os custos de manutenção de inventários e de transporte. *Enfoque: Reflexão Contábil*, *33*(2), 55–69.

Arampantzi, C., & Minis, I. (2017). A new model for designing sustainable supply chain networks and its application to a global manufacturer. *Journal of Cleaner Production*, *156*, 276–292.

Ballou, R. H. (2008). *LOGISTICA Administración de la cadena de suministro* (5th ed.). Prentice Hall - Pearson.

Biz-devolpment.com. (2011). Retrieved from http://www.biz-development.com/SupplyChain/6.20.1.supply-chain-management-overview.htm on 7/11/2016

Cachon, G. P. (2004). The Allocation of Inventory Risk in a Supply Chain: Push, Pull, and Advance-Purchase Discount Contracts. *Management Science*, *50*(2), 222–238.

Cardoso, S. R., Barbosa-póvoa, A. P. F. D., & Relvas, S. (2013). Design and planning of supply chains with integration of reverse logistics activities under demand uncertainty, *226*, 436–451.

Carvalho, J. C. et al. (2010). *Logística e Gestão na Cadeia de Abastecimento* (1st ed.). Portugal: Edições Silabo.

Çelebi, D. (2015). Inventory control in a centralized distribution network using genetic algorithms: A case study. *Computers and Industrial Engineering, Istanbul Technical University, Turkey*, *87*, 532–539.

Chopra, S., & Meindl, P. (2007). *Supply Chain Management: Strategy, Planning and Operations* (3rd ed.). USA: Pearson Prentice Hall.

Christopher, M. (2011). *Logistics & Supply Chain Management* (4th ed.). Great Britain: Prentice Hall Financial Times - Pearson.

Civiparts. (2016). Civiparts. Retrieved from http://www.civiparts.com/ on 7/12/2016

Coyle, J. J., Novack, R. A., Gibson, B. J., & Bardi, E. J. (2011). *Transportation - A Supply Chan Perspective* (7th ed.). USA: South-Western Cengage Learning.

Dhakry, N. S., & Bangar, P. A. (2013). Minimization of Inventory & Transportation Cost Of an Industry " -A Supply Chain Optimization. *International Journal of Engineering Research and Applications*, *3*(5), 96–101.

Li, J., Chu, F., & Chen, H. (2011). Coordination of split deliveries in one-warehouse multi-retailer distribution systems. *Computers and Industrial Engineering*, *60*(2), 291–301.

Marufuzzaman, M., Ekşioğlu, S. D., & Hernandez, R. (2015). Truck versus pipeline transportation cost analysis of wastewater sludge. *Transportation Research Part A: Policy and Practice*, *74*, 14–30.

Monthatipkul, C., & Yenradee, P. (2008). Inventory/distribution control system in a one-warehouse/multi-retailer supply chain. *International Journal of Production Economics*, *114*(1), 119–133.

Napolitano, M. (2015, February). 6 Tips for Optimizing Your Distribution Network. *Supply Chain 24/7*. Retrieved from http://www.supplychain247.com/article/6_tips_for_optimizing_your_distribution_network on

07/03/2017

Nors, G. (2016). NORS. Retrieved from www.nors.com on 7/12/2016

Pham, T., & Yenradee, P. (2017). Optimal Supply Chain Network Design with Process Network and BOM under Uncertainties : A Case Study in Toothbrush Industry $. *Computers & Industrial Engineering*, *108*, 177–191.

Rodrigues, E. (2016). *Supply Chain & Transports Optimization Volkswagen Autoeuropa Case Study*. Master Thesis, Department of Engineering and Management, Instituto Superior Tecnico.

Shapiro, J. F. (2006). *Modeling The Supply Chain* (2nd ed.). USA: Duxbury.

Simchi-Levi, D., Simchi.Levi, E., & Kaminsky, P. (2008). *Designing and Managing the Supply Chain Concepts, Strategies, and Cases* (3rd ed.). USA: McGraw-Hill College.

Speranza, M. G. (2018). Trends in transportation and logistics. *European Journal of Operational Research*, *264*(3), 830–836.

Sukati, I., Hamid, A. B., Baharun, R., & Yusoff, R. M. (2012). The Study of Supply Chain Management Strategy and Practices on Supply Chain Performance. *Faculty of Management and Human Resourse Development Universiti Teknologi Malaysia, UTM Skudai Malaysia*, *40*, 274–281.

Torkul, O., Yilmaz, R., Selvi, I. H., & Cesur, M. R. (2016). A real-time inventory model to manage variance of demand for decreasing inventory holding cost. *Computers and Industrial Engineering*, *102*, 435–439.

Tseng, Y., Yue, W. L., & Taylor, M. A. P. (2005). The role of transportation in logistics chain. *Proceedings of the Eastern Asia Society for Transportation Studies*, *5*, 1657–1672.

Varela, T. P., Póvoa, A. P. F. D. B., & Novais, A. Q. (2011). Bi-objective optimization approach to the design and planning of supply chains : Economic versus environmental performances. *Computers and Chemical Engineering*, *35*, 1454–1468.

Volvo. (2016). Volvo trucks. Retrieved from http://www.volvotrucks.com.pt/ on 7/12/2016

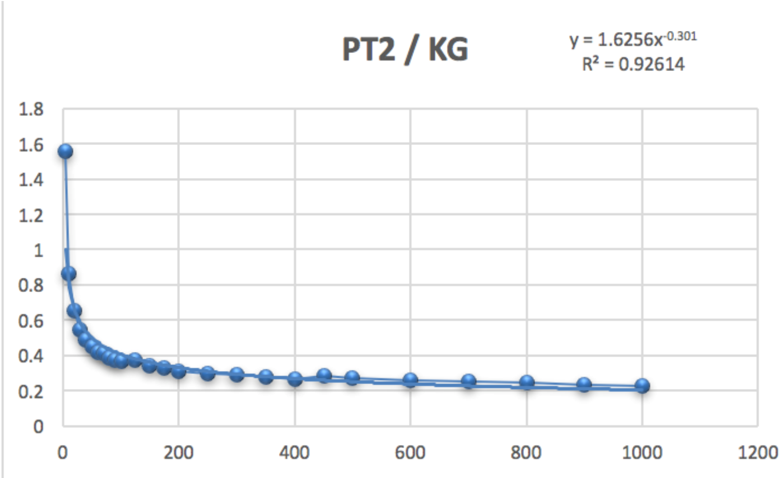
Wan, X., & Sanders, N. R. (2017). The negative impact of product variety: Forecast bias, inventory levels, and the role of vertical integration. *International Journal of Production Economics*, *186*, 123–131.

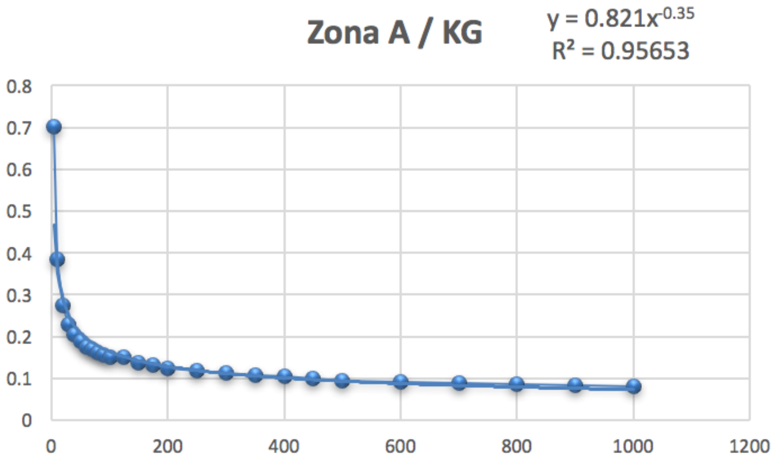
Wiles, P. G., & Van Brunt, B. (2001). Optimal location of transshipment depots. *Transportation Research Part A: Policy and Practice*, *35*(8), 745–771.

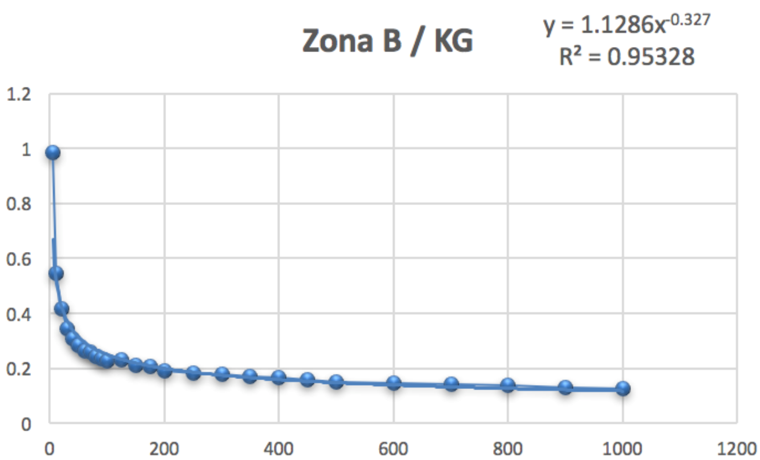
Zahran, S. K., & Jaber, M. Y. (2017). Investigation of a consignment stock and a traditional inventory policy in a three-level supply chain system with multiple-suppliers and multiple-buyers. *Applied Mathematical Modelling*, *44*, 390–408.

8 Appendices

8.1 – Power regressions for columns PT2, A and B







8.2 – Computational results for Baseline Scenario (Scenario 1)

```
--- Job Tese_sc1.gms Start 09/24/17 18:03:11 24.8.5 r61358 WEX-WEI x86 64bit/MS Windows
GAMS 24.8.5   Copyright (C) 1987-2017 GAMS Development. All rights reserved
Licensee: Small MUD - 5 User License                    S170228:0339AO-WIN
          Universidade Tecnica de Lisboa, Instituto Superior Tecnico DC2650
          License for teaching and research at degree granting institutions
--- Starting compilation
--- Tese_sc1.gms(258) 3 Mb
--- Starting execution: elapsed 0:00:00.008
--- Tese_sc1.gms(196) 4 Mb
--- Generating MINLP model tese
--- Tese_sc1.gms(199) 6 Mb
---   291 rows  281 columns  839 non-zeroes
---   1,263 nl-code  180 nl-non-zeroes
--- Tese_sc1.gms(199) 4 Mb
--- Executing KNITRO: elapsed 0:00:00.016

KNITRO           24.8.5 r61358 Released May 10, 2017 WEI x86 64bit/MS Windows

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Knitro presolve eliminated 140 variables
and 220 constraints.

datacheck:               0
hessian_no_f:            1
maxtime_real:            1000
newpoint:                3
par_concurrent_evals:    0
Knitro changing algorithm from AUTO to 1.
Knitro changing bar_initpt from AUTO to 3.
Knitro changing bar_murule from AUTO to 4.
Knitro changing bar_penaltycons from AUTO to 1.
Knitro changing bar_penaltyrule from AUTO to 2.
Knitro changing bar_switchrule from AUTO to 2.
Knitro changing linesearch from AUTO to 1.
Knitro changing linsolver from AUTO to 2.
Knitro shifted start point to satisfy presolved bounds (130 variables).
Knitro fixing 50 variables eliminated from the presolve.
Knitro reinitializing 90 variables eliminated from the presolve.

Problem Characteristics                    ( Presolved)
-----------------------
Objective goal:  Minimize
Number of variables:                   280 (       140)
```

```
    bounded below:                     130 (        90)
    bounded above:                       0 (        20)
    bounded below and above:            10 (        30)
    fixed:                               0 (         0)
    free:                              140 (         0)
Number of constraints:                 290 (        70)
    linear equalities:                  90 (        40)
    nonlinear equalities:               90 (         0)
    linear inequalities:               110 (        30)
    nonlinear inequalities:              0 (         0)
    range:                               0 (         0)
Number of nonzeros in Jacobian:        728 (       369)
Number of nonzeros in Hessian:          90 (        80)

  Iter      Objective      FeasError   OptError    ||Step||    CGits
--------  --------------  ----------  ----------  ----------  -------
       0   2.602068e+003   5.903e+003
      10   2.610217e+003   5.901e+003  2.619e+000  1.464e+004        0
      20   2.761114e+003   4.297e+003  2.675e+000  3.850e+002        0
      30   3.465751e+003   3.991e+003  2.711e+000  2.421e+002        0
      40   4.172066e+003   1.679e+003  2.776e+000  7.113e+001        0
      50   6.316826e+003   1.839e+001  9.051e+000  5.530e+002        0
      60   6.105804e+003   6.703e-009  1.303e-001  6.186e-001        0
      70   6.099512e+003   7.276e-012  1.081e-001  4.284e+000        0
      80   6.067085e+003   1.182e-011  1.095e+000  3.694e+000        0
      90   6.049543e+003   7.276e-012  1.203e-001  7.802e-002        0
     100   6.017246e+003   7.276e-012  2.109e-001  4.729e+001        1
     110   6.003579e+003   3.638e-012  8.681e-001  3.549e-002        0
     120   5.974986e+003   8.185e-012  1.391e-001  5.213e+001        0
     130   5.934716e+003   7.276e-012  7.033e-002  1.413e+000        0
     140   5.895443e+003   7.276e-012  5.981e+000  9.414e-001        0
     150   5.879771e+003   1.819e-012  9.012e-002  1.073e+000        0
     160   5.853046e+003   7.276e-012  5.998e-002  4.648e-001        0
     170   5.837601e+003   7.276e-012  1.349e+000  3.309e+001        0
     180   5.832676e+003   7.276e-012  1.809e-002  1.225e+001        0
     190   5.817790e+003   1.819e-012  7.930e-003  3.213e+001        0
     200   5.777961e+003   7.276e-012  8.952e-001  1.511e+002        0
     210   5.762494e+003   7.276e-012  1.001e+000  6.697e+001        0
     220   5.759876e+003   7.276e-012  9.354e-003  4.704e+001        0
     230   5.728690e+003   7.276e-012  1.668e-002  1.008e+001        0
     240   5.692917e+003   7.276e-012  8.083e-003  1.928e+001        1
     250   5.670049e+003   7.276e-012  1.229e-002  1.014e+002        0
     260   5.629361e+003   1.455e-011  9.428e-003  5.305e+001        0
     270   5.557415e+003   7.262e-010  1.093e-001  5.602e+001        0
     280   5.533502e+003   3.638e-012  4.111e-002  1.143e-001        0
     290   5.507007e+003   7.276e-012  1.193e-001  2.789e+001        0
     300   5.495719e+003   7.276e-011  1.078e-001  6.394e+000        0
     306   5.495032e+003   3.391e-009  2.556e-005  5.883e-002        0
```

EXIT: Locally optimal solution found.

```
Final Statistics
----------------
Final objective value               =  5.49503215199690e+003
Final feasibility error (abs / rel) =   3.39e-009 / 5.74e-013
Final optimality error  (abs / rel) =   2.56e-005 / 3.35e-007
# of iterations                     =        306
# of CG iterations                  =        319
# of function evaluations           =        361
# of gradient evaluations           =        308
# of Hessian evaluations            =        307
Total program time (secs)           =       0.247 (     0.219 CPU time)
Time spent in evaluations (secs)    =       0.040

===============================================================================

Solve finished: status = optimal
--- Restarting execution
--- Tese_sc1.gms(199) 2 Mb
--- Reading solution for model tese
--- Executing after solve: elapsed 0:00:00.352
--- Tese_sc1.gms(242) 3 Mb
*** Status: Normal completion
--- Job Tese_sc1.gms Stop 09/24/17 18:03:11 elapsed 0:00:00.354
```

8.3 - Computational results for Optimal Scenario (Scenario 2)

```
--- Job Tese_sc2.gms Start 09/24/17 18:14:01 24.8.5 r61358 WEX-WEI x86 64bit/MS Windows
GAMS 24.8.5   Copyright (C) 1987-2017 GAMS Development. All rights reserved
Licensee: Small MUD - 5 User License                    S170228:0339AO-WIN
          Universidade Tecnica de Lisboa, Instituto Superior Tecnico DC2650
          License for teaching and research at degree granting institutions
--- Starting compilation
--- Tese_sc2.gms(252) 3 Mb
--- Starting execution: elapsed 0:00:00.009
--- Tese_sc2.gms(190) 4 Mb
--- Generating MINLP model tese
--- Tese_sc2.gms(193) 6 Mb
---   289 rows  281 columns  829 non-zeroes
---   1,263 nl-code  180 nl-non-zeroes
--- Tese_sc2.gms(193) 4 Mb
--- Executing KNITRO: elapsed 0:00:00.020

KNITRO           24.8.5 r61358 Released May 10, 2017 WEI x86 64bit/MS Windows

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Knitro presolve eliminated 140 variables
and 220 constraints.

datacheck:               0
hessian_no_f:            1
maxtime_real:            1000
newpoint:                3
par_concurrent_evals:    0
Knitro changing algorithm from AUTO to 1.
Knitro changing bar_initpt from AUTO to 3.
Knitro changing bar_murule from AUTO to 4.
Knitro changing bar_penaltycons from AUTO to 1.
Knitro changing bar_penaltyrule from AUTO to 2.
Knitro changing bar_switchrule from AUTO to 2.
Knitro changing linesearch from AUTO to 1.
Knitro changing linsolver from AUTO to 2.
Knitro shifted start point to satisfy presolved bounds (130 variables).
Knitro fixing 50 variables eliminated from the presolve.
Knitro reinitializing 90 variables eliminated from the presolve.

Problem Characteristics                    ( Presolved)
-----------------------
Objective goal:  Minimize
Number of variables:                   280 (       140)
```

```
    bounded below:                       130 (         90)
    bounded above:                         0 (         20)
    bounded below and above:              10 (         30)
    fixed:                                 0 (          0)
    free:                                140 (          0)
Number of constraints:                   288 (         68)
    linear equalities:                    90 (         40)
    nonlinear equalities:                 90 (          0)
    linear inequalities:                 108 (         28)
    nonlinear inequalities:                0 (          0)
    range:                                 0 (          0)
Number of nonzeros in Jacobian:          718 (        359)
Number of nonzeros in Hessian:            90 (         80)

  Iter      Objective      FeasError   OptError    ||Step||    CGits
--------  --------------  ----------  ----------  ----------  -------
       0   2.602068e+003  5.903e+003
      10   2.619043e+003  5.885e+003  3.768e+001  1.276e+003        0
      20   2.793242e+003  4.000e+003  4.442e+001  1.445e+002        0
      30   3.455255e+003  3.989e+003  4.772e+001  9.217e+001        0
      40   3.510733e+003  3.990e+003  4.913e+001  2.172e+001        0
      50   6.507281e+003  7.261e+001  7.709e+001  1.641e+003        0
      60   6.021471e+003  7.276e-012  3.908e-001  2.908e+002        0
      70   5.909611e+003  3.638e-012  2.050e-001  7.338e-001        0
      80   5.882821e+003  3.638e-012  2.410e-001  8.143e-001        0
      90   5.866374e+003  7.276e-012  2.182e-001  1.559e+000        0
     100   5.851388e+003  7.276e-012  3.878e-001  2.858e+000        0
     110   5.842082e+003  7.276e-012  6.761e-002  2.302e-001        0
     120   5.817153e+003  7.276e-012  1.839e+000  6.265e+000        0
     130   5.785773e+003  7.276e-012  2.083e-002  2.488e+001        2
     140   5.769708e+003  3.638e-012  1.424e-002  4.337e+000        1
     150   5.754683e+003  7.276e-012  8.013e-003  1.173e+001        0
     160   5.736362e+003  7.276e-012  9.485e-003  3.618e+001        0
     170   5.690350e+003  1.819e-012  8.072e-002  1.023e+002        1
     180   5.684841e+003  7.276e-012  9.575e-003  9.062e+000        1
     190   5.642583e+003  7.276e-012  1.828e-002  4.740e+002        0
     200   5.611177e+003  7.276e-012  9.798e-003  1.793e+001        0
     210   5.589175e+003  7.276e-012  1.444e-002  2.665e+001        1
     220   5.549518e+003  7.276e-012  1.373e-002  3.074e-001        1
     230   5.546497e+003  3.638e-012  2.024e-002  3.114e+001        0
     240   5.488796e+003  5.124e-011  5.772e-001  5.920e+002        0
     250   5.424205e+003  7.276e-012  2.071e-002  3.278e+000        0
     260   5.401957e+003  3.638e-012  1.615e-002  4.805e+001        0
     270   5.367556e+003  7.276e-012  3.120e-002  1.199e+002        0
     280   5.349932e+003  7.276e-012  7.703e-003  4.217e+001        1
     290   5.288151e+003  6.366e-012  5.336e-002  5.102e+002        0
     300   5.267407e+003  7.276e-012  6.459e-003  5.114e-002        0
     310   5.219581e+003  7.276e-012  5.642e-003  4.629e+002        2
     320   5.212908e+003  7.276e-012  1.279e-003  4.259e+002        0
     326   5.198647e+003  7.276e-012  2.493e-005  1.032e+000        1
```

```
EXIT: Locally optimal solution found.

Final Statistics
----------------
Final objective value               =  5.19864748962237e+003
Final feasibility error (abs / rel) =   7.28e-012 / 1.23e-015
Final optimality error  (abs / rel) =   2.49e-005 / 3.26e-007
# of iterations                     =        326
# of CG iterations                  =        123
# of function evaluations           =        362
# of gradient evaluations           =        328
# of Hessian evaluations            =        327
Total program time (secs)           =       0.267 (     0.188 CPU time)
Time spent in evaluations (secs)    =       0.036

===============================================================================

Solve finished: status = optimal
--- Restarting execution
--- Tese_sc2.gms(193) 2 Mb
--- Reading solution for model tese
--- Executing after solve: elapsed 0:00:00.374
--- Tese_sc2.gms(236) 3 Mb
*** Status: Normal completion
--- Job Tese_sc2.gms Stop 09/24/17 18:14:02 elapsed 0:00:00.376
```

8.4 - Computational results for Centralization Scenario (Scenario 3)

```
--- Job Tese_sc3.gms Start 09/24/17 18:14:58 24.8.5 r61358 WEX-WEI x86 64bit/MS Windows
GAMS 24.8.5   Copyright (C) 1987-2017 GAMS Development. All rights reserved
Licensee: Small MUD - 5 User License                     S170228:0339AO-WIN
          Universidade Tecnica de Lisboa, Instituto Superior Tecnico DC2650
          License for teaching and research at degree granting institutions
--- Starting compilation
--- Tese_sc3.gms(270) 3 Mb
--- Starting execution: elapsed 0:00:00.008
--- Tese_sc3.gms(212) 4 Mb
--- Generating MINLP model tese
--- Tese_sc3.gms(215) 6 Mb
---   289 rows  281 columns  829 non-zeroes
---   1,263 nl-code  180 nl-non-zeroes
--- Tese_sc3.gms(215) 4 Mb
--- Executing KNITRO: elapsed 0:00:00.014

KNITRO           24.8.5 r61358 Released May 10, 2017 WEI x86 64bit/MS Windows

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Knitro presolve eliminated 140 variables
and 220 constraints.

datacheck:               0
hessian_no_f:            1
maxtime_real:            1000
newpoint:                3
par_concurrent_evals:    0
Knitro changing algorithm from AUTO to 1.
Knitro changing bar_initpt from AUTO to 3.
Knitro changing bar_murule from AUTO to 4.
Knitro changing bar_penaltycons from AUTO to 1.
Knitro changing bar_penaltyrule from AUTO to 2.
Knitro changing bar_switchrule from AUTO to 2.
Knitro changing linesearch from AUTO to 1.
Knitro changing linsolver from AUTO to 2.
Knitro shifted start point to satisfy presolved bounds (130 variables).
Knitro fixing 50 variables eliminated from the presolve.
Knitro reinitializing 90 variables eliminated from the presolve.

Problem Characteristics                    ( Presolved)
-----------------------
Objective goal:  Minimize
Number of variables:                   280 (       140)
```

```
    bounded below:                     120 (         80)
    bounded above:                       0 (         20)
    bounded below and above:            20 (         40)
    fixed:                               0 (          0)
    free:                              140 (          0)
Number of constraints:                 288 (         68)
    linear equalities:                  90 (         40)
    nonlinear equalities:               90 (          0)
    linear inequalities:               108 (         28)
    nonlinear inequalities:              0 (          0)
    range:                               0 (          0)
Number of nonzeros in Jacobian:        718 (        359)
Number of nonzeros in Hessian:          90 (         80)

  Iter      Objective      FeasError   OptError    ||Step||    CGits
--------  --------------  ----------  ----------  ----------  -------
       0   2.591715e+003  5.903e+003
      10   2.591776e+003  5.903e+003  1.635e+002  1.437e+004        0
      20   2.696102e+003  4.566e+003  1.150e+001  8.203e+000        0
      30   3.404291e+003  3.993e+003  1.145e+001  6.370e+001        0
      40   3.458075e+003  3.995e+003  1.134e+001  3.329e-001        0
      50   3.884305e+003  3.884e+003  1.041e+001  1.817e+003        0
      60   6.618337e+003  1.499e+001  1.722e+001  7.880e+001        0
      70   6.504992e+003  7.276e-012  7.882e-002  9.153e+001        0
      80   6.462817e+003  7.276e-012  8.099e-002  4.515e+001        0
      90   6.394033e+003  7.276e-012  4.134e-002  5.130e+001        0
     100   6.340182e+003  7.276e-012  7.500e-002  5.249e+000        1
     110   6.312118e+003  7.276e-012  5.705e-002  4.993e-001        1
     120   6.263896e+003  7.276e-012  3.153e-002  1.355e+000        0
     130   6.158331e+003  7.276e-012  3.441e-002  1.482e+000        0
     140   6.048372e+003  1.819e-012  1.032e+000  5.410e+000        0
     150   6.043633e+003  7.276e-012  8.138e-002  1.999e-003        0
     160   6.042753e+003  7.276e-012  6.411e-002  1.714e+000        0
     170   5.988581e+003  1.819e-012  7.469e-002  1.960e+001        1
     180   5.916002e+003  3.638e-012  4.621e-002  2.481e+001        1
     190   5.879339e+003  7.276e-012  4.149e-002  1.631e+001        2
     200   5.838583e+003  1.819e-012  1.357e+000  8.617e-002        0
     210   5.838142e+003  7.276e-012  2.212e-002  2.601e-001        0
     220   5.781461e+003  3.638e-012  3.211e-002  3.998e-001        1
     230   5.718283e+003  7.276e-012  2.231e-001  7.759e+001        2
     240   5.703907e+003  7.276e-012  1.712e-002  3.034e+001        1
     250   5.632304e+003  7.276e-012  1.178e-002  7.490e+001        0
     260   5.565184e+003  7.276e-012  7.103e-002  1.363e+002        1
     270   5.513695e+003  1.819e-012  9.013e-002  3.160e+001        1
     280   5.469978e+003  7.276e-012  3.409e-002  4.737e+001        0
     290   5.413946e+003  7.276e-012  6.872e-002  1.100e+003        0
     300   5.396896e+003  7.276e-012  1.146e-002  4.346e-001        0
     310   5.376660e+003  7.276e-012  3.419e-002  1.340e+002        1
     320   5.351763e+003  7.276e-012  4.607e-003  1.400e+002        0
     330   5.308456e+003  7.276e-012  1.059e-002  2.833e+002        0
     340   5.235629e+003  7.276e-012  1.391e-002  5.819e+001        0
```

```
    346   5.208151e+003  7.276e-012  4.407e-008  7.183e-004        0
```

EXIT: Locally optimal solution found.

```
Final Statistics
----------------
Final objective value               =  5.20815068149948e+003
Final feasibility error (abs / rel) =   7.28e-012 / 1.23e-015
Final optimality error  (abs / rel) =   4.41e-008 / 5.77e-010
# of iterations                     =        346
# of CG iterations                  =        165
# of function evaluations           =        409
# of gradient evaluations           =        348
# of Hessian evaluations            =        347
Total program time (secs)           =       0.298 (     0.234 CPU time)
Time spent in evaluations (secs)    =       0.050

===============================================================================

Solve finished: status = optimal
--- Restarting execution
--- Tese_sc3.gms(215) 2 Mb
--- Reading solution for model tese
--- Executing after solve: elapsed 0:00:00.400
--- Tese_sc3.gms(258) 3 Mb
*** Status: Normal completion
--- Job Tese_sc3.gms Stop 09/24/17 18:14:59 elapsed 0:00:00.401
```