TÉCNICO LISBOA

Locating Logistic Hubs

The Case Study of Worten

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Abstract

Nowadays is vital for a company to differentiate itself from the competition. For Worten, the solution is to offer a service capable of delivering online orders throughout Portugal's Mainland within a two-hour window. Currently, this is already being in some Worten's stores, only serving customers which are within a limited covering radius. To reach all of Portugal's demand, it is necessary to implement several logistic hubs to serve the 278 municipalities spread along Portugal with the purpose of serving online orders.

With the information provided by Worten, it was possible to design several scenarios that could meet the company's requirements. Based on the location and operational cost of each order; the coordinates, demand and cost per square meter of each municipality; and other factors, such as covering radius, hub capacity and percentage of demand covered, it was possible to reach interesting results.

From the different scenarios, it was possible to conclude that multiple allocations can be more cost-effective than single. In addition, the 25 km radius is the most realistic model but can easily be the most expensive due to the short covering area. Finally, with 5 logistic hubs, and depending on the covering radius, it is possible to cover between 51% and 88% of online orders.

To conclude, several scenarios will be presented in this project, providing several courses of action when implementing logistic hubs.

Keywords: Logistic Hubs, p-Hub median, Single Allocation, Multiple Allocation, Location Problems.

Resumo

Hoje em dia é crucial para uma empresa se diferenciar da concorrência. Para a Worten, a solução é oferecer um serviço capaz de entregar encomendas em online em todo o continente português dentro de um prazo de duas horas. Atualmente, isto já está a ser feito em algumas lojas da Worten, servindo apenas clientes que se encontram dentro de um raio de cobertura limitado. A fim de atingir toda a procura de Portugal Continental, é necessário implementar vários centros logísticos para servir os 278 municípios espalhados por Portugal com o objetivo de servir as encomendas online.

Com a informação fornecida pela Worten, foi possível conceber vários cenários que poderiam satisfazer os requisitos da empresa. Com base na localização e custo operacional de cada encomenda; as coordenadas, procura e custo por metro quadrado de cada município; e outros fatores, tais como raio de cobertura, capacidade do hub e percentagem da procura coberta, foi possível alcançar resultados interessantes.

A partir dos diferentes cenários, foi possível concluir que múltiplas alocações podem ser mais rentáveis do que uma única. Além disso, o raio de 25 km é o modelo mais realista, mas pode facilmente ser o mais caro devido à curta área de cobertura. Finalmente, com 5 hubs logísticos, e dependendo do raio de cobertura, é possível cobrir entre 51% e 88% das encomendas online.

Para concluir, serão apresentados vários cenários neste projeto, fornecendo várias linhas de ação na implementação de hubs logísticos.

Palavras-Chave: Logistic Hubs, p-Hub median, Single Allocation, Multiple Allocation, Location Problems.

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Acronyms

B2B Business to Business

B2C Business to Consumer

HD Home Delivery

HLP Hub Location Problems

LP Location Problems

MA Multiple Allocation

OC Operational Costs

OF Objective Function

PBL Pick-by-Line

PBLS Pick-by-Line-by-Store

PBS Pick-by-Store

PTL Put to Light

PTS Put to Store

PTZ Put to Zone

SA Single Allocation

SCED Complimentary Service of Home Deliveries

SD Store Delivery

SKU Stock Keeping Unit

SM Slow Mover

WMS Warehouse Management System

Introduction

In this first chapter of the Dissertation, a brief contextualisation of the problem at hand will be presented. Furthermore, we present the objectives that we aim to achieve and analyse throughout this work, and lastly, the structure adopted together with a small description of each chapter.

1.1 Problem Contextualisation

Worten's online channel has been growing in the past years, and with the pandemic, an increase in online orders was perceptible. Consequently, all the operations in the warehouse were adapted partially due to this new reality of sales, and with this Worten needs to distinguish itself from the competition.

A way of differentiating in the retail sector is by offering shorter delivery times, that nowadays represent a strong challenge to these types of supply chains while trying to optimise the transportation cost. Another important aspect to have in mind is that it is important to always have all the SKUs available to preserve and maintain customer loyalty.

It is important to point out that in Worten's supply chain already exist two logistic hubs, one located on the island of Madeira and the other one in the city of Coimbra, but currently they have become inefficient. Although these hubs were created to serve a necessity, these are locations where SKUs can be stored due to the lack of space in the stores and serve as a response to the high demand for some SKUs.

With the implementation of a logistic hub, Worten will have the possibility of freeing up space in the main warehouse by having inventory distributed among these hubs, reducing transportation costs. Also, the hubs will have the purpose of making possible deliveries within 2 hours, to draw more future customers. To sum up, this hub will be designed as a small size warehouse where inventory can be allocated along Worten's supply chain, being closer to customers and serving as a buffer for online orders of Home Delivery (HD) and Store Delivery (SD).

This dissertation aims to identify the relevant factors that Worten needs to consider for the implementation of logistic hubs. Furthermore, it will analyse the initial steps for locating and design these Logistic Hubs in Worten's Supply Chain.

1.2 Objectives

The objective of this Master Dissertation is to develop a method to locate logistics hubs in a retail distribution system. With this in mind, a model will be developed to estimate the right location for these hubs based on the ability of fulfilling Worten's demand within a two-hour delivery window and with a range of covering radius. This implementation will also be focused on reducing the cost of implementing the hubs and transportation costs. The type of allocation between logistic hubs and municipalities will also be studies as well as the area of each logistic hub depending on the location and demand. One can summarise the goals in a more simplified way:

- ❖ Main objective:
  - Locate the most appropriate locations for the Logistic Hubs, based on the Demand and Cost of the square meter of each Municipality, Number of Hubs, Objective Function, covering distance, Hub Capacity, Type of Allocation, Percentage of Demand to cover.
  - Reduce costs of hub implementation.
  - Reduce distance between Logistic Hubs and Municipalities.
  - Reduce Transportation Costs between Logistic Hubs and Municipalities.
- ❖ Secondary objectives:
  - Analyse the most appropriate type of allocation.
  - Provide the best solution for covering 100% and 90% of Worten's demand
  - Analyse a scenario with 5 Logistic Hubs for the different covering distances.

In conclusion, this project aims to develop an almost "Step-by-Step" guideline to help Worten understand how to implement a hub considering several aspects such as what directions to take when designing them.

1.3 Dissertation Structure

- **Chapter 1 – Introduction** → In this first chapter, the reader will be presented will a problem contextualisation, explaining the problem at hand, afterwards the objectives as well as secondary objectives, followed by the Structure of the Dissertation
- **Chapter 2 – Case-Study** → Brief introduction to Worten as an organisation, passing to a characterisation of Worten's warehouse and current flows. Later, a description of the problem at hand, and the main objectives will be explained.
- **Chapter 3 – Literature Review** → The state of the art will be presented, where similar case studies will be present and, from them, one can retrieve important insights on how to study them. Also, in this chapter, several Keywords will be presented, such as Hub Location Problem, Single and Multiple Allocation, among others
- **Chapter 4 – Methodology** → In this chapter, is where several steps to find a solution for the current problem are presented and studied. Also, the formulation and the different restrictions for each scenario will be analysed, for Single and Multiple Allocation.
- **Chapter 5 – Analysis of Results** → Regarding this chapter, the assumption and simplifications made in this project will be presented, followed by the several scenarios that analysed, providing the most appropriate solution for each of the scenarios.
- **Chapter 6 – Conclusions and Future Work** → Summary of the work done, where the main conclusions are present, and some limitations and future work are mentioned as well.

2. Case Study

The main objective of this chapter is to present the case study that will be discussed, the current scenario being used by Worten and the solutions that will be discussed. Starting by explaining Worten's business, describing the current supply chain and operations that have been implemented to respond to the increase in online orders, and optimising transportation costs and lead times. Lastly, the problem definition will be described, followed by a small summary of this chapter.

This Master's Dissertation was developed through a partnership with Worten and Instituto Superior Técnico, and the topic was discussed and worked with the Flows Engineering Department of the Warehouse in Azambuja, although the Business Intelligence Team made several suggestions on how to approach certain subjects. Several visits were conducted to the warehouse, to understand the operation and flows that should incorporate the logistic hubs. All the information obtained was through team members, especially Afonso Barroso and Pedro Rodrigues, such as the Total Online Orders of 2021, including the orders that went to Worten stores to then be pick-up by customers and the orders that went to the actual address of the customers.

2.1 Worten

Worten is a company that operates in the retail sector, where it sells large home appliances, to all types of electronics goods and recently expanded to the health and fitness sector, offering products like treadmills and other products that can be found in today's gyms.

Worten belongs to one of the largest Portuguese groups, SONAE SGPS, S.A. Being a multinational company, Sonae manages a diversified portfolio it operates in more than 80 countries and operates in several areas such as retail, financial services, and technology, among others. This group is being operating in Portugal since 1959.

The company was founded in 1996 when the first store was opened in the city of Chaves. Five years later the online store was launched and now Worten operates in Portugal with more than 180 stores. Worten also operates in Spain, but in 2019 proceeded to close the stores, making available only the online store.

Worten stores can have three different configurations, Megastores with more than 2000 m^2 like the ones in the shopping centres of Colombo and Expo in Lisbon, Superstores with more than 500 m^2 and finally the Mobile stores that focus on offering goods and services related to telecommunications.

Based on the recently released financial results for 2021, Worten compared to 2020 grew 8.8% (8.6% in 2020) in LFL (like for like) and reached €1,175 M of turnover last year. Online sales were the main driver of growth reaching more than €200 M, which represents a growth of 3 times compared with 2019 and represents 17.5% of the turnover, presented in figure 1. [1]

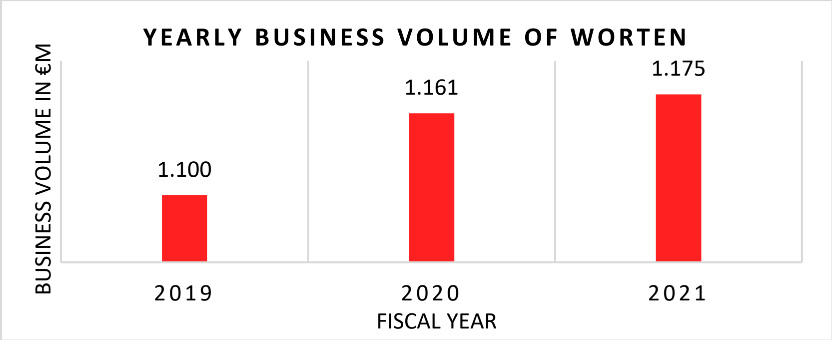

Figure 1 Yearly Business Volume of Worten

Worten over the years had the mission of gathering and providing the best that technology has to offer, to their customers, without exceptions, making available more than one million products at the best prices, while always being close to the Portuguese population. With this mission, Worten was able to receive awards such as Consumer's Choice 2022 (Portugal), among others. [2]

Since 2018, the company has been building an important journey in its Marketplace, where Worten was able to offer a broader range of products by allowing trusted partners to sell their products on the website, granting Worten the possibility to enter new retail categories, and the objective is to keep growing in this area of business. Furthermore, the services areas also expanded and, after the acquisitions of iServices, a smartphone company operating in Portugal in 2020, Worten acquired Zaask, which is an online platform for contracting home services, and Satfiel, a company mainly focused on the repairment of household appliances and other electronic devices, in 2021.

Finally, it is important to refer to the omnichannel based operations, and the evolution of different ways that a customer can purchase a product by integrating the online store with the physical stores. Services such as Click&Collect, which allows consumers to pick up their order within 15 min, Express Delivery, which delivers online orders within 2 hours, and finally next-day home delivery and the possibility of knowing if a certain store has in stock a specific product.

2.2 Worten's Warehouse

As was mentioned above, this case study is being developed with the Team of Flows Engineering at Worten's Warehouse. Here the flows, layout and operation of the warehouse will be presented and explained, separately. Currently located in Azambuja, near the city of Lisbon, this is the main warehouse in Worten's supply chain responsible for supplying all the Worten stores spread throughout Portugal. There is also a smaller warehouse in Madrid that supplies Spain, which in this case functions as a cross-docking centre. The warehouse floor can fit almost 4.5 football fields inside, in other words, has an area of around 45.000 square meters, with more than 200 workers and a wide variety of SKUs in storage, around 15.000, that grows day by day.

This warehouse is where Worten stores most of its products, from small memory cards to large home appliances. All of these products are separated into two different categories, 701, which represents products with larger volumes, such as fridges, large televisions (> 32-inches), washing machines, and fitness machines, among others, and the 708, which includes all the small electronic gadgets, gaming chairs, microwaves, PC monitors and so on.

2.2.1 Flows

Following the scheme present in Figure 2, one may understand that the warehouse has two main flows, one that represents the products that enter, the Inbound, and the other for the products that are sent to the warehouse in Madrid, stores and customers, which is the Outbound. The Inbound flow is only constituted by Business to Business (B2B), representing the transaction of SKUs between Worten and the suppliers. On the other hand, in the Outbound flow, there are three different flows, the B2B-Stores, B2B-Corporate Customers and Business to Customer (B2C). In this case, B2B is the transactions between the warehouse and Worten stores or Corporate Customers, while B2C are a transaction between the final customers. Taking a closer look at B2C is possible to see that it is composed by two different sub-flows, the Online, which is destined for online orders, like Home Delivery (HD), and the Complementary Services of Home Deliveries (SCED) which is responsible for the delivery of large home appliances.

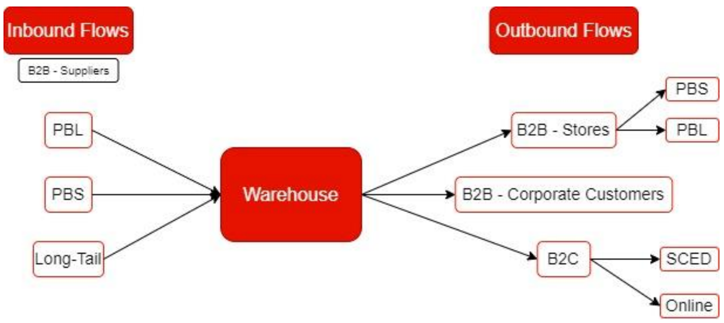

Figure 2 Worten's Warehouse Flows

Analysing the Pick by Store (PBS) represents the products that arrive at the warehouse to be stored and later picked and then shipped. This is one of the most traditional warehouse flows that exist, and on this topic, can be the most expensive and less efficient. The orders are received throughout the day and then the fulfilment is done by waves of picking, where a worker assisted by Material Handling Equipment (MHE), will transport empty pallets, each one designated to a specific store, and picks up the products in the order sheet. After the picking is done, the pallet will then be wrapped and proceed to the docking area, where it will wait to then be transported to the respective store. It is relevant to refer that PBS requires safety stock to handle the variability of supply. Moreover, 701 products correspond to the PBS flow because they have long delivery times, and are not stored in stores, therefore, these types of products are shipped from the warehouse right after an order is placed.

Now looking at the Pick by Line (PBL) flow, it refers to the products that are not stored in the warehouse, in other words, the products arrive at the warehouse and, in most cases, are shipped on the same day (Cross-Docking). Worten does not need to have these products in stock, since the supplier is capable of delivering them within short lead time. These products are picked by an operator, in the inbound area, with the help of an MHE, and they are placed, in bulk, in the area assigned to that placed the order. The suppliers of the goods that incorporate the PBL have a higher service level when compared to the PBS, plus several receiving windows throughout the week. Part of the stock of the PBL flow will satisfy online orders.

The last flow that enters the warehouse is the Long-Tail flow which is designed for products that Worten does not have physically in stock, due to the simple fact that these products have a highly variable demand. When an order is placed on a product of this type, Worten previously knows the level of stock of the supplier and the corresponding lead times, so then proceeds to place the order.

To be easy for the workers to understand where each product of the different flows in the warehouse, Worten developed different coloured tags to help identify the corresponding flow, Yellow is for PBL, White is for PBS, Pink is for Long-Tail and Blue is for the fulfilment of marketplace products.

2.2.2 Layout

Now moving on to the analysis of the layout of the warehouse, which is present in figure 3. The warehouse is divided into several departments such as the inbound area, where the products are received and audited (verification of quantities and quality of the SKUs), then there are several storage areas for two types of SKUs, 701 which are big-sized appliances and 708 that represent smaller products, followed by preparation, cross-docking, online and shipping areas. It is important to add that there are four more different areas reserved for quality control, marketplace and for assessing and repairment of damaged products.

Figure 3 Layout of Worten's Warehouse

Where the number corresponds to:

1- Offices (1st floor)
2- Mezzanine (1st floor)
3- Marketplace (1st floor)
4- Inbound Area
5- Outbound Area
6- 708 SKUs + 2928 SKUs
7- 701 SKUs
8- Repairment Area
9- Outlet SKUs?
10- Online Orders Fulfillment Area
11- Cross-Docking Area
12 – B2B Corporate

First Floor (Mezzanine and Marketplace)

The first floor of the warehouse is composed of two different areas. The first one is the Mezzanine, where some SKU, that fall into the 708 category, can be found, and furthermore offers more security to these products. In this case, these SKU have a smaller volume and higher retail price like smartphones, smartwatches, action cameras, portable computers, among others. On the other side of this floor, Worten is now dedicating this area to products that constitute the Marketplace, which is in its early stages. Since Worten has only started to offer the fulfilment operation to this sector, there are still a few products at the time being.

Inbound Area

The inbound area is where the receiving and checking of all products that arrive at the warehouse are made. Is in this same area that the put-away operation takes place but depends on which flow a certain product belongs to, this will be explained in section 2.2.2.

Outbound Area

Regarding the outbound area, there is the consolidation area where each location has a pallet that corresponds to a specific Worten Store, and in that pallet is where the SD Online orders are allocated as well as the products that will go to that store (inventory). There is also the dispatch area, where the pallets are placed and ready to be shipped to their destination.

708 – Small SKUs

There are several types of locations for the products of category 708, as the products that fall under this category are small appliances, ranging from a charger to a microwave for instance. Some of these products are in the mezzanine and the rest is on the ground floor of the warehouse. In this area, there are different products of category 708 which belong to the PBS flows. Through an ABC Analysis, it was possible to separate the different products into categories based on popularity, (number of times the pick location is visited) being A the category with the most popular products, and C being the category with the least popular ones. The SKU’s popularity will determine if it is placed closer or not to the consolidation area, to reduce the picking travel time. The area of the 708 located further to the right is for high-density storage, and where we can find owned brand products in pallets, like Kunft, Mitsai, and Becken, among others.

Important to make a brief reference to the fact that 708 products have active picking locations and reserve locations, and when there are no SKUs on the active location, a worker must do the Let-Down of the pallet located in the respective reserve location of that SKU.

2928 – Corporate Customers SKUs

In this particular area, 2928, which is exclusive for B2B flow, in particular Corporate Customers such as hotels and offices, it is possible to find products 701 and 708 categories. These products are stored in this area until the client picks them up. It is also possible to find temporary active locations for 701 and 708 products due to the space available in this location.

701 – Large Appliances/SKUs

Regarding category 701, it includes products with different storage options. Some of them are stored on the floor, such as block stacking, for example, since the products and their packaging are robust. In addition, the height for block stacking depends on product to product. In this area, it is possible to find fridges, washing machines, laundry machines or even stoves. This type of storage option makes it difficult to access the SKUs, can lead to damage by having the SKUs stacked up, makes it harder for stock rotation and the storage space is not being used in the most efficient way. On the other hand, it is a cost-efficient solution because there is no investment in storage equipment.

There is an area dedicated to the 701 slow movers, which are stackable products that are not very popular, and they are stored in racks without the need for pallets. Next to the slow-movers, there is the Drive-in racked storage or drive-through racking, very similar to Block Stacking, where stronger pallets are used, the floor space efficiency improves, and the products are more secured. Then we have SKUs that are stored in pallets, a normal wide aisle pallet racking, which is a versatile storage option and makes the pallet accessible at all times. There also exists an aisle where Pallet Flow or Live Storage is used (gravity racks) where one worker does the loading of SKUs in pallets from one side, and the other is made the unloading operation. Lastly, and closer to the consolidation area, we have the 701 IMG, dedicated to all types of televisions and larger monitors (>32 inches), where the level of the racks is higher than normal, to store these SKUs.

The lack of space in the warehouse puts Worten in a position where it needs to store some of its larger SKUs (701) in another warehouse, which represents an additional cost since the warehouse where these SKUs are being placed belongs to another company that rents out warehouse floor to several other companies.

In conclusion, there are several types of storage solutions currently being used by Worten within the warehouse. Those solutions are:

- Racked Storage with wide aisle pallet racking → for smaller and bigger appliances
- Racked Storage with narrow aisles racking → for slow movers SKUs
- Drive-in Racking → for Owned Brands SKUs
- Gravity Racks → present in the 708 storage area of the warehouse
- Block Stacking → For the bigger home appliances (Fridges, Stoves, Dishwasher machines)
- Mezzanine Storage → where smaller and more valuable SKUs are stored
- Alveolus → small cardboard box, this is used in the Mezzanine and the Rack area of 701

2.2.3 Operations

The warehouse has three main operations, firstly, inbound operations where the products are received checked for quantities and quality (based on the appearance of the box/pallet) and put-away where products will be placed into their allocated locations. Secondly, storage, where each type of SKU is placed in the appropriate location, and finally the outbound operations, composed of cross-docking, picking, consolidation, packing and dispatch/shipping. As was mentioned above, the warehouse has three different flows, and there are different steps/procedures for the products that complement those flows, starting with PBL and Long-Tail, where receiving, checking, cross-docking, consolidation and dispatch occurs. And PBS, with receiving, checking, put-away, storage, (order) picking, consolidation and dispatch.

Inbound operations

Starting with the receiving, the products arrive at the warehouse by trucks and usually, the smaller products arrive in boxes with other different products inside as well. After all the products are retrieved from the truck, the driver must wait for the worker to perform the task of verifying the quality of the boxes, the right quantities by counting each one, and in the end stick a coloured tag on each box, representing the flow that it belongs to. Finally, the put-away will be for products that belong to the PBS, since the products belonging to PBL or Long-Tail, will move directly to the cross-docking area.

Storage

This operation is very complex and is different depending on the flow of each product. Is important to have in mind that there are two different categories in storage, the active locations, where products are stored are ready to be retrieved by the picker and the reserve location, where products are stored in bulk (Boxes or pallets). The active locations are closer to the ground and the reserve ones are in higher locations within the racks. When the active locations do not have more SKUs, a task enters the system, so that a worker can do the let-down of the pallet and "refill" that location.

For the 708 SKUs there are several locations, Slow-Movers, where the main characteristics is high-density storage, in Racks, where most of SKUs can be found with different location, the Drive-In Racks, for the owned brand SKUs, where they are stored in pallet, and the mezzanine for the high value SKUs, where there can be different locations depending on the SKU.

For the 701 SKUS, they can be placed in Racks, having 5 types mentioned in storage solution, racked storage with different aisles width, drive-in racks, gravity racks and the conventional racks, there is also the 701 Slow-movers, as was mentioned for the 708 SKUs, and finally there is the option of block-stacking, the SKUs are piled up, and the floor area is separated into rectangles, where each location corresponds to a different SKU. For this case, all the locations are active and for simplicity, the name of this area is 701 SOLO.

Outbound operations

The cross-docking operation starts with a sorting phase based on volume and their destination for the next phase. In this operation, there are three stages, Put-to-Zone (PTZ), Put-to-Light (PTL), and Put-to-Store (PTS).

The PTZ, belong to the PBS, and basically serves as a pre-sorting of the products that leave the reception area. In this stage, the pallet will be unboxed, and the products will be placed in smaller cartoon boxes that will be then sorted into 8 different sectors belonging to the PTL. In the PTL the SKUs are placed in different cartoon boxes that represent the different Worten stores. Then, when full, a worker moves them to the PTS and puts a new empty cartoon box in the location that the previous box was. When the box arrives at the PTS, there are several pallets on the floor, each one assigned to a store, and the operator must put the PTL box on the correct pallet. When the pallets are full, they will be moved to a different area to be wrapped and then move to the docks of the respective store to be shipped at the end of the day.

PBS is the only operation that works with both 701 and 708 SKUs, meaning that it does the picking in both areas. During the day, the orders that have been placed, are accumulated until a wave of picking tasks is released. The picking strategy that is the most used in this operation is batch picking which consists of picking two or more orders simultaneously by the same worker, but the products go into different containers/pallets.

Online Operations

The Online Operation ARE important for understanding better the problem that will be presented. The moment that the orders are received there is several paths to analyse. As the picking will be done in batches, meaning, several orders will be prepared at the same time by each picker. Then, if the order has only one SKU, the worker in the Online Fulfilment Area will scan the product and attach a sticker with all the information required to reach its final destination. If the order is composed of multi-SKUs, the process is the same, but while waiting for one missing item, the remaining items of the order will be placed in a designated area, Put-to-Wall, to them be packed and sent out. In the eventuality that one SKU is not in stock, by the end of the day, the remaining SKUs in that order will be packed, and the order will be split into two different orders. The next step of this operation is to separate HD and SD orders, so they can be separated by the carrier and by store.

2.3 Problem Definition

The current scenario that we are living

In the context of the Covid-19 pandemic, the e-commerce sector had a substantial increase in online orders and the need to satisfy customers became the main concern for many online retailers. In this new reality of online shopping, companies are now adopting an approach of Customer Centricity, where customers' needs, and preferences are the starting point of all major decision-making within each company. Even though this concept is not that recent, it is very difficult to achieve, and nowadays many organisations have defined it as_their vision. As a way of responding to this approach, many organisations have been focused on trying to offer a vast variety of products and shorter lead times, as a form of distinguishing themselves from competitors and gaining more market share. The higher uncertainty now resulting from recent events, also had an impact on the storage space of Worten's warehouse, so one strategy implemented by Worten was to increase their safety stock, which also affected their storage space.

Logistic Hubs and the benefits that they offer

Logistic hubs have become a major solution in response to important challenges in e-commerce logistics, such as faster order deliveries and efficient last-mile delivery in city centres. These hubs perform activities like transportation, sorting, picking and distribution of goods. With the creation of a logistic hub, companies not only have the objective of placing the customer as the main priority but also the purpose to offer reduced delivery times, optimised transportation costs and a reduction in CO2 emissions.[3] Also, it allows distributing inventory along the supply chain, rather than having it in only one location, far from the customer.

Current scenario of hubs in Worten

Looking at Worten's supply chain and the current hubs that have been implemented, one can say that the hubs appeared as a response to the high transportation cost of some SKUs, and to serve as a smaller warehouse where is possible to store several products since stores have limited storage space and the main warehouse is running out of space due to the current situations that were already mentioned. The Logistic hubs already in operation are in Madeira and Coimbra, and both supply the Worten stores in the respective areas, although when they were implemented, the purpose was to serve a necessity and now they have not reached their maximum efficiency.

It is relevant to add that, due to the pandemic, Worten used some stores to operate as a fulfilment centre for online orders and to serve as a warehouse for other stores, but this operation is far from being optimised, and situations such as shipping an order from a Worten store to a customer is something that must be analysed because it will result in higher transportation costs, while impacting the service level and time to deliver.

The objective of the project

The main focus of this thesis is to help Worten with the implementation of logistic hubs, therefore the optimal solution will be presented with the different locations for each hub, depending on the covering distance, followed by a solution which is more suitable and realistic. Regarding the location of the logistic hub, some concepts will be taken into consideration, such as Network Design, Last-Mile Deliveries and Hub Location Problems. To identify the municipalities in Portugal which have more online orders, it was decided to use clusters to help and simplify the problem.

Is worth to mention that there are two flows to obtain a product from Worten, which will help to understand better the purpose of the Logistic Hub. The first one is the offline flow, being the traditional pick-up at the store, which has the most impact of Worten's sales volume. The next one is the online flow, where the customers have two options, HD or SD. By choosing the HD option, the customers receive the online order at home on the next business day or within two hours if the order meets certain parameters (supplied by a pilot "HD 2 hours" store). The SD option, known as Click&Collect, allows the customer to pick the order at a nearby store on the next business day or within 15 min if the respective stock has stock available for that product.

The objective is to implement logistic hubs within Worten's supply chain in order to expand the "HD 2 hours", currently in pilot phase, to cover all the demand in Portugal's Mainland, or partial coverage depending on the results obtained from this study and Worten's strategical decision.

In Worten's operation, there are three different options to transport the SKUs to the stores or logistic hubs. The first one is the box which aggregates the small SKUs which can fit inside this container. The SKUs that have larger dimensions, but still belong to 708 are shipped individually in pallets. The last one is 701 SKUs that are shipped individually to the sites but will not be considered in this study, since they are not eligible for "HD 2 hours".

Requirements for the implementation of the logistic hub:

- Be able to meet the 2 hours lead times, within the respective covering distance.
- Have the capacity to fulfil the online demand autonomously.
- The area of a logistic hub must be the minimum possible in order to fulfil the orders that are allocated to it, to assure the minimum cost without comprising the service level.
- The logistic hub location must be the one that minimises the cost per square meter without compromising the optimal solution
- The distance travelled between nodes must be minimised in to reduce the transportation cost.

KPIs considered:

- Demand covered.
- Minimum and Maximum Capacities.
- Cost of each Hub.
- Transportation Cost.
- Total Cost.
- Cost per order.
- Cost per one percentual point of coverage.

Problem Statement and Objectives

To understand where to place a hub, based on demand, lead time restrictions, transportation costs optimisation and other factors, the model must be designed to provide the best possible results to Worten. This model will have as inputs, the demand aggregated by municipality, the cost per square, covering radius of the hubs and the number of hubs to implement. Other inputs that must considered is the percentage of orders covered. The main objective is to determine the number of logistic hubs, location and costs to implement them, in order to cover 100% and 90% of Worten's online orders.

2.4 Summary of Chapter 2

In this chapter it was possible to analyse the Worten's growth in 2021 compared to the two previous years. In addition, it was mentioned the importance that the warehouse has on the entire supply chain of the company, as well as the different flow, layout and operations that take place. Furthermore, contextualisation of the problem is given, explains the current situation of Worten, a brief explanation of what are logistic hubs and what is currently being done by Worten regarding that topic. Lastly, it was defined the main requirements for the implementation of a logistic hub, the KPI's that were considered to evaluate a possible solution and the main objectives of these study.

3. Literature Review

Following the presentation of Chapter 2 about the Case Study, this following chapter will be focused on the Literature Review on some of the relevant topics and concepts that the problem being discussed is related with. The main objective is to refer to the most important concepts that are related to this work, as well as to present the methodology based on literature reviews of previous works with similar problems.

Structure of this chapter is composed by five subchapters, which are specified below:

- **3.1 Supply Chain** - where the concepts of Supply Chain, Supply Chain Management, Impact of Covid-19 and Network Design will be presented.
- **3.2 Implementing a Logistic Hub** – In this subchapter the definition of logistic hub will be given, then different types of delivery will be presented, Last-Mile and respective Challenges, Same-day and Express delivery. The concept of Urban Logistic will be presented as well.
- **3.3 Network Hub Location Problems** – The first step is to present the definition, objective and applications of HLPs, followed by the type of allocation that can be used in HLPs, and finally different types of HLP will be presented, with the respective formulation.
- **3.4 Operational Costs of a Warehouse/Logistic Hub** – Here it will be presented some operational costs to considered when implementing a warehouse. This logic can also be applied to logistic hubs.
- **3.5 Optimisation and Simulation** – In this last subchapter, the importance of the role of optimisation and simulation is explained.

3.1 Supply Chain

3.1.1 Supply Chain

According to Chopra and co-authors, "The supply chain consists of all parties involved, directly or indirectly, in fulfilling a customer request". In fact, entities such as manufacturers, suppliers, transporters, retailers and customers are a part of the Supply Chain. In addition, the authors state that "Within each organisation, such as a manufacturer, 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." [3]

Other authors complement the supply chain definition by saying that the supply chain is concerned with the physical flow and storage of products throughout the supply chain, as well as the information flow. [4]

3.1.2 Supply Chain Management

Regarding Supply chain management, specifically, it not only manages the assets and products of the supply chain but also the information and flow of funds to maximise the overall supply chain surplus. A rise in supply chain surplus enables supply chain contributors to profit. [3]

Furthermore, Slack and co-authors explain their version of Supply Chain Management to be the management of the interconnection of various related organisations through upstream and downstream linkages between processes that produce value for the consumer in the form of products and/or services. [5]

3.1.3 Impact of COVID-19 Pandemic

Prior to the pandemic, the e-commerce phenomenon was growing in both B2B and B2C sectors, as well as grocery home shopping and delivery. To keep up with this growth, the supply chain would need more fulfilment centres, while also considering cost-saving techniques. Moreover, warehouses would be expected to become even more efficient and cost-effective, which would also lead to an increase in transhipment, consolidation centres and cross-docking operations. [6]

Due to the need for more fulfilment centres, companies must bear in mind that transportation costs and stock reduction targets could eventually bring production closer to customers. Also, warehouses in the future should be carbon positive, such as one UK retailer who built a distribution centre intending to reduce its carbon footprint by 40% and save about £250k, adding water and energy costs. [6]

Arnaud et al. stated that the COVID-19 pandemic disrupted retail and accelerated the trend toward electronic commerce. The author also adds that with the pandemic the first immediate effect on consumption and consumer behaviour was hoarding, in other words, consumers stockpiled essential products such as “toilet paper, bread, water, meat, disinfecting and cleaning products”. And with the lockdown and the social distancing measures have “disrupted buying and shopping practices and led consumers to experiment with new channels”, and the closure of all “non-essential” stores due to the lockdown, contributed to an increased volume of electronic commerce. Finally, the author states that “consumers may discover that online shopping and home delivery is practical and cheaper [7]

3.1.4 Network Design

According to Slack et al, network design starts with setting the network’s strategic objectives. This helps the operation to decide how it wants to influence the overall shape of its network, the location of each operation, and how it should manage its overall capacity within the network. [5] The author adds that one must consider the supply side, which impacts labour, land and utility costs and varies with the location, and the demand side, which includes convenience for customers and the suitability of the location as well.

Supply chain network design decisions must include decisions such as the assignment of facility role, the location of manufacturing/storage/transportation-related facilities and allocation of capacity and markets to each facility. It is also known that network design decisions can impact performance because they determine the configuration and constraints of the supply chain. Regarding the assignment of each facility, it is important because it decides on the role and processes performed in each facility. Facility location decisions will have a long-term impact on supply chain performance since it is costly to close or relocate a facility. And finally, capacity allocation is a factor that can be easily changed in comparison to the location of a facility. If a company allocates too much capacity to a location it will result in higher costs, but on the other hand, if it allocates too little capacity, the responsiveness if demand is not satisfied will be very poor and could result in increased transportation costs, as another facility will have to meet that demand. [3]

Regarding the aspects that influence the distribution network design, several factors are influenced by the distribution network structure, such as response time, product availability, customer experience and so on. When talking about response time, it is the time it takes for a customer to receive an order. Product availability is the probability of having a product in stock when a customer order arrives, and customer experience includes the ease with which customers can place and receive their orders. [3] Then, when a firm is deciding on the number of facilities required on the distribution network there are also some variables to account for. In figure 4, we can see that if a firm wants to decrease the response time, an increase in the number of facilities is required in their network. The author also refers that due to this increase of facilities in the supply chain, firms will obviously have an increase in facility costs as well as an increase in inventory, which means more inventory costs. [3]

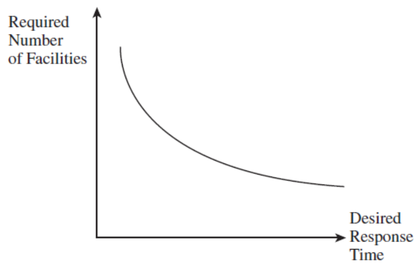

Figure 4 Relationship between Desired Response Time and Number of Facilities [4]

If a firm delivers its product to customers, using rapid means of transportation it will allow it to build fewer facilities while providing a short response time, which would, however, increase transportation costs. Also, if a certain company can find the most consumer-friendly way to quickly increase last-mile capacity at the lowest cost will have an advantage over the competition. [3] Regarding the optimal number of facilities for lower transportation costs, Chopra et al. explain that “If the number of facilities is increased to a point where inbound lot sizes are also very small and result in a significant loss of economies of scale in inbound transportation, increasing the number of facilities increases total transportation cost” [3].

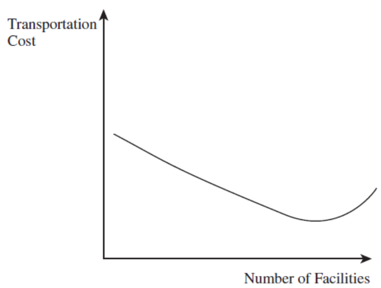

Figure 5 Relationship between Number of Facilities and Transportation Cost [4]

A similar graphic to the one in figure 5, figure 6 is the one that takes into consideration the total logistics costs, being the sum of inventory, transportation and facilities costs from the supply chain, and response time, depending on the number of facilities. And analysing the figure below, one can say that as facilities increase, the response time to customers will decrease.

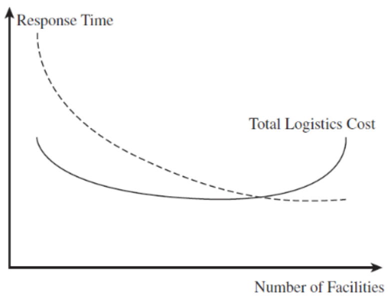

Figure 6 Relationship between Number of Facilities and Response Time and Total Logistic Cost [4]

3.2 Implementing a Logistic Hub

In order to better understanding the role of a logistic hub, figure 7, shows the position in Worten's supply chain that each logistic hub will occupy.

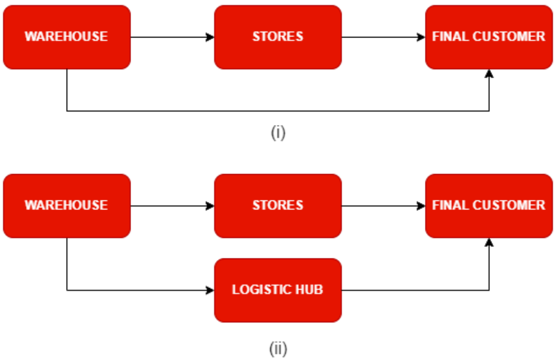

Figure 7 (i) Current Worten's Network, (ii) Purposed Network

3.2.1 Definition of Hubs

Hubs are facilities that offer several operations like consolidation, connection and switching points for flows between demand points. [8] In addition, they provide super-fast order deliveries and allow companies to be closer to major cities and can ensure the efficiency of last-mile deliveries. [9]

Other authors, refer to them as a large-scale structure where there is a collaboration between service providers to provide value-added services by sharing goods. They also have an impact on transportation efficiency, but to achieve this, the hub must be in the most appropriate position within the network. [10] The objective of placing the logistic hub in the best possible location is to increase the product availability in multiple markets through optimal connections, allowing better use of the logistics and transportation available. [11]

3.2.2 Last-Mile Delivery and its Challenges

When comparing normal carrier delivery with last-mile delivery there are several factors to consider. The first one is the location of the facilities, which in last-mile delivery are located closer to city centres. The second and third ones, are the cost of inventory and transportation, that increase with last-mile delivery. In contrast, the response times, will decrease since the facilities are located closer to customers. And finally, the facility and handling costs are also more expensive with the last-mile delivery, when compared to the normal carrier delivery. [3]

In Last-Mile deliveries, the fulfilment process is characterised by three stages: (1) order acceptance, (2) order selection and fulfilment and (3) order delivery. They are essential to providing the best customer service at an affordable price for the customer. The order delivery to the customer is logistically changeling because of the various factors involved and can become very expensive. [12] [13]

Micro-hubs can be used as distribution centres or urban consolidation centres for last-mile deliveries, where the products will be delivered to the micro-hubs from outside the city, to then be distributed to end consumers. This type of infrastructure has the potential to minimise trips and distances and as they are closer to the end consumers, it allows a greener type of transportation, such as bicycles, therefore reducing the carbon footprint. [14]

Because urban areas are usually characterised by a mix of traffic and/or congestion, it becomes difficult to maintain the deliveries reliable, affordable, and fast. By using micro-hubs in city centres, express deliveries can be made. Implementing this solution would result in a decrease in the number of diesel kilometres and CO_2 emissions. Verline and co-authors performed an impact assessment, and regarding the environmental impact, they obtained a reduction of 24% in CO_2 emissions and an increase of vehicles throughout the different delivery time windows. [15]

3.2.3 Same-Day Delivery (SDD)

Same-day deliveries are a powerful tool for online retailers and serve as a strategy to increase sales. SDD, as the name implies, offers the possibility for the customer to order goods online and receive them the same day. [16] Several authors refer to it as being the most common delivery mode. [17]
This strategy has seen massive growth with the pandemic, which provides convenience to the customer by eliminating the need to go to the store to pick up their product(s). This growth also leads to significant cost challenges for logistic carriers. It is relevant to point out that conventional last-mile delivery is the main driver for overall delivery costs, and these tend to increase due to dynamic customer orders and tight delivery windows for products with low stock. [16]

3.2.4 Express/Instant Deliveries

“The growth in e-commerce has led to an increase in door-to-door, same-or next-day delivery services within the courier, express, and parcel (CEP) sector, in particular for home deliveries” [14] Consequently, instant Deliveries is a growing market segment where consumers can buy products online and receive their delivery within less than one or two hours. The creation of this new service comes from the fact that customer demands are becoming more sophisticated, meaning a fast delivery at a low price. A better definition given by the author is "Instant delivery services provide on-demand delivery within two hours – by either private individuals, independent contractors, or employees – by connecting consignors, couriers, and consignees via a digital platform. [18] Primarily, to meet consumer demand, shippers need to build solutions for last-mile delivery. Secondly, given the capital investment and operational expenses involved, the path to cost-effective delivery will likely require a mix of available options. [19] "Express providers supply fast delivery at fixed time windows the next day or the second day relying on their powerful networks" [20]. To deliver online orders within 2 hours, companies must be capable of organising their e-commerce operations to have faster fulfilment and lower operational costs, and this can be achieved by placing their operations in urban areas. [21]

3.2.5 Urban Logistics

Urban logistics (or city logistics) usually refers to the systems and processes which make possible the supply of commodities in urban areas. [22] This can be applied to both in terms of supplying B2C and B2B sectors. Services such as courier, express or parcel are necessary to supply these areas. [23] Two main objectives of urban logistics, that motivate vehicle route optimisation in cities are to reduce congestion and increase the mobility of freight transportation services in urban areas at minimum cost. And the second one is to have a positive contribution to the environment and sustainable development. Reducing CO_2 emissions and noise. [24] In other words, reduce all negative impacts while offering improved and faster deliveries. [25]

For private companies, the primary objective is to satisfy a daily demand at the lowest cost. The problems are operational, and the data is not the same every day and can change throughout the day. The first aspect that planners must consider is the strong relationship in urban areas between the time of the day and travel times, due to traffic. [26] [27] Several authors follow this line and include time-dependency in their VRP models. [26] [28] Small vehicles must be used, but they have limited capacity, therefore these smaller vehicles perform several round trips during the day. Route optimisation then differs from the traditional VRP where a single trip is allowed for each vehicle. [29] [30] Cattaruzza, who mentions other authors such as Thompson et al. and Quak, to show how the use of intermediate facilities (HUBS) can improve the quality of service, and transportation costs and decrease CO_2 emissions. [24] [31] [32]

The authors, Çetiner et al. [33], studied a problem where they combined the hubbing and routing problem in a postal delivery system, developing an iterative two-stage solution procedure for their problem. A hub-and-spoke network proved to be effective in reducing mail delivery times, and there is space for more improvement if the non-hub nodes are served in the route, instead of being served separate. The authors solved their problem through a Hub Location-Routing Problem (HLRP), where they must decide on the location of hubs and generate multiple-stop routes for non-hub nodes allocated to the hubs, assuming that the hubs and vehicles are uncapacitated. They referred to several other authors, such as Bruns, where whose paper was about restructuring the postal services in Switzerland while deciding on the number, capacity and location of transhipment points [34], and also Ernst and Krishnamoorthy, who studied single allocation p-hub media problem f or Australia post's delivery system was presented. [35]

3.3 Network Hub Location Problems

Over the years several authors performed studies to solve the problem of Hub Location. The first authors to begin the study of this problem were Morton E. O'Kelly [36] and James F. Campbell, in 1986. [37] Since then, several other researchers have been studying and investigating this problem, thus arising variants of the Hub Location Problem (HLP) with different objective functions and constraints as well. [38] The hub location problem consists of which nodes should become hubs, followed by the allocation of these hubs to a set of different nodes with different demands associated with them.

3.3.1 Definition, Objectives and Applications

The hub location problem concerns the location of hub facilities and the assignment of demand nodes to hubs to route traffic between origin-destination pairs, also there can be two types of allocation, single hub or multiple hubs. [38] This type of problem is an extension of the typical facility location problems. [39]

Hub location problems (HLPs) provide several models based on real-world transportation and telecommunications systems. HLPs mainly address the location of hub facilities but also include network design decisions. The location of hub facilities, hub network design, determining routes of the flows and optimisation of the total costs are some of the objectives that the HPL are focused on. [36] It is important to consider that hub facilities need to provide two relevant functions, the first one is a switching, sorting, or connecting function that allows flows to be redirected at each hub. The second function is a consolidation or breakbulk function allowing flows to be aggregated and disaggregated. [41]

The Hub Location Problem is a very important topic for Industrial Engineering as for Operations Research. [39] In fact, Hub Location Problems (HLP) have numerous real-world applications, such as at, (1) airlines and airports, (2) transportation and handling problems, (3) post-delivery services and fast delivery packing companies, (4) telecommunication systems and message delivery networks, (5) emergency services, (6) chain stores in the supply chain, (7) productive companies based on transportation correctly and (8) public transit. [42] [9]

Regarding the cost in HLPs, there can be considered two different types of costs, the cost of locating hub nodes and the cost of connecting non-hub nodes to hub nodes. In both cases, there is the possibility of assuming that is no cost associated, a fixed cost that is the same for every hub and/or connecting pair and a variable cost that can vary in the location of each node and/or with the dimensions of each hub node. [8]

3.3.2 Single and Multiple Allocation

The main concern is to locate the hub facilities and allocate the demand nodes to those hubs, to then study the routes of the flow. In the literature review of hub location problems, there are two types of allocation, single and multiple allocation. In the single allocation, each node must be assigned to exactly one hub facility, which was first studied by O'Kelly [37]. Multiple allocations were first studied by Campbell [38], where non-hubs nodes can be assigned to more than one hub facility. O'Kelly et al. added that "allowing multiple allocations obviously allows much greater routing flexibility and hence is expected to have a lower objective cost of operation". The authors complement by saying the multiple allocation hub-and-spoke models allow each pair of nodes to choose from the different routes, the most cost-effective. [39] Having explained the main difference between most of the hub location problems, the other factors to consider will be presented in the following sub-chapter.

3.3.3 Different types of problems

In 2008, Alumur and Kara [40], mentioned in their paper that they reviewed over 100 papers related to the network hub location problem, and it was clear that the hub location literature was influenced by the location literature. The authors also referred to the number of publications regarding the different models for Hub Location Problems, as well as the distribution throughout the years. In addition, it is important to refer to the fact that this paper was presented in 2008, and since then, there was an increase in papers studying these HLPs. From 1986 until 2000, the research was more focused on the definition and formulation of new problems (p-Hub median models), figures 8 and 9. After 2000, the focus of researchers become the hub location models with fixed costs. In comparison to other models, the total number of papers regarding the p-hub centre and Hub Covering is very low. These two types of problems mentioned are the most recent, therefore, there are still a lot of studies to be conducted so that more exact solution procedures and heuristic algorithms can be developed. From figures 8 and 9, is possible to see that the four types of discrete facility location problems that have more publications are p-hub median, followed by fixed cost, p-hub centre and hub covering Problem, although there is much more that has been studied by researchers throughout the years.

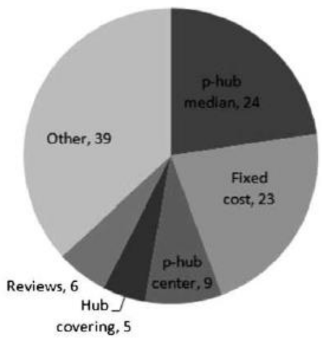

Figure 8 The total number of publications among presented models [40]

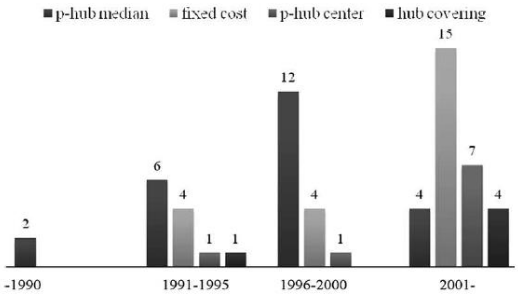

Figure 9 The number of publications among presented models in years (2008) [40]

In table 1, is possible to understand the various types of hub location problems that were studied throughout the years. Regarding the capacity, it is possible to consider that the hub has capacity limitations, meaning that the total flow, incoming or outcoming, must be less than or equal to a fixed value, and the type of problem is called Capacitated hub location problem. The other option is that the hub does not have any limitation, therefore being uncapacitated.

For the types of assignment of non-hub nodes to hub nodes, the two types of allocation were previously explained above. Analysing the number of hub nodes, it is possible that an HLP can have either only one hub or multiple hubs. It is important to point out that when determining the number of hubs to locate, the number of hubs is primarily specified (exogenous) or the number of hubs is not pre-specified but is determined as part of the solution (endogenous).

3.3.4 Related Literature

Moving on, the different types of HLPs that one may encounter during the literature review will be presented next. Starting with the p-hub median problem, O'Kelly was the first author to study this problem, but these models had a single allocation. The number of hub nodes is known (exogeneous), there are no costs associated with the installation of each hub node, nor capacity restrictions. From a given set of nodes with demand associated with them, this HLP will choose p nodes to locate hubs and allocate non-hubs to each one. The objective function is to minimise the total cost associated with the p hubs and respective assignments. [37] On the other hand, Campbell studied the same problem but with multiple allocations, with a linear objective function, and tries to minimise the total transportation costs. [38] [41] [42] This type of problem has clear and simple applications to transportation and telecommunication networks. [40]

The p-hub centre location problem (LP) was also first studied by Campbell and is suitable for emergency facility locations, with similar characteristics to the p-hub median problem, except that some decision variables are relaxed. If an origin-destination pair is introduced as a demand node in a p-centre problem, the purpose of a hub centre problem is to implement a set of hubs that minimise the maximum travel time (cost) of each origin/destination pair. This problem can be used for sensitive/decomposable goods in the hub system. [8] [41] [42] There are three different types of problems, where the maximum cost is minimised, and the cost can be associated with any origin-destination (time-sensitive products, cost=time), movement on any single link (products sensitive to temperature) or movement between a hub node and a non-hub node. The author of this paper also presented formulations of single and multiple allocations for the three types of p-hub centre problems [43].

The p-hub covering problem is an extension of the classical covering LP and is more suitable for products with time-sensitive deliveries. The demand nodes are considered to be covered if they are within the covering radius of the hub. In this model, the objective is to locate hub facilities so that an origin/destination pair (i,j) is covered by a pair of hub nodes (m,k), but this only happens if there are hub facilities at pre-specified distances from their links. One may add that the objective is to minimise the number of hubs to implement so that the maximum distance/cost does not exceed a certain limit. [47] To conclude, the origin/destination pairs are covered if the (transportation) cost of i → j via m,k hubs is less than or equal to a certain fixed value. This type of HLP was first purposed by Campbell [43]. [8] [42]

The Hub Set Covering problem is also an extension of hub covering LP, which is similar to the p-hub median LP. The number of hubs is not known (endogenous), making it a decision variable. Also, the fixed cost of establishing a hub facility is incorporated into the model. The objective function of this problem minimises the established cost of hubs. Campell developed a mixed-integer formulation for this model and maximal hub covering problem as well. [8] [43]

Lastly, the Hub Maximal Covering LP is also a special case of hub covering LP. Here, if the time (cost or distance) to cover all origin-destination pairs is greater than the time available (budget or distance), one may solve the problem by maximising the demand covered with a given number of hub facilities. Therefore, the objective function of this type of HLP is to maximise the total flow between nodes. When compared to the p-hub median problem, they are very similar except that the number of hubs is known (exogeneous) and the fixed cost of hub location is disregarded. [8] [41] [42]

Regarding these last two models referred, Kara et al. proposed three different linearisations of the original model as well as a new approach for the hub set covering problem. [44]. On the other hand, Wagner proposed a set of formulations for the two types of hub allocation, having formulations that required fewer variables and constraints compared to Kara et al. [45]. Finally, Kartal et al. presented a new formulation for a single allocation hub set covering problem, and also studied the multiple allocations for this type of HLP. In terms of performance, the formulation presented by Kartal et al. has faster CPU times compared to Kara et al. [14]

Table 1 Different types of HLPs [8]

The capacity of the hub node	Assignment of non-hub nodes to the hub node	Type of the HLP	Number of hub node	Cost of hub node
Capacitated (C) Uncapacitated (U)	Single Allocation (SA) Multiple Allocation (MA)	Median (M) Center (T) Covering (V) Set Covering (SV) Maximum Covering (MV)	Single (1) Multiple (P)	Fixed (F) Variable Cost (VC) No Cost (NC)

Although is not present the table 1, the minimum value flow on any spoke/hub connection problem is a different type of problem compared to the ones previously mentioned. It takes into consideration that the flow between connections must be greater than or equal to some minimum flow threshold value. The assumptions for this type of HLP are very similar to the p-hub model, except for the minimum flow mentioned before. [46] [8] [41] [42] There are several other HLP that will not be analysed because they are not suitable for the present work, mainly because there are single allocation HLP (Multi-Objective p-HLP and Continuous p-HLP).

The capacitated p-hub median problem, which selects an exact p among a set of candidate hubs so that the total hub flow (incoming and outgoing) must be less than or equal to a fixed value. And the transportation cost of the resulting pure capacitated hub-and-spoke network is minimised. Regarding the formulation of this problem, it is similar to the p-hub median LP, plus the capacity constraint. [43] In the case of the p-hub median LP with fixed costs, it is a p-hub median LP with fixed-link costs for connecting non-hub nodes to hub nodes. For this problem, the number of hubs is not pre-specified, so it is considered a decision variable and a part of the final solution.

There are several types of solutions domain. With network, the domain of candidate hub nodes is all of the network nodes. In discrete, the domain of candidate hub nodes is a series of particular nodes. And lastly, with continuous, the domain of hub nodes is a plane or a sphere. [8]

3.3.5 Formulation

Having all of the types of Hub Location Problems presented above, for the scope of the present work, only the p-hub media LP with single and multiple allocations, including or not restrictions regarding capacity and covering radius will be considered.

P-HLP

The p-HLP model is referred to as a single allocation p-hub location problem, which means that one non-hub can only be allocated to one hub node. The objective function of this model is a MiniSum, giving solutions that are discrete and finite. All of the hub nodes are connected, and each non-hub node is connected to one hub. Also, the number of nodes is known (*exogenous*) since this number is established at the beginning of the formulation. Each non-hub node must be connected to a hub node. For this case, the model will not consider the installation (implementation) costs, the capacity of each hub and the covering radius (distance). As presented above, all decision variables of the model are binary variables. [9] [42] [41]

This model will have 4 input variables and 2 output variables. Regarding the model inputs, starting with α, that is the discount factor for line-haul movement between hubs, $0 \leq \alpha \leq 1$, followed by P, which is the number of hubs to locate. The next is h_{ij}, that represents the amount of demand/flow between nodes i and j and lastly, C_{ij}, which is the unit cost of transferring from non-hub node i and node j. For the model outputs, there are two variables, X_j, that tells if a hub is located at node j or not, and Y_{ij}, which is equal to 1 if node i is allocated to a hub located at node j (and 0, otherwise). The objective function and constraints of this model are presented below [9] [42] [41]:

$$(1)\ Min \sum_{i}\sum_{k} C_{ij}\, Y_{ik}\left(\sum_{j} h_{ij}\right) + \sum_{k}\sum_{i} C_{ki}\, Y_{ik}\left(\sum_{j} h_{ij}\right) + \alpha \sum_{i}\sum_{j}\sum_{k} h_{ij}\, C_{km} y_{ik} y_{jm}$$

Subject to,

$$(2)\ \sum_{j} y_{ij} = 1\ \forall\ i,$$

$$(3)\ \sum_{j} x_j = p,$$

$$(4)\ y_{ij} - x_j \leq 0\ \forall\ i, j,$$

$$(5)\ y_{ij} = 0, 1\ \forall\ i, j,$$

$$(6)\ x_j = 0, 1\ \forall\ j.$$

The first equation, (1), aims to minimise the total cost related to the p hubs location and the respective assignment of nodes to each hub. The first term is related to the cost of the travelled distance between node i to hub k, starting in i. The second term is the connection cost destined from node i to hub. And the third is the cost of connecting two hub nodes. Moving to equation (2) ensures that each node I is assigned to one hub node. Equation (3) that the number of hub nodes equals p. Equation (4) specifies that node i can only be allocated to a hub in j if there is no hub at j. And finally, (5) and (6) specify that both variables are binary. [42]

P-Hub Median LP

For the p-Hub Median LP model, the assumptions are very similar to p-HLP, with the difference that now, a new variable is introduced, $\mathrm{Z}_{\mathrm{ij}}^{\mathrm{km}}$, which is relaxed, $\mathrm{Z}_{\mathrm{ij}}^{\mathrm{km}} \geq 0$, and each non-hub node can be allocated to one or more hub nodes. This variable will be a model output, and is equal to the flow from origin i to destination j, which uses hubs at candidates' sites k and m. The inputs are also similar to the p-HLP model, with a new additional variable, $\mathrm{C}_{\mathrm{ij}}^{\mathrm{km}},$ which represents the unit cost of travel between origin i and destination j when going via hub at nodes k and m ($\mathrm{C}_{\mathrm{ij}}^{\mathrm{km}} = \mathrm{C}_{\mathrm{ik}} + \alpha\, \mathrm{C}_{\mathrm{km}} + \mathrm{C}_{\mathrm{mj}}$). The model's objective function and constraints will be presented and explained below: [9] [42] [41]

$$(7)\ \mathrm{Min} \sum_{i}\sum_{j}\sum_{k}\sum_{m} C_{ij}^{km} h_{ij} Z_{ij}^{km}$$

Subject to,

$$(8)\ \sum_{k} x_k = P,$$

$$(9)\ \sum_{k}\sum_{m} Z_{ij}^{km} = 1\ \forall\ i, j,$$

$$(10)\ Z_{ij}^{km} \leq x_m\ \forall\ i, j, k, m,$$

$$(11)\ Z_{ij}^{km} \leq x_k\ \forall\ i, j, k, m,$$

$$(12)\ Z_{ij}^{km} \geq 0\ \forall\ i, j, k, m,$$

Equation (7) minimises the demand-weighted total travel cost. Equation (8) stipulates exactly what P hubs should be located. Equation (9) ensure that each origin-destination pair (i, j) must be assigned to precisely one hub pair. Equations (10) and (11) stipulate that flow from origin i to destination j cannot be assigned to a hub at location k or m unless a hub is located at these candidate nodes (when travelling from one node to another, via one hub node, m and k coincide with each other). Equation (12) is standard integrality constraints. One of the most critical difficulties associated with this hub location model is a large number of assignment variables Z_{ij}^{km}. By using equation (10), the number of decision variables will reduce, but it does not provide much help to solve the problem more easily. [42]

P-Hub Median LP with Fixed Costs

In this type of HLP, similar to the p-hub problem, but now the number of is not known and a fixed cost will be considered to connect non-hub nodes to hub nodes. Campbell proposes that g_{ik} is the fixed cost of connecting a non-hub i to a hub node k, W_{ik} is a binary variable denoting selection of link (i, k) if it is equal to 1. [43] And a cost term is also added to the criterion, which is similar to the p-hub median LP: [9]

$$(13) \sum_{i} \sum_{k} g_{ik} W_{ik}$$

For the model inputs, there are two new variables, β, which represents the weight on the capital or fixed costs to allow exploration of the tradeoff between capital costs and transport (or operating) costs, and f_k, that is a fixed cost of hub location in candidate node k. The model outputs remain the same and in the objective function, equation (12) will be eliminated, and equation (14) will be added in its place. [42]

$$(14)\ B \sum_{k} f_x\, x_k$$

P-Hub Median LP with Capacity Limitations

This type of p-hub median location problem includes a constraint regarding the total flow, inbound and outbound, which must be equal or less to a fixed value for the hub nodes, which Campbell presented in 1994. The model's assumptions are similar to the p-Hub problem, except that the capacities of each hub are limited. The inputs have an additional variable, θ_k, which is the capacity of a hub at candidate node k. And the model outputs are similar to the p-hub problem model. Finally, the objective function is similar to the median P-hub model, except that the following constraints are added to the model. The left side of the above inequality shows the total incoming and outgoing flows of node k. [9] [42] [41]

$$(15) \sum_{m} \sum_{i} \sum_{j} h_{ij} Z_{ij}^{km} + \sum_{s} \sum_{i} \sum_{j} h_{ij} Z_{ij}^{sk} \leq \theta_k X_k\ \ \forall k.$$

Hub Covering LP: Maximal Covering LP (Campbell 1994)

This model is used to solve p-Hub centre models, as it tries to locate hub facilities so that an origin-destination pair (i,j) is covered by a pair of hub nodes (m,k). And this (i,j) is covered by (m,k) if the cost between the first pair via the second pair is less or equal to a fixed value. The formula is presented in equation (16). It is worth mentioning that the p-hub maximal covering LP is a particular case of the hub covering LP, the formulation is very similar to the p-hub median LP. [43][9] [42] [41]

$$(16)\ C_{ij}^{km} \leq \gamma_{ij}$$

Regarding the model assumptions, it will be very similar to the p-hub model, except that the number of hubs is known before solving the model. No fixed cost of the hub is considered as well. Moving on to the model inputs, two new variables will be introduced, the first one is γ_{ij}, that represent the maximum cost for going from origin i to destination j (distance covering), and the second one is V_{ij}^{km}, which says that node hubs k and m cover the origin-destination i, j. The model outputs remain the same as the p-hub median model. To conclude, in the objective function for this model it is introduced equation (17), which has de objective of maximising the amount of transportation demand covered and constraints are the same presented in the p-Hub Median LP, equations (8) to (12). [42] [41]

$$(17)\ \text{Max} \sum_{i} \sum_{j} \sum_{k} \sum_{m} h_{ij} V_{ij}^{km} Z_{ij}^{km}$$

3.4 Operational Costs of a Warehouse/Logistic Hub

On average the cost of operating a warehouse can vary between 1% and 5% of total sales, depending on the type of company and the value of the product that it is selling. For example, for a retail company, a pallet with laptops can be of the same size as a pallet of gaming chairs, but the value of each pallet is very different. Warehousing and inventory costs take up 22% and 23%, respectively, of the total logistics costs. This being said, the author suggests that warehouse managers must have the knowledge and understanding of all costs and cost drivers of a warehouse while maintaining optimum customer service with the pressure of reduced inventory but increased numbers of SKUs. [48]

Figure 10 it is presented the costs that are typically associated with a warehouse operation, but regarding the operation for the present work, the overhead costs such as management and administration, sales and marketing and miscellaneous can be dispensable and ignored. With this, the focus of warehouse cost will be on the storage, incorporated by rent, electricity, water, cleaning, among other, the labour, that takes into consideration the salary, insurance, protective gear and so on, and finally, the handling equipment, where the maintenance, rental costs or depreciation comes in. [48] Another author such as Speh complements this by saying that the warehouse cost is separated into four categories, handling, storage, operations administration, and general administrative expenses, and inside each one, the author break-down the different types of expenses into more depth**.** [49]

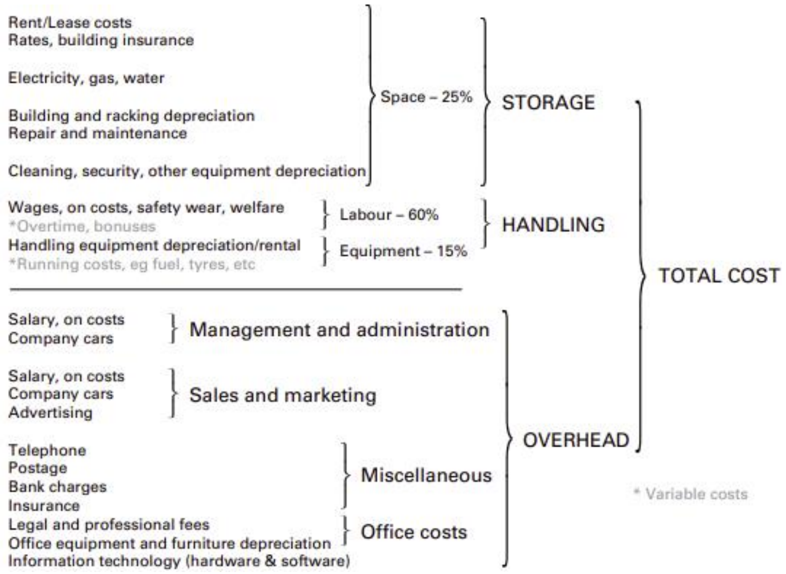

Figure 10 Simple warehouse cost tree (warehouse management book, 2nd edition)

3.5 Solution Methods

3.5.1 Optimisation

Optimisation is defined as the creation of more favourable conditions to develop a model or a process which helps to achieve the best possible outcome either for a model or a system. Can also be a path to follow to build tools that help decision-makers. [55]

Chopra et al. allude to the fact that in network design in the supply chain the use of optimisation for facility location and capacity allocation decisions is very important, referring relevant network optimisation models, such as allocating demand to production facilities, locating the plants considering the capacity restriction, among other. [3]

Optimisation models are used to quantitively deal with logistics challenges. Caunhye et al. refer that most facility location optimisation models in emergency logistics combine the process of location, either building new facilities or choosing existing ones, with stock pre-positioning, evacuation or relief distribution, although there are more operations. [56] An optimisation model determines the number and location of facilities, with the objective of minimising the transportation costs or the distance travelled. [57] So it is possible to say that each model can be modified according to strategic imperatives that require for example. Chopra et al. refer that when locating several warehouses, there is the possibility of one warehouse being placed in a specific location, and that constraint could have an impact on the transportation costs or total distance travelled. [3]

Network Optimisation Models can also include inbound and outbound transportation costs, contribution margins, tariffs, taxes, production and inventory costs, that will be used to maximise profitability. Finally, Chopra et al. finish by saying that these models are useful when locating facilities and allocating capacity to them. [3] The first step for the optimisation model is to collect data in a form that can be used for a quantitative model. [3] But the collection of data and its availability is one of the optimisation models' limitations because they rely on data. Another limitation is the great amount of time that is needed to solve the model until reaching optimality. [56]

In the context of global competition, the optimisation of logistics systems is fundamental. This led to more research resulting in more optimisation models based on operational research tools. Optimisation models, mainly the ones regarding facility location, are usually based on mixed integer linear programming (MILP) models with binary location variables. [58] [59]

In order to solve problems regarding facility location, many research studies address this by using a heuristic. Among heuristic methods, iterative heuristics, which are the most recent trends in research, that have algorithms generating a solution or a set of solutions at each iteration. [58] Using a heuristic algorithm requires less time to employ and can also solve a more complicated problem, but the downside is that this approach does not provide the best solutions. The other approach, the exact algorithm, is used to check the heuristic algorithm and can be used to solve the problem. [59]

When determining solutions for distribution centres' location, normally it is used a logistics strategy simulation or optimisation model. Rushton et al. suggest the steps necessary for distribution centres' location. Starting by determining the data and running the model for the current operation. The next step is to validate the model and make some adjustments that reflect supply change and demand forecast. Following this, the model will run again for the base case and different options. Finally, a sensitivity analysis and a comparison between the results obtained will be performed.

The authors also refer that are two fundamental stages of logistics simulation, model validation and option testing. The validation exercise starts with a situation where the outcome is known, and the flows and customer service are reproduced to test if the cost was predicted with reasonable accuracy. It is essential to ensure that the model or method of analysis is representative of the system being investigated and that during the modelling check and test if the model and results are suitable. [4]

The design of supply chain networks is very important, and the focus is on locating and si ing facilities and defining material flows through the network. Optimisation techniques have always been a key tool for addressing these problems. [60] In addition, the collaboration among researchers would lead to a more realistic model and optimal solution methods to solve the optimisation problems. [60] And is important to bear in mind that for the effort of optimisation to be worthwhile, it must be easy to implement a computed solution. [61]

3.5.2 Simulation

Mourtzis et al. stated that "Simulation comprises an indispensable set of technological tools and methods for the successful implementation of digital manufacturing since it allows for the experimentation and validation of the product, process and system design and configuration". The author also referred that nowadays simulation has must more value due to globalisation and the constantly increasing requirement for a higher degree of product customisation and personalisation. When simulating a model, is possible to test numerous configurations before implementing them into the real-life system. [62] Is through simulation modelling and analysis that is possible to gain information on more complex systems, and to develop and test new operating policies and new concepts, and before the implementation of such models, is important to gather information and knowledge without impacting the actual system. [62] When designing a model, and due to the complexity of some systems, simplifications must be done, such as aggregation of demand.

Simulation is considered a descriptive method, regardless of the mathematical relation between the variables and the objective function. When developing and integrating simulation software, the primary function is to respond to specific questions regarding design and/or engineering. This tool is the pinnacle of the decision-making process for highly complex systems. [63].

Several restrictions limit the decision when planning the supply chain. Capacity, service level and demand are the main ones. The authors also refer to some of the decision variables present throughout the supply chain, such as the location, number and equipment regarding the infra-structures. [64]

At a strategic level, decisions about locations of infrastructures, like expansion or closure, and product allocation. [65] Other authors refer that the location problems depend on customers and infrastructures to serve the demand of those customers. But one must also consider the location of both customers and infrastructures and the distance (time) between them. [66] [67] Regarding the tactic level, it deals with problems associated with the necessity of integration between several decisions instead of analysing them separately. [68] Finally, for the operational level, plan in an efficient way supply chain, one must consider restrictions regarding transportation and capacity in the infrastructure. It considers decisions such as forecasting demand as well. [69]

There are two resolution methods, mathematic resolution using optimisation algorithms with a heuristic that helps find acceptable solutions and simulation models. There is a tendency to choose mathematical optimisation models due to better computational capacities that provide better optimal solutions. It is also worth mentioning that heuristics can lead to wrong decisions [70] Whereas simulation is better suited to observe the model's performance by changing the input variables. Also, the success of optimisation depends on identifying the constraints allocated to various parameters, and for simulation starts with realistic inputs and proceeds to change them to analyse the output of the model. Optimisation methods aim to support strategic planning decisions, while simulation can be considered a more experimental method. Finally, simulation is easier to compute and has fewer assumptions, and in contrast, optimisation requires more computational power and assumptions.

3.6 Summary of Chapter 3

This chapter provides the literature and necessary information to formulate a methodology to help solve the current problem properly. This chapter also presents the literature review related to supply chain and supply chain management, network design, logistic hubs and their purpose. Later it was presented types of problems that can be applied to Worten's current situation. With the Network Hub LP, 3.3, it was provided information related to the definition, objectives and applications of the HLPs, the two types of allocations that will be analysed in Chapter 5, the different types of HLPs and the formulation for several HLPs which will be studied, which were shown in 3.3.3 to 3.3.5. Finally, a comparison between Simulation and Optimisation was made, addressing several differences and objectives.

4 Model Proposal

In this chapter, the model characterisation will be presented, followed by the mathematical formulation of the model, composed of the parameters, variables and equations used in the several models. This chapter will also mention the previous mathematical formulation referred to in chapter 3, as well as additional parameters to help with the analysis of each model.

4.1 Model Characterisation

Regarding the implementation of this model, the production and delivery of the products from the suppliers will not be analysed. The model will focus on the connections between the hub nodes and non-hub nodes as well as providing the best possible locations for the hub nodes taking into consideration several restrictions. Within each non-hub node is where the orders belonging to a certain municipality are located. The model also has de objective of minimising the distance travelled between nodes and the total cost associated with the logistic hubs.

Data:

- Demand aggregated by municipalities.
- Coordinates of each municipality.
- Coordinates of all possible locations of the logistic hubs, which will be in the centre of a municipality.
- Distance between every hub and non-hub node.
- Transportation cost between the hub and non-hub nodes.
- Cost per square meter for each municipality.
- Covering distances of the logistic hubs, with the appropriate number of hubs require to cover all demand.
- Formula relating the number of orders with logistic hub capacity.

To determine:

- Number and location of logistic hubs.
- Areas and costs of implementation of the logistic hubs.
- Percentage of demand coverage (100%, 90% and lower).
- Type of allocation to implement (Single or Multiple).

With these factors will be possible to provide results that minimise the overall costs of models as well as the distances between nodes and still be able to fulfil all of Worten’s demands.

4.2 Mathematical Formulations

In this subchapter, the model parameters and variables will be presented, followed by the mathematical formulations, composed of linear equations that will serve as restrictions in each model. It is essential to consider two indexes: *i* for the municipalities and *j* for the logistic hubs.

4.2.1 Parameters

The models’ formulation use the following parameters:

- Cap – capacity of the logistic hubs.
- Cob – Percentage of Demand Covered by the logistics hubs.
- Costkm – Fixed cost per kilometre travelled.
- Costm(j) – Cost of a square meter of a logistic hub.
- DEM(i) – Demand of each municipality i.
- d_{ij} – The linear distance between each municipality and logistic hub.
- Disth – Maximum distance that each Hub can cover in kilometres.
- i – Represents the municipalities.
- j – Represents the logistic hubs.
- Karea - Constant value represents the relation between number of orders and area.
- Latn(i) and Latm(j) – Latitude of each municipality and hub, respectively.
- Longn(i) and Longm(j) – Longitude of each municipality and hub, respectively.
- P – The number of logistic hubs to implement.
- R – Earth's radius.
- Rad – Constant to change degrees to radians.
- Tdem – Total demand of Portugal Mainland.

4.2.2 Variables

For these models, there will be 6 different variables, which are presented in table 2.

Table 2 Variables used in the models

Variable	Domain	Description	Allocation
x_{ij}	Binary	If a connection between node i and j exist, then is equal to 1, 0 otherwise.	Single
y_j	Binary	Is equal to 1 if the logistic hub is located at municipality j, 0 otherwise.	Single
t_i	Binary	It is used to restricts variable X_{ij}. The sum of variable X_{ij} must be equal t_i, meaning that the sum of the connection between node i and nodes j must be equal to 1 if node i is covered by at least one hub.	Multiple
v_{ij}	Binary	Represent the variable X_{ij}, is equal to 1 if a connection between node i and j exist. If the variable x_{ij} assumes values such as 0.01 or 0.72, for example, the variable v_{ij} will assume the value 1. This will help to calculate the distance between to nodes and to respect the covering distance restriction.	Multiple
X_{ij}	Positive	If it is greater than 0, there is a connection between node i and j, allowing node i to be connected to more than one node j.	Multiple
F_{ij}	Positive	Represents the flow of orders between node i and j. The sum of F_{ij} multiplying by X_{ij} must be equal to the total demand of node i.	Multiple

4.3 Formulation

Based on the formulation presented in Chapter 3, related to several models regarding HLP, this subchapter will simplify and adapt the linear equation to this specific problem that is being discussed. The following formulation considers the P-median Location Problem without any restriction. Throughout this chapter, several restrictions regarding distance, capacity, coverage, fixed costs and type of allocation will be presented. All models shown below will be used for the scenarios found in the next chapter.

Having in mind the several types of HLPs presented in Chapter 3, and for the purpose of this problem, in the context of this project, a simplified p-hub median problem with single and multiple allocations will be utilised. This problem can be implemented with and without a coverage radius, with fixed costs of implementing logistic hubs depending on their location. Also, a capacity constraint will be used, stipulating the maximum capacity a logistic hub can have/tolerate. Lastly, a constraint that allows the model to cover a certain percentage of Worten's demand.

4.3.1 P-Median LP (Single Allocation)

The objective of this model is to find the most appropriate location for the p logistic hubs to serve the demand nodes, so that the total weighted distance between nodes i and j is minimised. For this model, the demand coverage is equal to 100%.

Model Assumptions – Firstly, in this model each non-hub node is connected to only one hub node, and two non-hub nodes are never connected directly. Secondly, the number of hubs to implement in the model is known (*exogenous*). Moreover, the installation cost of the hub nodes is not considered, and it is considered that the capacities of these hub nodes are *unlimited* (*uncapacitated* model). Lastly, all decision variables of the model are binary variables (0–1).

Model Inputs - The number of logistic hubs to implement, p. Longitude and Latitude of the Municipalities and possible locations for the logistic hubs, followed by the radius of the Earth and the constant that allows changing to coordinates from degrees to radians. The demand corresponding to each municipality is also included. And finally, the cost per kilometer travelled.

Model Outputs - The location of each logistic hub and the municipality allocated to them, the total capacity, total distance travelled and respective cost and the maximum distance between a logistic hub and a municipality.

Objective Function and Constraints:

$$(1)\ \text{Min} \sum_{i}\sum_{j} DEM_i \times d_{i,j} \times x_{i,j}$$

Subject to,

$$(2)\ \sum_{j} x_{ij} = 1\ \forall\ i\ \in I,$$

$$(3)\ \sum_{j} y_j = p,$$

$$(4)\ x_{ij} \leq y_j\ \forall\ i,j\ \in I,$$

$$(5)\ x_{ij} = 0,1\ \forall\ i,j\ \in I,$$

$$(6)\ y_j = 0,1\ \forall\ j\ \in I.$$

The objective function (1) minimises the travelled distances between logistic hubs and municipalities, considering the existence of a connection between nodes. Regarding the restrictions, equation (2) ensures that one node can only be served by one logistic hub. Equation (3) guarantees that the sum of all the p-median nodes equals the value p, predetermined in the model. Equation (4) points out that the connection between a logistic hub and a municipality only exists if the p-median exists as well. Finally, the last two equations, (5) and (6), refer to the domain of both variables, in other words, the values they can assume in the model.

4.3.2 P-median LP with fixed costs

Model Assumptions - Equal to the p-median problem, the only difference is that the cost per square meter of each possible location is added for logistic hubs, which will also be placed in the objective function.

Model Inputs and Outputs – Regarding the inputs, they will be the same as the p-median problem plus the fixed cost of the square meter depending on the location of the logistic hubs. The outputs will be consistent to the ones presented in the p-median problem. KPIs will be introduced to analyse this model.

Objective Function and Constraints - The only change is regarding the objective function, which now aims to minimise the cost related to the hub, but also the distance between nodes. The constraints remain the same.

$$(7)\ \text{Min} \sum_{i} \sum_{j} (x_{i,j} \times DEM_i \times Karea \times CostM_j) + (x_{i,j} \times CostKM \times d_{i,j}).$$

4.3.3 P-median LP with Covering Radius

Model Assumptions – Equal to the p-median problem, but now there is a restriction regarding the maximum distance between a logistic hub and a municipality that is being served by that hub.

Model Inputs and Outputs – Both inputs and outputs are equal to the p-median problem. In addition, in the inputs of this model it is added the maximum covering distance of a hub. It is worth mentioning that KPIs will be introduced in the model to understand if this restriction is being fulfilled.

Objective Function and Constraints - The objective function can now be equal to the one presented in the p-medial problem (1) or to the one from which includes the fixed costs (7), but there is one more constraint added to the model, equation (8):

$$(8)\ d_{ij} \times x_{ij} \leq DistH\ \forall\ i,j\ \in I.$$

4.3.4 P-median LP with Capacity Limitations

Model Assumptions - Similar to the p-median problem and the only addition is regarding the maximum capacity of the hubs.

Model Inputs and Outputs - This model is similar to the p-median problem. However, an input regarding the capacity of each hub will be added. It is essential to keep in mind that this value is in orders per year.

In addition to the output from the previous models, it will be introduced a KPI which another output shows the total capacity of each logistic hub, which will also help verify if the constraint found below is respected.

Objective Function and Constraints - The objective function can now be equal to the one presented in the p-medial problem (1) or to the one from which includes the fixed costs (7). The one difference is that now there is a constraint regarding the capacity, equation (9), where the demand allocated to a hub cannot exceed the maximum capacity previously established.

$$(9)\ \sum_{i} x_{ij} \times DEM_i \leq Cap,\ \ \forall j.$$

4.3.5 P-median LP with Partial Coverage of Demand

Model Assumptions - Similar to the p-median problem, with the difference that now, the model does not need to serve all the municipalities.

Model Inputs and Outputs - For this model, and considering the p-median problem, the inputs and will be added are the total demand of Portugal Mainland and the percentage of demand that Worten wants to cover. The output will remain unchanged, and another KPI will be added to obtain the percentage of demand covered by the logistic hubs.

Objective Function and Constraint – The objective function can be the one presented in the p-median problem (1) or the one related with the cost minimisation (7). For this model, when compared to the p-median LP, a new constraint regarding the percentage of the demand covered by the hubs is added, presented in equation (10), and the constraint (2) now says that the sum of x_{ij} in order to j, can be lower than 1.

$$(10)\frac{\sum_i DEM_i \sum_j x_{ij}}{TDEM} \geq Cob\ \forall\ j\ \ \in I.$$

4.3.6 P-median LP with Multiple Allocation

As was mentioned before, with the multiple allocation LP, municipalities can now be served by more than one hub node. Having in mind the p-median LP with single allocation, to implement the model of multiple allocations, and new variables and equations were added. Four new variables will be added, as was mentioned before, which are X_{ij} , f_{ij}, v_{ij} and t_i.

Models Inputs and Outputs – For the multiple allocations, the inputs will vary depending on the restriction that will be considered in the model. In contrast the output of this model will be the variables X_{ij} , v_{ij} and y_j.

Objective Function and Constraint - Although the Objective Function will remain the same, equation (7), having only to replace the variable x_{ij} by the variable v_{ij}, some constraints will be subjected to changes, but compared to the p-median LP for single allocation, the only equations that will still be used are the equations (3), (4) and (10). The new equations are as follows:

$$(11)\ \sum_{j} x_{ij} \leq 1\ \forall\ i,j\ \in I,$$

$$(12)\ \sum_{j} x_{ij} = t_i\ \forall i\ \in I,$$

$$(13)\ f_{ij} = x_{ij} \times DEM_i\ \forall\ i,j\ \in I,$$

$$(14)\ \sum_{j} f_{ij} \leq\ DEM_i \times \sum_{j} x(i,j)\ \forall\ i\ \in I,$$

$$(15)\ \sum_{i} f_{ij} \leq\ Cap\ \forall j\ \in I,$$

$$(16)\ v_{ij} \geq x_{ij}\ \forall\ i,j\ \in I,$$

$$(17)\ \sum_{j} v_{ij}\ \leq 4\ \forall\ i\ \in I,$$

$$(18)\ v_{ij} \leq y_j\ \forall\ i,j\ \in I,$$

$$(19)\ d_{ij} \times v_{ij} \leq DistH\ \forall\ i,j\ \in I.$$

As was mentioned, x_{ij}, it is now a positive variable and equation (11) reflects that by saying that it can have value between 0 and 1. Equation (12) states that the sum of the variable x_{ij} will be equal to t_i, in other words, if a municipality is allocated to one or more hubs, the sum of the percentages of the node i distributed by the logistic hubs which are allocated to must be equal to 1, and equal to 0 if it is not covered by any logistic hub. The equation (13) ensures that the flow from i to j related to the demand of the municipality i must be equal to variable x_{ij}. Equation (14) refers to the sum of the flow of the several hubs j to municipality i, which must be equal or lower to that municipality's demand. The next equation, (15), says that the sums of the flows that will go from the hub to the municipality must be equal to the total demand of that municipality, in other words, it ensures that the demand of each municipality is covered 100% by the logistic hubs. Regarding the other new variable v_{ij}, that basically will transform the value of x_{ij} into a binary value, equation (16), resulting in situations that x_{ij} assumes values such as, 0.63 or 0.092, that will be changed into 1, so that the distance restriction is respected. Equation (17) stipulates that the sum of variable v_{ij} for node i can have a maximum of four allocation to logistic hubs. In addition, for equation (18) the variable v_{ij}, need to be higher than a y_j, because with multiple allocations, the total number of municipalities that will be selected will exceed the 278 municipalities introduced in the model. And the last equation, (19) focuses on complying with the distance restriction, but in this case, for the v_{ij} variable instead of the x_{ij}.

4.4 Summary of Chapter 4

In this chapter, the model characterisation was presented, followed by the mathematical formulation, composed of the different parameters that belong to the model, as well as the formulation used to solve this project. The different models present in this subchapter 4.3, which are formed by the equations (1) to (19), belong to the Mixed-Integer Programming (MIP) problems, and they modulate a generic problem, providing a set of logistic hubs with the respective location, demand and municipalities that are allocated to each one.

5 Results and Discussion

In this chapter will be presented the Data Treatment, where it is possible to retrieve the strategies used to deal with the complexity of the real-world models, data assumptions related to potential locations of logistic hubs and aggregation of demand, among other factors. From here, six different scenarios will be presented, and restrictions will be added gradually to each scenario. It is also relevant to refer that each scenario will be composed of more than one model, diverging in covering distance. Finally, the results obtained will be discussed.

5.1 Data Treatment

In this subchapter, the strategies applied to the data treatment will be introduced, mainly the strategies to deal with the complexity of the problem and the assumptions assumed as well. All the models developed for this project aim to study different scenarios depending on various factors that may be adapted/adjusted to meet Worten's requirements. With these models is possible to choose the number of logistic hubs based on the covering distance, percentage of order coverage and even maximum hub capacity.

5.1.1 Strategies to deal with the Complexity

The simplifications done to implement the model will be presented. These simplifications were done to make the model easier to compute while still providing results close to reality.

Aggregation of Clients (Orders)

Through a document provided by Worten, it was possible to obtain the location of each online order to either a Worten's store or the customer´s location (place of work or home address). So, in order to simplify the problem, the orders were allocated to the respective parishes and Municipalities based on the postal code and address, obtaining the number of orders located in each Municipality. Then, the coordinates of the centre of each municipality were obtained to have the location of each cluster of clients. Thus, the demand of each municipality responds to the total number of orders located within the municipality itself.

Due to some addresses being incomplete or with another type of error associated, some orders were not possible to allocate to a parish/municipality, representing a total percentage of 6.4%. The number of orders considered in this project represents 90.8% of the total number of orders, including only the orders for Portugal Mainland. If the demand of Madeira and Azores were to be included in this project, the percentage would increase by 2.8%. The table 3 presents all the values mentioned.

Table 3 Types of Orders with respective percentages

	Orders	Percentage
Orders Received	1 346 727	100%
Orders Mainland	1 222 224	90.80%
Orders Madeira+Açores	37 940	2.80%
Orders with errors	86 563	6.40%

Aggregation of Products

Also, to simplify the problem, it was assumed that all the orders received by Worten were for a generic product reference, since there are thousands of references in Worten's Warehouse. To conclude, only one type of product will be considered focusing this project on finding the best possible location for the logistic hubs.

Location of Logistic Hubs

Regarding attributing a location to the demand and possible locations for the logistic hubs, it was assumed that both parameters would be located in the centre of each municipality. The centre of each municipality was obtained through the respective coordinates.

5.1.2 Data and Assumption

5.1.2.1 Demand

Worten provided a document with the orders received in the year 2021. This document includes orders that were then delivered to a Worten store or to the address inserted by the customer. The next step was to allocate each order to a parish and/or to a municipality so that was possible to aggregate the orders in clusters, which are the municipalities. Therefore, the demand of each municipality is the sum of all the orders located in that specific municipality. In total there are 2882 parishes and 278 municipalities. Figure 11 shows a heatmap for the 278 municipalities of Portugal's Mainland, which takes into account the number of orders associated with each one. In annex 1 there is a table which provides the coordinates, demand and cost of the m^2 of each municipality.

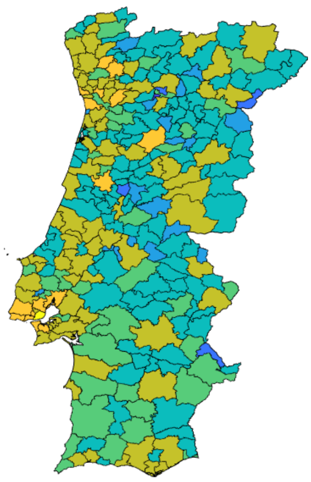

Figure 11 Heatmap of Portugal's Mainland

With this heatmap is possible to understand which municipalities have the most order. The brightest yellow municipality is located in Lisbon, which has the most orders. The darkest blue represents the municipalities with fewer orders, like Mesão Frio or Santa Marta de Penaguião. This will also help to locate the hubs and, depending on the demand of the respective municipality, and study the possibility of having several hubs allocated to one Municipality.

5.1.2.2 Distance

The distances calculated between logistic hubs and municipalities are linear and were obtained using the Haversine Formula (1), which takes into consideration the Latitude (φ) and Longitude(λ) between two points, the radius of Earth, the angle between the two points and the constant value to change the angle from degrees to radians. This linear distance does not represent the actual distance between nodes. The distance that will be present at the end of each model from each scenario is the total distance travelled from each logistic hub to deliver each order to the municipalities that are served by it (2), therefore, the demand must be included in the formula.

$$(1)\ d = 2r \times \arcsin(\sqrt{sin^2\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1) \times \cos(\varphi_2) \times sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}$$

$$(2)\ \mathrm{Dist_{total}} = \sum_{\mathrm{i,j}} \mathrm{DEM(i)} \times \mathrm{x_{ij}} \times \mathrm{d_{ij}}$$

5.1.2.3 Covering Radius

In order to determine the coverage area of a logistic hub, two factors were taken into consideration, the first being the average velocity of the vehicle responsible for delivery of the order from the logistic hub to the municipality. The average velocity assumed for the project was 45 Km/h. With this velocity, it is possible to assume that Worten can serve the demand at a maximum distance of 50 to 60 kilometres, considering the time it takes to prepare an order. For example, if it takes 50 minutes to prepare an order, Worten can serve the 50 kilometres radius, and if it takes 40 minutes, then it can serve the 60 kilometres radius.

The second factor that was considered was the fact that Worten already provides a two-hour delivery window in some areas of Portugal, and their current radius, in other words, the radius served by a Worten store, is 25 kilometres. With this information, it is possible to conclude that this radius should also be considered for the model.

5.1.2.4 Locations of Hubs

Regarding the location of Hubs, they can be located in any municipality. And the same logic applied to orders will also be used here, which refers to the fact that each logistic hub will be in the centre of each municipality. Also, there also the condition that each municipality can have a maximum of one hub allocated to it. The possible locations for each hub were provided through coordinates, longitude and latitude, and the same was done for the demand. There are 278 possible locations for the logistic hubs, and the next step is to define the number of hubs to implement.

5.1.2.5 Number of Hubs

Considering the total area of Portugal's Mainland is 88.890 km^2 and establishing a certain covering radius and consequently a coverage area for each hub. It is possible to reach a minimum number of the hub needed to cover the entire country. Along with the result of these calculations, it may be required to add more hubs since Portugal's borders are irregular, as in most countries. Following this line of thought, having the annual number of online orders and the number of logistic hubs needed, it is possible to reach a capacity constraint for each hub, assuming that all hubs have similar dimensions (and volume of products). It is through the expression (3) that the required number of hubs is calculated, making it possible to obtain the results in table 4.

$$(3)\ \#\ \text{hubs} = \frac{\text{Portugal Area (Mainland)}}{\pi \times \text{CovRad}^2}$$

Table 4 Different Covering radius, with area and number of hubs necessary

Covering Radius	25	30	35	40	45	50	55	60	65	70
Covering Area	1963.5	2827.4	3848.5	5026.6	6361.7	7854	9503.3	11309.7	13273.2	15393.8
Number of Hubs (3)	45	31	23	18	14	11	9	8	7	6
Final Number of Hubs	53	41	32	25	20	17	15	12	11	10

The next step was to run a single allocation model (p-hub median problem) without restrictions to understand if the calculations performed with expression (3) were enough to reach the minimum number of logistic hubs needed to cover Portugal's Mainland depending only on the covering radius. Focusing solely on the number of hubs for the 25, 50 and 60 kilometres, the total amount of hubs needed so that the model can run correctly and provide feasible solutions are 53, 17 and 12 logistic hubs, respectively, meaning that the values obtained while using the previous expression were insufficient. This procedure was done for the different covering radius, to obtain the final number of hubs displayed in the last line of table 5.2.

Furthermore, even though it has been determined that the appropriate number of hubs needed to cover the total area of Portugal depends on the coverage radius, it will also be considered a scenario where only 5 hubs will be implemented. Still, in this scenario, the demand for Portugal will not be met entirely.

5.1.2.6 Area of each hub

The total number of orders in 2021 that left Worten's Warehouse to be delivered on Portugal's Mainland were 1.222.224. And having in mind the total area of the warehouse in Azambuja, 45.000 m^2, it was possible to obtain the formula presented below, which shows the calculation that must be done:

$$(4)\ \mathrm{A_j} = \frac{\mathrm{n} * 45000}{1222224}$$

$$(5)\ n = \sum_i DEM_i * x_{ij}$$

Therefore, to obtain the respective area of each hub j, one must get the number of online orders of each hub, *n* and multiply it by the area of Worten's warehouses. And then divide it by the total number of online orders in Portugal Mainland. It Is also worth mentioning that the physical dimensions for each order were assumed to be the same, to simplify the model.

5.1.2.7 Cost of a Logistic Hub

This cost is composed of two different costs, the first is the cost per square meter and the second one is a fictitious value regarding the operational cost of each order. For the cost of the m^2 of each logistic hub depends on the municipality it is located in. This cost represents the rental cost of property in each municipality. The values were retrieved from the site idealista.pt, which provides the rental cost for most of the municipalities in Portugal.

In order to obtain the operational cost of each order, it was assumed that the operational cost of the warehouse in Azambuja has a fictitious value of 850.000€/year associated with the online orders. And dividing this value by the total amount of orders received in 2021, it was possible to reach an estimated cost of 0.70€/order. It is relevant to point out that, due a confidentiality agreement, this value was assumed and does not represent the real operational cost per order of Worten. This value online depends on orders and not the location of the orders or other relatable factors.

The cost of opening a hub, denoted by $CostH$, will depend on its area and location. The area can be obtained through the formula (4), and the cost per m^2, denoted by $Costm_i$, will be retrieved from the table in the annex 1. In conclusion, the cost of a logistic hub will be determined by equation (6), where the first part will provide the cost of the area occupied by the hub, followed by the total operational cost of the hub based on the number of orders that the hub will fulfil.

$$(6)\ CostH = Costm_i * A_n + n * 0.7$$

5.1.2.8 Transportation Costs

For this model, and to simplify it, a cost per kilometre at a fixed rate was assumed. In reality, the transportation costs vary with the distance travelled and with the dimension of the order, but it is also a service that does not fall under Worten's responsibilities. This value takes into consideration several factors, such as fuel consumption and the cost of CO_2 emissions. Still, as Worten uses other companies to perform the deliveries, a constant value that represents the previously mentioned factors was assumed, plus a profit margin for the companies which provide this service (Parcels). Therefore, the cost assumed was 0.5€/km.

5.2 Scenarios

The p-median problem with some adaptations will be used for the several scenarios. In the Scenario 1, the logistic hubs will serve the demand of the 278 Municipalities, meaning that each municipality will be allocated to a single logistic hub. No restrictions regarding coverage radius, cost of implementation, capacity limitations or partial coverage of demand will be used. In this first scenario, two different objective functions will be studied, one that minimises the travelled distance and the other that focuses on minimising the total costs.

For the Scenario 2, a covering distance will be applied, with the respective number of hubs to implement to fulfil the demand entirely and obtain feasible solutions from the model. With this new constraint, the objective is to limit the maximum distance between a logistic hub and the municipality allocated to it. Similar to the Scenario 1, two objective functions will be applied for each covering distance.

In the Scenario 3, a constraint regarding the maximum capacity that a logistic hub can handle will be added. With this, the objective is to obtain a more uniform area for the logistic hubs since there are significant discrepancies between the minimum and maximum area/capacity throughout the different hubs. In this scenario, the Multiple Allocations models will also be implemented to study the impact on the Hub Cost and Transportation Cost.

For the Scenario 4, a constraint will be implemented, allowing the model to cover at least 90% of Worten's demand. With this, not all municipalities will be served by the logistic hubs, which can positively impact the cost of each hub and distances travelled. This scenario will be composed of two sub-scenarios, Scenario **4.1** and Scenario **4.2**. In Scenario 4.1, for each covering radius, the same number of hubs obtained in Scenario 2 will be used. Scenario 4.2 will optimise the first one, reducing the number of hubs and then analysing the difference between hub cost transportation costs. In Scenario 4.2, the model will be run without capacity restriction to obtain the lowest possible number of logistic hubs for each covering radius and with 90% coverage of demand.

Lastly, there will be the Scenario 5, which will study the implementation of 5 logistic hubs in the model. These 5 hubs will be applied to the three covering distances, and for each covering distance, three models will be run for different maximum hub capacities restrictions, 128k, 200k and 500k orders.

For the scenarios, it is possible to check the coordinates for every municipality and possible location of the logistic hubs, the demand of each municipality and the cost of m^2 for each possible location of the hubs in Annex 1. Table 5 summarises each scenario, with the respective purpose, objective functions, types of allocations, number of logistic hubs and percentage of demand covered by the hubs.

Table 5 Summary of the Scenarios

Scenarios	Purpose	Objective Functions	Type of Allocation	Number of Hubs	Coverage
1	Run the model without restrictions	Dist Min and Cost Min	Single	5, 12, 17 and 53	100%
2	Implement a covering radius so that logistic hubs can comply with the time window	Dist Min and Cost Min	Single	12, 17 and 53	100%
3	Logistic hub capacity restriction and multiple allocations	Cost Min	Single and Multiple	12, 17 and 53	100%
4.1	Partial coverage of demand (90%)	Cost Min	Single and Multiple	12, 17 and 53	90%
4.2	Optimises the number of logistic hubs based on scenario 4.1	Cost Min	Single and Multiple	6, 8 and 19	90%
5	Fixed number of logistic hubs. Studies the impact that the covering radius and hub capacity on coverage percentage	Cost Min	Single	5	-

To arrive at the values in table 6, it was considered an average velocity of delivery (45 km/h). As mentioned, the distance that will be studied are the 25, 50 and 60 kilometres. The 45 km radius will not be considered due to the significant number of hubs needed, present in table 3. Moreover, due to the limited process time, the 65 and 70-kilometre radius will also not be considered.

Table 6 Radius of each Hub and the corresponding number

Hub Radius (KMs)	25	30	35	40	45	50	55	60	65	70
Number of Hubs	53	41	32	25	20	17	15	12	11	10

The models that were developed for this project will be implemented into a generic programming language, known as GAMS Studio 39 and solved through CPLEX (Mixed-Integer Programming), with a computer with the following characteristics: Processor Intel@ Core(TM) i7-7700HQ CPU @ 2.80GHz, 2.81 GHz.

KPIs obtained from the Models

These KPIs were introduced in the model to help to understand if the constraints were respected and to further study and analyse some relevant factors for the different scenarios.

- Maximum registered distance between i and j, through the Haversine Formula (1).
- Municipalities that are not allocated to any hub when coverage is under 100%, by retrieving the null value of the variable x_{ij}.
- Percentage of demand covered by the hubs, calculated by summing the total demand served and dividing it by the total number of orders received.
- Total distance travelled between municipalities and hubs, is obtained by using the distance between each pair of nodes i and j and multiplying by the number of orders of node i.
- Cost of the distance travelled, is achieved by multiplying the total distance by a fixed cost per km.
- The area of each hub is attained by multiplying the number of orders by the area's constant (karea).
- The cost of each hub is based on the area that each one will have, and then multiplied it by the rental cost of each hub location.
- The total cost of each model is the sum of all hubs' costs and the distance cost.
- The total number of municipalities allocated to each hub is reached by summing x_{ij} of each node j.
- Cost per order for each model is obtained by adding the model's total cost with the operational cost multiplied by the number of orders covered and then dividing it by the same number of orders.
- Municipalities with multiple allocations are acquired by summing all v_{ij} in order to node i. If the value is greater than 1, then there is multiple allocation in that municipality i.

5.2.1 Scenario 1 – No Restrictions

In this first scenario, there will be two objective functions, one to minimise the distances between logistic hubs and municipalities, O.F. Dist Min, and another whose objective is to minimise the cost associated with the distance travelled between nodes and the cost of implementation of each selected hub. Furthermore, for each objective function, it will be conducted 4 simulations with a different number of logistic hubs to implement, being 5, 12, 17 and 53, as mentioned. For both objective functions in this scenario, only the single allocation will be studied, and all the demand will be covered.

To better understand the layout of the tables containing the results obtained, table 7 for the instances with 5 logistic hubs will be presented. The remaining tables will be present in the annex 2. Each table is composed of 5 columns. The first one identifies the location of each Logistic Hub (which are numbered from H1 to H278), the number of municipalities allocated to each HUB, followed by the number of orders, area and hub cost. It is relevant to mention that the hub cost considers the cost of the m^2 and operational cost of each order.

In the Distance Minimisation OF for 5 logistic hubs, the hubs cover 100% of the demand. The hub that covers more municipalities is H35, located in Santo Tirso, covering 81 in total. The hub with the highest number of orders and consequently the highest area is hub H192, located in Lisbon, having a total of 470k orders and an area of 17.300 m^2. Finally, H192 will also be the hub with the highest hub cost, costing almost 87.7M€. In the Costs Minimisation, the hub H69, located in Sabrosa, is capable of covering 88 municipalities since there are no restrictions regarding hub capacity. Despite the number of municipalities covered, the hub H97, located in Sobral de Monte Agraço, will have the highest number of orders, 434k, thus also having the highest area, almost 16.000 m^2. The hub h97 not only has the largest area, but it also has the highest cost of m^2, meaning that it is the most expensive hub to implement, costing 17.3M€, which represents 56% of the total cost of implanting the 5 logistic hubs.

Table 7 Hubs' Characteristics for the 5 Logistic Hubs model (S1)

	O.F. Dist Min						O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H35	81	382631	14087.76	14848674		H69	88	232756	8569.64	2588137
2	H146	71	146808	5405.2	2902660		H97	22	433964	15977.74	17288112
3	H160	59	131423	4838.75	2583952		H108	57	285602	10515.33	5552224
4	H192	36	470200	17311.88	87702198		H160	70	155417	5722.16	3055704
5	H270	31	91162	3356.41	10784187		H215	41	114485	4215.12	2756741

In the 12 logistic hubs instances, in Annex 2, starting with the OF Dist Min, the logistic hub that covers more municipalities, 36 in total, is H66, located in Murça. The hub with more orders and the highest area will be H192, which belongs to Lisbon, with almost 290k orders and an area of 10.700 m^2. This same hub is also the one with the most expensive implementation cost of 74.3M€. And for the OF Costs Min, H213 covers the most significant number of municipalities, 70, and is located in Carrezeda de Ansiães. The hub that serves the most orders and has the highest area is H97, located in Sobral de Monte Agraço, serving 404k orders, which corresponds to an area of approximately 15.000 m^2, and with the implementation cost equal to 16.1M€. This hub, H97, is the most expensive, representing 51% of the total cost of the hubs.

Moving to the instances where 17 logistic hub, in the OF Distance Minimisation, the hub H165, located in Ourém, serves 26 municipalities, which is the highest number. For the most orders served and highest area, hub H192 dominates, serving almost 290k orders, occupying an area of 10.700 m^2, with an implementation cost of 54M€. The following hub is H32, located in Porto, serving 143k orders, with dimensions close to 5300 m^2, costing 16.2M€. In the second OF, Cost minimisation, the logistic hub H69, located in Sabrosa, is capable of serving 33 municipalities. Regardless of this, the hub with the most orders and the highest area is H97, in Sobral de Monte Agraço, with 363k orders and 13.400 m^2. This hub will also have the maximum implementation cost of 14.5M€. The table is locatedd in Annex 2.

Finally, in the last two models, where the number of logistic hubs to implement is equal to 53, for the Dist Min, the hub that registered the highest number of municipalities served is H77, located in Vila Real, serving a total of 17. Moving to the hub with the most orders and respectively highest area will be again the H192, in Lisbon, with approximately 128k orders in total. As seen previously, an area equal to 4.680 m^2. As expected, the hub h192 also has higher implementation costs, 23.7M€, followed by hub H41, located in Vila Nova de Gaia, at 4.7M€. The hub with the smallest area and cost is H215, in Castro Verde, with 215 m^2 and costing 141k€. For the second OF, which focuses on minimising costs, hub H108 can serve 16 municipalities and is in Sever do Vouga. Finally, as seen in the previous models, hub H97 has the most orders and area and is the most expensive to implement. It covers 314k orders, with an area equal to 11.550 m^2 and costing 12.5M€. On the other hand, the hub H85, in Vimioso, is the one with the smallest area and the lowest cost, 22 m^2 and 8k€.

Taking a closer look at table 8 and 9 is possible to analyse the minimum and maximum capacities depending on the number of hubs and different objective functions. The same goes for the cost of implementing the logistic hubs, the maximum distance between one hub and a municipality that is served by that same hub, the total distance travelled and cost of that distance as well, and finally, the total cost and considered the cost of hubs and cost of distance.

From the first OF, the largest logistic hub belongs to the 5 hubs instance, and the smallest belongs to the 53 hubs instance, as expected. The highest total implementation cost of hubs is 123M€, which is present in the 12 hubs instance. And the 5 logistic hubs instance has the longest distance registered between nodes, the most kilometres travelled and the highest overall costs. In the second OF, the largest and smallest areas belong to the 5 and 53 hub instances, respectively. The longest distance between nodes, the most distances travelled, and the highest overall cost is present in the 5 hubs instance. And in the 53 hubs instance has the most expensive total cost of implementation, 34.7M€, but the lowest total cost of 51.7M€.

Comparing both OF, as would be expected, the maximum distance between nodes and total distance travelled are lower in the first OF. For example, in the 5 hubs instances, the total distance travelled increases 1.5 times when compared to the Distance Min OF to the Costs Min OF. Regarding the cost of implementation of the hubs, the lowest value depending on the number of hubs, are present in the second OF. Analysing the 12 hubs instances is where the highest implementation cost can be found. From the first OF to the second, the costs decrease from 124M€ to 32.1M€, representing only 25% of the cost in the first O.F. In the remaining instances, a similar decrease can be observed.

It is also worth mentioning that with the increase of logistic hubs in the model, the maximum distance registered between hubs and municipalities decreases. This happens since the number of hubs spread along Portugal is increasing.

Table 8 Models' Outputs for both Objective Functions (S1)

		5 Hubs	12 Hubs	17 Hubs	53 Hubs
O.F. Distance Min	Minimum Capacity (m^2)	3356.41	1167.21	733.67	215.1
	Maximum Capacity (m^2)	17311.88	14666.21	10658.15	4680.62
	Cost of Hubs (€)	118821669	124028128	110856962	91491315
	Maximum Distance (KM)	185.161	99.245	80.137	80.137
	Total Distance (KM)	40431380	24419520	19262734	6047951
	Cost of Distance (€)	20 215 690	12 209 760	9 631 367	3 023 975
	Total Cost (€)	139 037 359	136 237 888	120 488 329	94 515 290

		5 Hubs	12 Hubs	17 Hubs	53 Hubs
O.F. Cost Min	Minimum Capacity (m^2)	4215.12	690.49	443.18	22.13
	Maximum Capacity (m^2)	15977.74	14878.13	13364.61	11544.91
	Cost of Hubs (€)	31240918	32147568	32343076	34707120
	Maximum Distance (KM)	146.483	99.702	87.561	87.561
	Total Distance (KM)	61121260	45139230	42648780	34014440
	Cost of Distance (€)	30 560 630	22 569 615	21 324 390	17 007 220
	Total Cost (€)	61 801 548	54 717 183	53 667 466	51 714 340

In table 10, it is possible to analyse the model statistics. In both objective functions and for all 4 different inputs regarding the number of logistic hubs to locate, the block of equations and variables, the single equations, variable and discrete variables, the number of nodes and relative gap are the same for all models. The only factors that differ are the values of the objective functions, the number of iterations and the resource usage of the model.

For the Distance Minimisation OF, the instance whose objective function value is the highest is in the 5 hubs model, also having the highest number of iterations and the resource usage. The 53 hub instance also has the lowest OF value and number of iterations. In the Costs Minimisation OF, as was observed in the previous OF, the instance with 5 hubs has the highest OF value and the most iterations, whereas the 53 hubs instances have the lowest OF value, fewest iterations and the lowest resource usage.

Table 9 Models' Statistics for both Objective Functions (S1)

		5 Hubs	12 Hubs	17 Hubs	53 Hubs
O.F. Dist Min	Objective Function	40 431 380	24 419 520	19 262 734	6 047 951
	Block of Equations	4	4	4	4
	Block of Variables	3	3	3	3
	Single Equations	77,564	77,564	77,564	77,564
	Single Variables (Discrete)	77,563 (77,562)	77,563 (77,562)	77,563 (77,562)	77,563 (77,562)
	Iterations	14901	7212	5947	1795
	Number of Nodes	0	0	0	0
	Resource Usage (Seconds)	3.766	3.313	3.344	2.672
	Relative Gap	0.0%	0.0%	0.0%	0.0%

Table 10 Continuation of Table 9

O.F. Costs Min	Objective Function	60 945 974	53 861 600	52 664 553	50 858 750
	Block of Equations	4	4	4	4
	Block of Variables	3	3	3	3
	Single Equations	77,564	77,564	77,564	77,564
	Single Variables (Discrete)	77,563 (77,562)	77,563 (77,562)	77,563 (77,562)	77,563 (77,562)
	Iterations	7533	2416	1459	456
	Number of Nodes	0	0	0	0
	Resource Usage (Seconds)	4.921	3.000	2.797	2.562
	Relative Gap	0.00%	0.00%	0.00%	0.00%

Having the Objective Function focused on reducing the travelled distance will increase the cost of implementation of the hubs while having lower distance costs when compared to the Objective Function that prioritises the reduction of overall costs, mainly the cost of implementation of the hubs.

From the table is possible to retrieve that in the first OF, independently of the number of hubs, the total costs are lower than in the second OF, and the main cause of this is the total distance travelled that is nearly the double the distance of the first OF. It is worth mentioning that in the Cost Minimisation Objective Function, there is a notable difference between the value of the objective function and the sum of the total cost, since the operational costs were not introduced in the formulation, being only considered the rent and transportation costs for each hub. And the operational costs were later added to the total costs.

Another conclusion that can be taken from this table is that regarding the increase in the number of hubs, the lowest maximum distance between a logistic hub and a municipality is 80 kilometres, which does not allow Worten to comply with the two-hour time window for both objective functions. Therefore, it is necessary to add a new constraint to the model.

5.2.2 Scenario 2 – Covering Radius Constraint

With the covering distance restriction of the logistic hubs, it will allow the allocation of municipalities within that certain distance of the hubs while considering that the demand is entirely covered (100%). By running the model with for different instances, it was possible to obtain the table in Annex 3, which show the location of the hubs, the number of municipalities allocated to each hubs, the number of orders, areas and cost of implementing each logistic hub. For the different distances that will be used in this Scenario, table 11 shows the number of hubs necessary so that the model can run and return feasible solutions. These values were obtained using the single allocation formulation.

Table 11 Covering radius and corresponding number of logistic hubs

Hub Radius (Kms)	25	50	60
Number of Hubs	53	17	12

As was done in the previous scenario, regarding the covering radius constraint, a comparison between the Objective Function that minimises the travelled distance and the one that reduces the cost of implementing logistic hubs and the cost of the distance travelled will be analysed. Remember that the allocation will be single for both objective functions.

The first covering distance to be analysed is 25 kilometres. From the first table in Annex 3, it is possible to explore the locations of the various logistic hubs, the number of municipalities allocated to each one, the number of orders assigned to each logistic hub, followed by the respective area and cost. The different outputs were studied for both objective functions.

With the first objective function, Distance Min, it is possible to retrieve some relevant information, such as hub H27, located in Gondomar, serving 12 municipalities. The hub with the most orders and, consequently, the highest area is hub H197, with 293k orders and a corresponding area of 10.776 m^2. This hub is also the most expensive one to implement, costing 25.8M€. The second most costly hub is H27, costing 8.1M€. In addition, hub H213 in Barrancos has the smallest area and cost, with only 12 m^2 and a cost of 2k€. In the second objective function, the highest number of municipalities served is 14, allocated to hub H190, which belongs to Barreiro. This hub has the most orders, meaning it also has the largest area and, consequently, the highest implementation cost. In total, the hub H190 has 325k orders, an area of 12.000 m^2 and a cost equal to 19.9M€. In contrast, as happened in the previous O.F., hub H213 is also the one with the smallest area and lowest cost.

Table 12 gathers all the important information obtained from the instance, the maximum and minimum capacity recorded from the several hubs, the total cost of implementing these hubs, the total distance travelled, and the responding cost of it, and the total cost of the results of the sum between the cost of implementing the hubs and the cost of the distance travelled. To compare the several scenarios and instances, a cost per order will also be calculated. It is possible to conclude that regarding the capacity, in both objective functions, there is a big discrepancy between the maximum and minimum values. Comparing the costs, for the implementation costs (rent plus operational costs), there is a difference of 11.8M€, and for the transportation costs, the difference is around 2.2M€, which results in a total difference of 11.8M€ between the two objective functions. Finally, the cost per order differs by 9.69€. (OC – Operational Costs = 855.556€).

Table 12 Models' Outputs for both the 25 KM instance(S2)

25 Km	O.F. Dist Min	O.F. Costs Min
Maximum Cap (m^2)	10775.97	11983.56
Minimum Cap (m^2)	11.6	11.6
Cost of Hubs (€)	71 754 727 + OC	57 706 983 + OC
Total Distance (KM)	13375090	17789972
Cost of Distance (€)	6 687 545	8 894 986
Total Costs (€)	79 297 829	67 457 525
Cost per Order	64.88	55.19

Regarding the Model Statistics in table 13, as has happened in the previous scenario, the only differences between objective functions are the values of the OF, the number of iterations, having a difference of 477, and the resource usage, which differs by 0.25 seconds. For the value obtained in the objective function, the significant discrepancy is due to the parameters within each OF. The remaining factors are the same for both objective functions.

Table 13 Models' Statistics for the 25 KM instance (S2)

25 KM	O.F. Dist Min	O.F. Costs Min
Objective Function	13 375 089	66 601 939
Block of Equations	5	5
Block of Variables	3	3
Single Equations	154,570	154,570
Single Variables (Discrete)	77,563 (77,562)	77,563(77,562)
Iterations	1643	1923
Number of Nodes	0	0
Resource Usage (Seconds)	0.547	0.797
Relative Gap	0.0%	0.00%

The same analysis for the 25 km radius will be conducted for the 50 km and 60 km radii instances. In the 50 km, the second table in Annex 3, provides information on which hub locations were selected for each objective function, followed by the number of municipalities allocated and the respective capacity of the hub. For the objective function of distance minimisation, hub H38, located in Vale de Cambra, serves the most municipalities, 35, representing 224k orders in total. But the logistic hub with more orders and highest dimensions is H192, in Lisbon, with 443k orders and an area equal to 16.317 m^2. This hub located in Lisbon is also the hub with the highest implementation cost, 82.4M€, representing 73% of the total cost of all logistic hubs. It will have a significant impact on the total costs when compared to the other instances. In contrast, the hub H219, in Moura, has the smallest area and cost, 192 m^2 and 123k€.

For the second objective function, H25 in Arouca covers most municipalities, 33 in total. But the logistic hub with the most orders is H195, located in Moita, with 397k orders and an area of 14.628 m^2. This hub is also the most expensive, costing 21.1M€, weighing 43% of the cost of implementing the 17 logistic hubs. On the other hand, hub H256 has the smallest area and cost as well, 214 m^2 and 130k€

Table 14 shows different factors, such as the maximum and minimum capacities of the hubs and a notable difference between the extreme hubs. The cost of the hubs is higher in the first OF, which was also mentioned before, with a difference of almost 64M€ to the other OF. The total distance travelled and the cost of transportation is higher in the second OF, and the difference is f 2.7M€. As expected, the OF with the highest total costs is the one focused on minimising only the distance between the logistic hubs and municipalities (OF Dist Min), being almost double the value in the Cost Minimisation OF. The total difference between objective functions is 61.4M€. Finally, the difference between costs per order is equal to 50.30€.

Table 14 Models' Outputs for the 50 KM instance (S2)

50 Km	O.F. Dist Min	O.F. Costs Min
Maximum Cap (m^2)	16317.17	14628.28
Minimum Cap (m^2)	192.37	213.99
Cost of Hubs (€)	112 659 040 + OC	48 581 256 + OC
Total Distance (KM)	29926677	35300940
Cost of Distance (€)	14 963 340	17 650 470
Total Costs (€)	128 477 936	67 087282
Cost per Order	105.19	54.89

For the 50 Km radius instance, table 15 shows all the model statistics between the objective functions. The only differences between the two objective functions for the 50-kilometre covering distance is the value of the OF, which is usually higher in the Cost Minimisation. Since more parameters are involved, the number of iterations, which has a difference of 250 iterations between the two OF, and the generation time, is almost the same but differs by 0.25 seconds, same difference registered in the 25 km. The remaining factors are equal to the 25 kilometres models.

Table 15 Models' Statistics for the 50 KM instance (S2)

50 KM	O.F. Dist Min	O.F. Costs Min
Objective Function	29 926 677	66 231 696
Block of Equations	5	5
Block of Variables	3	3
Single Equations	154,570	154,570
Single Variables (Discrete)	77,563 (77,562)	77,563 (77,562)
Iterations	6094	6344
Number of Nodes	0	0
Resource Usage (Seconds)	0.813	1.063
Relative Gap	0.0%	0.0%

The third table in Annex 3 presents the same factors as the two previous covering distances for both objective functions. For the 60 km radius, the instance ran with 12 logistic hubs. And for the objective function, whose objective is to reduce the distances between hub nodes and non-hub nodes is possible to conclude that the hub H11, in Amares, covers the most municipalities, 43, with a total of 236k orders. Despite this, the hub with the most orders is H89, in Arruda dos Vinhos, with 459k orders and an area of 16.900 m^2, representing a cost of 22.5M€, which is equal to 35% of the total cost of implementing the hubs. Furthermore, the hub this the lowest dimensions and cost is H221, in Serpa, with 775 m^2 and costing 524k€.

For the second OF, the most municipalities served are 33 by hub H25, in Arouca. On the other hand, hub H195 in Moita has the most orders, with 398k, and occupies an area of 14.628 m^2, with an implementation cost of 21M€. This implementation cost is among the other logistic hubs, representing 43% of the total cost of implementation. The lowest area and cost are 214 m^2 and 130k€, which belong to hub H256, located in Mourão.

Table 16, similar to the ones of the 25 and 50 km radius, shows the maximum and minimum capacity register from the logistic hubs, which do not vary must between the two objective functions. Regarding the cost of implementing the logistic hubs, the difference is around 20.3M€, being the higher cost in the objective function focused on minimising the distance between nodes. The transportation cost differs by 2.8M€. As was also analysed in the previous radius, the total distance travelled is lower in the first OF. However, the total cost results in a difference of 17.5M€. It is relevant to refer that the difference between the costs per order is equal to 14.33€.

Table 16 Models' Outputs for the 60 KM instance (S2)

60 Km	O.F. Dist Min	O.F. Costs Min
Maximum Cap (m^2)	16909.5	17590.49
Minimum Cap (m^2)	775.43	575.43
Cost of Hubs (€)	63 118 161 + OC	42 848 524 + OC
Total Distance (KM)	41102168	46631014
Cost of Distance (€)	20 551 085	23 315 507
Total Costs (€)	84 524 802	67 019 587
Cost per Order	69.16	54.83

Regarding the model statistics for the 60 km radius instances, table 17 presents the only differences will be in the values of the OF, which was mentioned before, in the number of iterations, where the Dist Min OF has more than the compared to the Cost Min OF, and the number of nodes will be equal to 11 for the Distance Min and 0 for the Costs Min. The resource usage takes more 1.7 seconds in the Dist Min OF.

Table 17 Models' Statistics for the 60 KM instance (S2)

60 KM	O.F. Dist Min	O.F. Costs Min
Objective Function	41 102 168	66 163 996
Block of Equations	5	5
Block of Variables	3	3
Single Equations	154,570	154,570
Single Variables (Discrete)	77,563 (77,562)	77,563(77,562)
Iterations	14451	6608
Number of Nodes	11	0
Resource Usage (Seconds)	2.640	0.938
Relative Gap	0.0%	0.00%

Disregarding the homogeneity of the number of municipalities among the hubs, there is an accentuated difference between the maximum and minimum hubs' capacities, ranging between 11.000 m^2 and 17.000 m^2, depending on the number of logistic hubs and objective functions. In addition, a restriction regarding the capacity is necessary to establish a limit in terms of the maximum area that one hub can have. It is also important to refer that in this scenario, it is not possible to consider the implementation of five logistic hubs due to the covering distance and the total coverage demand constraints. Figure 12 makes a comparison between the total costs for both objective functions.

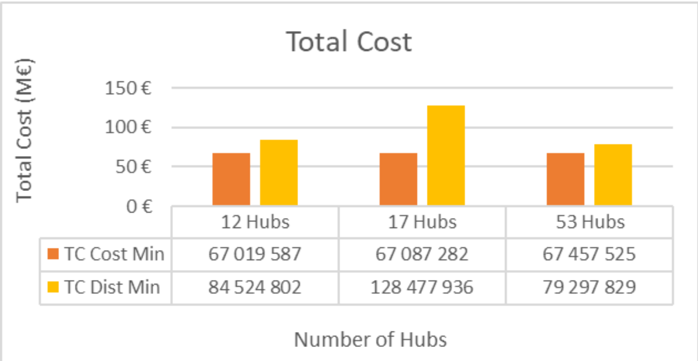

Figure 12 Total Cost depending on the OF and number of hubs

Compared to Scenario 1, the total costs for the OF which minimises distances travelled between nodes, have a lower value for the instance regarding the 12 and 53 logistic hubs but are more expensive by 8M€ in the 17 logistic hubs instance. For the second OF, for the three instances, the total costs are higher in Scenario 2, but contrarily to Scenario 1, Scenario 2 complies with the two-hour delivery window. In addition, the second OF will be the one that will be used for the remaining scenarios since is more relevant to Worten.

5.2.3 Scenario 3 – Capacity Constraint

The next step is to implement a capacity constraint in order to have homogeneity among the logistic hubs and limit the maximum capacity a logistic hub can have. For this scenario, the Objective Function of the instances will minimise the cost of opening the hubs, as well as the distance between the municipalities allocated to each hub, having a cost per travelled kilometres included.

This constraint will help to better distribute the demand throughout the several logistic hubs available in the instances and to study the application of multiple allocations in the model. To have the model running properly for multiple allocations, some changes regarding the model's formulas had to be made. The model will return similar but improved results with the same inputs of a single allocation and using the multiple allocation formulation. One possible downside of this type of allocation is the slight increase in hubs cost, but on the other hand, there is a higher decrease in transportation costs.

Figure 13 presents a scenario with three municipalities and three hubs to better understand the purpose of multiple allocations. With multiple allocations, one municipality may be covered by more than one logistic hub, due to capacity constraints or other factors such as cost per square meter. For this example, shown in figure xx, with a hub capacity constraint of 6 units, municipality 1 needs to be served by more than one hub. As a result of this, hub 2 is still capable of serving municipality 2.

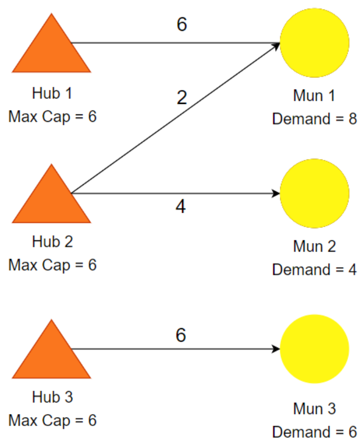

Figure 13 Multiple Allocations Example

Starting with the single allocation for the 25 km radius instance, the maximum capacity of each logistic hub must be at least 200k orders in order to obtain feasible solutions. If for any reason, this value decreases while maintaining the same inputs, the instance will not be capable of providing any results. With the constraint established is possible to retrieve from the table that the hub H124 is the one capable of serving more municipalities, 12 in total, but is not the one with the largest area. The hub with the largest number of orders is hub H190, located in Barreiro, with almost 200k orders, an area equal to 7.323 m^2 and costs 12.2M€. But the hub with the highest cost in this instance is H197, in Odivelas, costing 17.5M€. This last hub has a similar area to H190, but the cost per m^2 is higher on the H197, costing 2379€/m^2, whereas the H190 costs 1645€/m^2. The table 14 presents a summarised table of the one in Annex 4.

In the case of the Multiple Allocation, the number of logistic hubs and covering distance are equal to the single allocation instance, as well as the percentage of demand covered (100%) and the capacity restriction. Similar to what happened in the SA, if the value of the maximum hub capacity decreases, the instance will not produce any feasible solutions.

So, with the multiple allocation formulation and the inputs used in the single allocation instances for the 25 km, it was possible to obtain similar results but with a few improvements, present in table 18 and Annex 4. Starting with the hub that serves the most municipalities, it remains the hub H124, with 12 municipalities. Moving to the hub with the most orders and the most expensive hub, H190 remains the one with the most orders, 200k exactly, which increases its cost by 67k€, and H197 is still the most expensive, but now costing 17.4M€, less 97k€ than in single allocation. These changes are due to M192, also located in Lisbon, which is now covered by two logistic hubs, H190 and H197.

Table 18 Summarised table with the Hubs' Characteristics for the 25 KM instance (S3)

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
17	H124	12	36019	1326.15	628612		H124	12	36019	1326.15	628612
29	H190	7	198898	7323.05	12185646		H190	11	200000	7363.63	12253171
30	H197	11	198457	7306.82	17521845		H197	8	197355	7266.24	17424533

Table 19 compares several factors regarding the two types of allocation when implementing 53 logistic hubs for 25 km covering radius. Regarding the areas, as was mentioned, the maximum hub capacity registered was higher in the multiple allocation instance, while the smallest area remained the same. For the total cost for implementing the hubs, with multiple allocation, that value decreases by 30k€, while the cost of transportation is 227k€. The decrease in the transportation cost is due to the reduction in km travelled from single to multiple allocation. The total difference between these two types of allocations is 257k€. And finally, the difference between the cost per order is equal to 0.21€. (OC – Operational Costs = 855.556€, in total).

Table 19 Models' Outputs for the 25 KM instance (S3)

25 KM	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	7323.05	7363.63
Minimum Cap (m^2)	11.6	11.6
Cost of Hubs (€)	61 127 821 + OC	61 098 035 + OC
Total Distance (Km)	16980606	16525914
Cost of Distance (€)	8 490 303	8 262 957
Total Costs (€)	70 473 680	70 216 548
Cost per Order	57.66	57.45

Moving on to the comparison between models' statistics, presented in table 20, the only factor that is equal to both allocations is the relative gap, which is 0.0%. In terms of the block of equations and variables, single equations, single and discrete variables, as well as the number of iterations, nodes and resource usage, are different because each allocation has different formulas and variables. From all factors mentioned, multiple allocation model is larger and take more time to be solved.

Table 20 Models' Statistics for the 25 KM instance (S3)

25 KM	Single Allocation	Multiple Allocation
Objective Function	69 618 070 €	69 360 943 €
Block of Equations	7	13
Block of Variables	3	6
Single Equations	154,849	387,535
Single Variables (Discrete)	77,563(77,562)	232,409 (77,840)
Iterations	3300	3337
Number of Nodes	37	15
Resource Usage (Seconds)	1.047	3.063
Relative Gap	0.00%	0.00%

The next covering distance that will be analysed is the 50 km instance, with the respective table in Annex 4 and the summarise table 21. For the single allocation instance, the maximum capacity for which the model was capable of providing feasible solutions must be at least equal to 390k orders. This value comes from reducing the number of logistic hubs to be implemented. From this single allocation instance is possible to conclude that the highest number of hubs served is 33, and the hub capable of doing that is H25, located in Arouca. Despite this, the hub with the most orders to fulfil and consequently the most prominent area is hub H195, in Moita, with 389k orders and an area equal to 14.300 m^2. Due to having the largest area by far, this hub also has the highest implementation cost, 20.9M€, representing 41% of the total hub cost. In contrast, the hub H256, located in Mourão, is the hub with the smallest area and cost, with 214 m^2 and costing almost 134k€.

Moving to the Multiple Allocation instance, the inputs are the same as for the single allocation. The only difference is the formulation, which was adapted so that the instance could provide results where one or more hubs can serve one municipality. With this in mind was possible to obtain information about the logistic hubs very similar to the single allocation instance. The hub H25 is the one that covers more municipalities, whereas the H195 is the one with the most orders, the largest areas and also the most expensive to implement. In this instance, H195 has more orders, 390k, a larger area of 14.360 m^2 and costs 20.7M€. This happens due to the multiple allocations of the municipality M202, Setúbal, which are allocated to H195 and H206, located in Moita and Grândola, respectively. With this MA, the number of orders will increase in H195 and decrease in H206. The complete table with the 17 logistic hubs is present in the Annex 4.

Table 21 Summarised table with the Hubs' Characteristics for the 50 KM instance (S3)

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Hub Cap	Hub Area	Hub Cost
2	H25	33	203938	7508.62	5834291		H25	33	203938	7508.62	1381801
9	H195	16	388360	14298.69	20847667		H195	17	390000	14359.07	20935702
10	H206	4	17183	632.65	2393323		H206	4	15543	572.26	2164867

Starting by comparing some outputs of the model, in table 22, the maximum and minimum hub capacity are very similar between the two instances, with a small increase in multiple allocation due to hub H195 having more orders. Although there is an increase in the maximum capacity of a hub, the cost of the 17 logistic hubs is reduced by 140k€ for the multiple allocation model. Regarding the total distance travelled and cost of transportation, both values are reduced when multiple allocation is implemented, costing less than 26k€. The total difference between instances comes to 166k€. The difference between the cost per order is equal to 0.14€. (OC – Operational Costs = 855.556€, in total).

Table 22 Models' Outputs for the 50 KM instance (S3)

50 Km	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	14298.69	14359.07
Minimum Cap (m^2)	213.99	213.99
Cost of Hubs (€)	50 183 166 + OC	50 042 744 + OC
Total Distance (KM)	35 706 050	35654640
Cost of Distance (€)	17 853 025	17 827 320
Total Costs (€)	68 891 747	68 725 620
Cost per Order	56.37	56.23

Comparing the model statistics, for the 60 km covering distance, in table 23, some factors such as block of equations and variables, single and discrete variables and relative gap will assume the same values of table 20. Aside from the value of the objective function, which represents the total costs, and the number of iterations, that increase, and the multiple allocation instance has more 639 iterations and the number of nodes, that now is zero for both instances. It is worth mentioning that the resource usage is lower in the single allocation, whereas, in the multiple, it increases by 2.8 seconds.

Table 23 Models' Statistics for the 50 KM instance (S3)

50 KM	SA	MA
Objective Function	68 036 105	67 870 021
Iterations	7117	7756
Number of Nodes	0	0
Resource Usage (Seconds)	1.297	4.094

The third and last covering distance will now be analysed, 60 km. The same logic used in the two previous distances will be applied here as well, therefore, the maximum hub capacity must be greater or equal to 380k, in order to allow the model to provide feasible solutions. This value is smaller than the one used for the 50 km, since the number of hubs decreases by 5, but the covering radius increases by 10 km. Table 24 summarises the information present in the third table of Annex 4.

Having run the single allocation instance with the value presented above is possible to conclude that hub the hub with more municipalities covered, 46 in total, is H139 and it is located in Porto de Mós. On the other hand, H97, located in Sobral de Monte Agraço, fulfils almost 380k orders, with an area of 13.974 m^2. This hub is also the most expensive, costing around 15.1M€.

In the multiple allocation instance, is also possible to conclude that the hub H139 has the most municipalities, and H97 is the one with the largest area, most orders and most expensive. Despite this, by having multiple allocations in the municipality M190, in the municipality of Barreiro, which is served by H97 and H205, with the respective locations in Sobral de Monte Agraço e Alcácer do Sal. The number of orders will increase by 464 in hub H97, which will increase its cost by 18k€. On the other hand, the number of orders will decrease by the same amount and save a total of 51k€ in hub H205.

Table 24 Summarised table with the Hubs' Characteristics for the 60 KM instance (S3)

	Single Allocation					Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Hub Cap	Hub Area	Hub Cost
3	H97	25	379536	13973.81	15119835	H97	25	380000	13990.89	15138316
5	H139	46	77199	2842.32	938001	H139	46	77199	2842.32	938001
8	H205	12	91956	3385.65	10014795	H205	13	91492	3368.56	9964242

Now comparing the value of both allocations in table 25, as was mentioned, the maximum hub capacity will increase in the multiple allocation instance. In contrast, the minimum capacity remains the same for both instances. It is possible to retrieve from the table that with the multiple allocation instance, it is possible to save 32k€ in hub costs and 37k€ in transportation costs. So, in total, the implementation of multiple allocation for this scenario and with a radius of 60 km, the total cost reduces 69k€. Regarding the cost per order, only 0.04€ separates the two allocations. (OC – Operational Costs = 855.556€, in total).

Table 25 Models' Outputs for the 60 KM instance (S3)

60 Km	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	13973.81	13990.89
Minimum Cap (m^2)	590.78	590.78
Cost of Hubs (€)	50 379 117 + OC	50 347 046 + OC
Total Distance (KM)	44 178 746	44 105 488
Cost of Distance (€)	22 089 373	22 052 744
Total Costs (€)	73 324 046	73 255 346
Cost per Order	59.99	59.94

The only relevant factors worth mentioning between the two allocations are the number of iterations, nodes and generation time, shown in table 26. The single allocation instance has in total 16.423 iterations, 1128 more than the multiple instance, but in terms of nodes, the multiple allocation instance has 9, whereas the single only needs one node. Comparing the resource usage with the 50 km radius, the values differ by 5.375. This multiple allocation instance is the one that takes longer to solve, when compared to the other 5 instances analysed in this scenario.

Table 26 Models' Statistics for the 60 KM instance (S3)

60 KM – 100%	SA	MA
Objective Function	72 468 437	72 399 760
Iterations	16423	15295
Number of Nodes	1	9
Resource Usage (Seconds)	5.500	10.875
Relative Gap	0.00%	0.00%

As it was possible to observe in the objective functions for each covering distance, the multiple allocation model is more beneficial for the inputs introduced in the model. But the implementation of multiple allocation can involve another management level, which can become more costly to Worten. The instance with the lowest total costs and cost per order belongs to the 50-kilometre radius. In this instance single and multiple allocation are the lowest of each type of allocation, but the multiple's costs are lower than the single's.

Scenario 2 vs 3

Now comparing the best objective function obtained in Scenario 2, which is the Costs Minimisation, with the type of allocation which provides lower costs, multiple allocations, it is possible to reach figure 14. The total costs increased when the capacity restriction was applied since the capacity of the hubs had decreased. Several hubs needed to be located in more expensive municipalities in order to cover all the demand from Portugal's Mainland. Therefore, although Scenario 3 becomes more expensive, it serves the purpose of trying to uniformise the hubs' areas.

It is also important to mention that comparing both scenarios, in Scenario 3, the 25 and 60 km radius have lower transportation costs than in Scenario 2. In the 50-km radius instances, it increases by 177k€ due to the different locations of the hubs. Finally, as the demand covered for both Scenarios is the same, it is logical that the cost per order is lower in scenario 2, and the lowest belongs to the 60 km radius in on the cost minimisation OF, costing 54.89€.

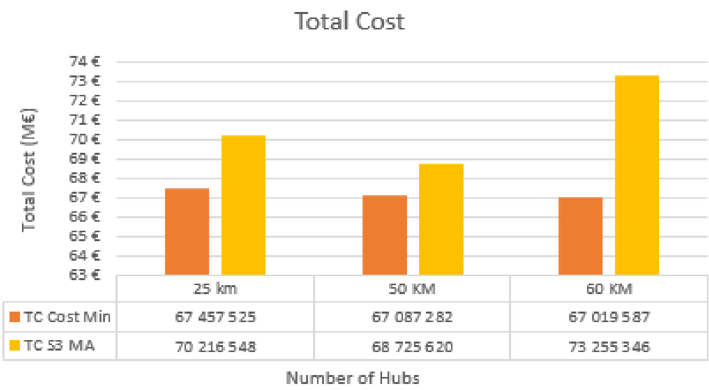

Figure 14 Comparison of Total Costs between Scenario 2 (CostMin OF) and 3 (MA)

5.2.4 Scenario 4 – Partial Coverage of Demand

For this Scenario, instead of assuming that Worten will fulfil all the online orders within a time window of 2 hours, now it will be studied the coverage of at least 90% of the orders. With these assumptions, it will be possible to reduce transportation costs and the number and area of the hubs. For the 90% coverage scenarios, the total operational cost equals 770k€. As was mentioned, this value depends on the total number of orders covered by the logistic hubs, which is then multiplied by a cost of 0.70€/order.

This Scenario will also be composed of two sub-scenarios, Scenario 4.1 and 4.2. In Scenario 4.1, the number of hubs will be the one obtained in Scenario 2 for the corresponding covering distances, which allows the models to provide feasible solutions. The Scenario 4.2 will be an optimisation of the first, where the number of hubs will be reduced, and the areas will be larger, to reduce the overall costs of the hubs and transportation.

Scenario 4.1 – Partial Coverage

As was mentioned, Scenario 4.1 will study 90% coverage and the impact on the hubs' locations and costs. For the single allocation model, the maximum capacity must be equal to or greater than the demand from M192 in Lisbon since this demand represents 10.4% of the total demand. With this in mind and knowing that the demand of Lisbon is equal to 127.128 orders, the constraint regarding the maximum capacity of a logistic hub will be equal to 128k orders. If the value of this restriction is lower than the 127.128 orders, the model will not be able to provide a feasible solution for 90% coverage. In addition, the capacity restriction will be the same, for the three different covering distances, in the single allocation (SA) model.

From the two types of allocations, it is possible to obtain the location of each municipality, the number of municipalities allocated to each hub, the total number of orders, the hub area and the hub cost.

Starting with **25 km** radius and using 53 logistic hubs, for the single allocation instance, where one municipality can only be served by one logistic hub, the hub that serves more municipalities, 11 in total, is H52, located in Celorico de Basto. The hub H195, which belongs to Moita, is the hub with the highest number of orders, 127128, with the largest area, 4680.6 m^2. Despite this, the most expensive hub to implement is H190 in Barreiro. This hub has a smaller area than H195, but the cost per square meter is higher, costing 1645€/m^2, resulting in a total cost of 7.2M€. The total number of municipalities covered is equal to 234, making up the 90% of coverage. The table regarding this instance is in Annex 5 and in table 27.

For the Multiple Allocation (MA), where one municipality can be served by more than one logistic hub, the restriction regarding the maximum capacity of a hub does not follow the same logic as in the single allocation. For this type of allocation, the capacity can be lowered to a capacity of 35k orders while still providing a feasible solution. But, to compare both types of allocations, it was decided that capacity restriction would be the same used in the single allocation instance. There the restriction will be equal to 128k orders.

From the first table in the Annex 5, it is possible to obverse the most municipalities covered by a hub is 11, and the hub H52 in Cinfães is capable of doing it. For the logistic hubs with the highest number of orders and largest areas, there are H190 and H195, located in Barreiro and Moita, respectively, with 128k orders and an area of 4713 m^2. In addition, H190, is also the most expensive hub, costing almost 7.85M€. For this instance, the number of municipalities covered is 234 and covering 90% of the demand.

Regarding the municipalities served by more than one logistic hub. For this model, there are 2 municipalities with multiple allocations. The first one is M192, in Lisbon, which is served by H190 and H195, located in Barreiro e Moita, respectively. And the second is M198, in Oeiras, served by H190 and H203. Hub H203 is located in Sintra.

In both allocations, the number of municipalities served by the logistic hubs is equal to 234. The values of the maximum hub capacity are much lower in the SA instance, while the minimum capacity is the same. The cost of hubs decreases by 56k€ from the SA to the MA instance. Similar to what happened in the cost of the hub, the transportation cost decreases by 82k€ when multiple allocations are implemented. The overall difference in cost between allocations is equal to 137k€. And finally, the cost per order is higher in the SA model by 0.13€.

Table 27 Models' Outputs for the 25 KM instance (S4.1)

25 Km, 90%	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	4680.62	4712.72
Minimum Cap (m^2)	52.83	52.83
Cost of Hubs (€)	41 379 350	41 323 633
Total Distance (KM)	16146822	15983544
Cost of Distance (€)	8 073 411	7 991 772
Total Costs (€)	49 452 761	49 315 405
Cost per Order (€)	44.96	44.83

By running both instances is possible to retrieve the model statistics information as well, in table 28. Multiple allocation instance has more equations and variables compared to the single allocation, having more than double the single variables. The number of iterations and nodes is much higher in MA, and the difference in resource usage is around 2.1 seconds. Finally, the relative gap for both allocations is equal to 0.0%.

Table 28 Models' Statistics for the 25 KM instance (S4.1)

25 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	48 682 689 €	48 545 348 €
Block of Equations	7	13
Block of Variables	3	6
Single Equations	154,849	387,535
Single Variables (Discrete)	77,563(77,562)	232,409 (77,840)
Iterations	3376	3374
Number of Nodes	399	207
Resource Usage (Seconds)	1.562	3.704
Relative Gap	0.00%	0.00%

In the **50 km** radius, with the single allocation, the capacity restriction will follow the logic explain at the start of this scenario 4. Therefore, a logistic hub's maximum capacity will be equal to 128.000. For this single allocation instance, the hub that can cover more municipalities is H69, located in Sabrosa, having 27 municipalities. In this instance, the hub with the highest number of orders, area and most expensive to implement is H97 in Sobral de Monte Agraço, with 127.435 orders, 4692 m^2 and costing 5.1M€. The total number of municipalities covered is 233 and the coverage percentage is 90%. This information is present in Annex 5 and table 29.

Regarding the multiple allocations, the value for maximum capacity can be reduced, as was observed in the previous covering distance (25 Km), being capable of providing a feasible solution for a maximum capacity of at least 70k orders. But, to better compare the two allocations, the maximum hub capacity restriction will equal 128k orders. And from this instance, H69 is also the hub capable of serving more municipalities (26). Despite this, the highest number of orders in the hub is 128k, corresponding to an area of 4.713 m^2. And the hubs with the most orders are H52, H88 and H97, located in Cinfães, Alenquer and Sobral de Monte Agraço, respectively. Hub H195, located in Moita, may not have the most municipalities or orders, but it is the most expensive one, costing 5.6M€, and the reason for this is due to the cost per square meter (1439€/m^2). With multiple allocations, it is possible to cover 234 municipalities, with the same percentage covered as the single allocation.

Some relevant changes between the two types of allocations are the number of municipalities covered by the hubs and the number of orders, hub area and costs. The only similarity between them are the locations of the hubs and the minimum hub capacity. Concerning the municipalities with multiple allocations, table 30 shows the three municipalities and the respective hubs that serve them.

Table 29 Summarised table with the Hubs' Characteristics for the 50 KM instance (S4.1)

	Single Allocation						Multiple Allocation				
	Hubs	**Mun**	**Hub Cap**	**Hub Area**	**Hub Cost**		**Hubs**	**Mun**	**Orders**	**Hub Area**	**Hub Cost**
2	H24	13	114915	4230.96	3689449		H24	13	110328	4062.07	3542175
3	H52	14	123413	4543.84	2585501		H52	15	128000	4712.72	2681596
6	H88	1	127128	4680.62	5003641		H88	5	128000	4712.72	5037956
7	H91	10	65963	2428.63	2142082		H91	8	39607	1458.26	1286203
8	H97	6	127435	4691.92	5076715		H97	5	128000	4712.72	5099221

Table 30 Municipalities with MA and the respective Hubs for the 50 KM instance (S4.1)

Municipality	Hubs	
M56 – Paços de Ferreira	H24	H52
M192 – Lisbon	H88	H97
M193 - Loures	H91	H97

Now comparing some factors between the two types of allocation in table 31, it is possible to observe that for both allocations, the difference between maximum and minimum capacity is slightly higher in MA, differing by more than 4.000 m^2. The fact that the MA instance has a larger logistic hub, this will have an impact on the hub capacity, costing more 400k€ than the SA. For the transportation costs, there is a decrease of 493k€ between instances. In addition, the SA instance serves less than 1 municipality than the MA. Finally, the cost per order is lower in the MA instance, costing less 0.09€ per order.

Table 31 Models' Outputs for the 50 KM instance (S4.1)

50 Km, 90%	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	4691.92	4712.72
Minimum Cap (m^2)	596.79	596.79
Cost of Hubs (€)	31 416 455	31 817 041
Total Distance (KM)	32057860	31071226
Cost of Distance (€)	16 028 930	15 535 613
Total Costs (€)	47 445 385	47 352 654
Cost per Order (€)	43.14	43.05

When comparing the models' statistics between both allocation instances for the 50 km radius, presented in table 32, the only factors that change their values are the objective function already discussed, the iterations, the number of nodes and the generation time. As expected, the MA instance has more iterations and nodes, more 22 than the SA instance. The difference between resource usage increases to 4.766 seconds, being the multiple allocation instance the one that requires more time to solve the model.

Table 32 Models' Statistics for the 50 KM instance (S4.1)

50 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	46 675 347	46 582 626
Iterations	5993	9597
Number of Nodes	156	178
Resource Usage (Seconds)	2.297	7.063

Lastly, in the 60 km covering distance, in the single allocation instance, presented in Annex 5 and table 33 the lowest maximum hub capacity is 128.000 orders, a value equal to both previous covering distances. For single allocation, hub H69, located in Sabrosa, can serve most municipalities, having 40 in total, corresponding to 77k orders and a 2.839 m^2 and costing 860k€. Despite having the most municipalities, the logistic hub with the most orders is H92, located in Candaval, with almost 128k orders, with an area equal to 4.710 m^2 and costing 4.2M€. But the most expensive hub in this model is H97 in Sobral de Monte Agraço, costing 5M€. Overall, this instance can serve 223 Municipalities while covering 90% of the demand.

In the multiple allocation instance, when compared to the single allocation, the maximum capacity of the hubs can be reduced until the instance can still provide a feasible solution. For covering a distance of 60 km, the maximum hub capacity restriction is 95k orders. Still, in order to understand and compare the two allocations, the maximum hub capacity restriction will be 128k orders.

For this type of allocation (MA), the hub that covers more municipalities is H69, which belong to Sabrosa, with 41 municipalities. However, the hub with the highest number of orders and largest area, 128k and 4713 m^2, are H24, H88, H97 and h108, located in Vizela, Arruda dos Vinhos, Sobral Mt Agraço e Sever de Vouga. These are also at full capacity. Despite having the largest areas, the hub with the highest cost is H195 in Moita, with a cost of 6.5M€. In total, these 12 logistic hubs cover 234 municipalities. To identify each municipality which has more than one logistic hub. Table 34 shows each municipality and the respective hubs that served them.

Table 33 Summarised table with the Hubs' Characteristics for the 60 KM instance (S4.1)

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Hub Cap	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H5	17	81658	3006.49	1758834		H5	17	74738	2751.71	1609784
2	H24	16	121446	4471.41	3899125		H24	16	128000	4712.72	4109550
4	H88	8	127536	4695.64	5019697		H88	5	128000	4712.72	5037956
6	H97	2	127171	4682.2	5066198		H108	24	128000	4712.72	2488374
7	H108	19	127804	4705.5	2484562		H124	35	73699	2713.46	1286214
8	H124	37	73449	2704.25	1281848		H156	13	38831	1429.68	603343
9	H156	13	38831	1429.68	603343		H160	33	105831	3896.5	2080779
10	H160	31	101603	3740.83	1997650		H195	9	121250	4464.2	6508859

Table 34 Municipalities with MA and the respective Hubs for the 60 KM instance (S4.1)

Municipality	Hubs		
M13 - Braga	H5	H24	
M151 – Viseu	H108	H124	
M192 – Lisbon	H88	H97	H195

Comparing some output from both instances, in table 35, it is possible to analyse that the discrepancy between maximum and minimum hub capacity is very similar for both. Since there are 4 hubs at full capacity and the minimum hub capacity also increased in the MA instance, the cost of hubs will increase by 2.6M€ compared to the SA. Moreover, by changing the allocation from SA to MA, it is possible to save up to 2.7M€ in transportation costs. One can add that the SA instance covers 223 municipalities, while the MA covers 230. To conclude, the difference between total costs is 141k€, and the MA instance has a lower cost per order.

Table 35 Models' Outputs for the 60 KM instance (S4.1)

60 Km	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	4709.55	4712.72
Minimum Cap (m^2)	1222.07	1223.28
Cost of Hubs (€)	29 625 392	32 208 950
Total Distance (KM)	39798146	34349888
Cost of Distance (€)	19 899 073	17 174 944
Total Costs (€)	49 524 465	49 383 894
Cost per Order (€)	45.02	44.89

In the models' statistics for this 60 km covering distance, the blocks of equations and variables, the single equations, and variables and the discrete variables have the same values as was registered in the two previous covering distances for the respective type of allocation. So, the only factors that are different, shown in table 36, are the values of both objective functions, iterations, the number of nodes and the generation time. The number of iterations and nodes remains higher in the MA model. The resource usage increases substantially in the MA instance, taking more 1 minute and 28 seconds to solve the model when compared to the SA instance.

Table 36 Models' Statistics for the 60 KM instance (S4.1)

60 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	48 754 452	48 613 870
Iterations	37494	147706
Number of Nodes	442	735
Resource Usage (Seconds)	7.735	88.578

Conclusion of Scenario 4.1

Like in Scenario 3, the multiple allocation instances provide less expensive solutions for the same demand coverage, the same number of logistic hubs and capacity restriction. Having multiple hubs serving municipalities helps to decrease the area of hubs with a higher cost per square meter. It also reduces transportation costs by placing demand on more strategic hubs closer to a specific municipality.

It is also possible to conclude that from the three different covering distances, the 50 km instances have the lowest total costs and cost per order. To choose which instance to implement, Worten must first consider the covering radius of each hub. From there, it needs to consider if the model will have single or multiple allocations. It is worth mentioning that the MA instance can require more strategic planning before implementation.

Scenario 3 vs 4.1

In order to make a fair comparison between scenarios 3 and 4.1, 100% and 90% of demand coverage, respectively, and the factor that will be used to compare these two scenarios is the Cost per Order. But for both models, there is the SA and MA cost per order, so it was decided to compare the best result, or in other words, the lowest cost per order of each scenario. The lowest cost per order belongs to the MA models for both scenarios, which are presented in figure 15. By reducing the demand covered by the hubs by 10% is possible to obtain a reduction in cost per order between 12€ and 15€. Although not presented in this figure, the investment necessary to implement the hubs reduces, since the respective area can reduce. It is also possible to observe that, in both scenarios, the lowest cost per order is registered in the 50-kilometre radius.

In addition, to compare both scenarios, it is possible to present the impact that the difference of 10% has on the total costs. Regarding the 25-kilometre radius for MA, the difference from 100% to 90% represents less 20.9M€. For the 50-kilometre, the difference increases to 21.4M€, and for the last covering radius, 60-kilometre, the difference between scenarios equals 23.9M€.

Figure 15 Comparison of the Cost per Order between scenarios 3 and 4.1 for MA

If, for the MA instances, the capacity assumed for each covering distance was the minimum value for which each instance was capable of providing feasible solutions, different results would have been obtained, meaning that the logistic hubs would have smaller and more uniform areas. Table 37 shows the various capacities, orders and areas, municipalities covered and other factors that were obtained if the lowest capacity for each covering radius was applied. It is also worth mentioning that for these capacities, the instances are much more expensive when compared to the results obtained in Scenario 4.1. Another interesting point is that for these values, it is possible to obtain 8 to 9 municipalities with multiple hubs serving them, whereas, for the models with the same capacity as the single, only 2-3 multiple allocations are registered.

Table 37 Models' Outputs for the optimal hub capacity for each covering radius (S4.1)

Scenario 4.1	25 KM	50 KM	60 KM
Maximum Cap (Order)	35.000	70.000	95.000
Maximum Cap (m^2)	1290	2577	3498
Municipalities Covered	229	201	208
Muns with MA	8	9	8
Cost of Hubs with OC (€)	44 895 896	36 284 204	32 924 391
Cost of Distance (€)	7 854 858	16 571 800	19 442 760
Total Costs (€)	52 750 754	52 856 005	52 367 151
Cost per Order (€)	47.91	48.05	47.61

Scenario 4.2 - Optimisation of the Number of Hubs Depending on the Coverage Radius

This scenario considers that the number of hubs used in scenario 4.1 are the minimum values for which the model could provide feasible solutions for 100% coverage of the online orders with single allocation. So, the objective is to reach the minimum number of logistic hubs and respective capacity/area to cover 90% of the orders while allowing feasible solutions.

For the single allocation models, to achieve the minimum number of hubs, depending on the covering distance, each model was run without the capacity restriction. For the multiple allocation models, the initial idea was to run with the same number of hubs obtained in the single allocation models and with a restriction equal to the maximum capacity retrieved from the SA as well. Using these inputs, it was not possible to have a multiple allocation solutions since SA was the most advantageous (lowest cost for these inputs), so the maximum hub capacity restrictions had to decrease slightly.

Starting with the analysis of the first covering distance, 25 km, in table 38 and Annex 6, in the single allocation model, the lowest number of hubs for which the model could provide feasible solutions was 19. For this value, the maximum capacity registered belongs to hub H190 in Barreiro, with 325.500 orders and a corresponding area of 11.984 m^2, making this hub the most expensive one, costing 19.9M€. And for the MA model, with the same number of logistic hubs, the model was able to provide multiple allocations with a capacity restriction of 325.000 orders, less 500 orders than the SA model. It was possible to have multiple allocations in M197 in Odivelas, which is served by hubs H197 and H190, and with this, the number of orders decreases in H190 and increases in H197. In both models, the number of orders and municipalities covered are the same, 1.100.003 orders and 164 municipalities, and the 19 logistic hubs have the same locations.

Table 38 Summarised table with the Hubs' Characteristics for the 25 KM instance (S4.2)

	SA (25KM, 90%) Cap – 326k					MA (25KM, 90%) Cap – 325k				
	Hubs	**Mun**	**Orders**	**Hub Area**	**Hub Cost**	**Hubs**	**Mun**	**Orders**	**Hub Area**	**Hub Cost**
4	H54	15	92778	3415.91	3521846	H54	15	92778	3415.91	3521846
14	H190	14	325480	11983.56	19940792	H190	14	325000	11965.89	19911389
15	H197	5	92478	3404.87	8164920	H197	6	92958	3422.54	8207293

It is worth pointing out that, in table 39, the increase of 13k€ in hub cost from SA to MA is because, in MA, there is now a capacity constraint that limits the hub capacity to 325k orders. With this, hub H190 finds itself at full capacity, and the remaining 480 orders will be allocated to hub H197, which has a higher cost per square meter. From here, and considering that the transportation cost decreases by 4k€ in the MA, although the transfer of orders from H190 to H197 increases hub cost, these orders are closer to H197, representing a lower transportation cost. The total cost of each allocation differs by 8.650€. Finally, the cost per order is lower by 0.01€ on the SA.

Table 39 Models' Outputs for the 25 KM instance (S4.2)

25 KM – 90%	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	11983.56	11965.89
Minimum Cap (m^2)	649.62	441.63
Cost of Hubs (€)	59 194 502	59 207 471
Total Distance (Km)	17619740	17611100
Cost of Distance (€)	8 809 870	8 805 550 €
Total Costs (€)	68 004 372	68 013 021
Cost per Order	61.82	61.83

As was mentioned in the two previous scenarios, MA has more blocks of equations and variables, single equations and variables and higher generation time. Regarding the number of iterations, the SA instance has a higher number than MA, whereas the number of nodes is higher for the MA instance. The difference between resource usage is equal to 1.5 seconds. All of these information is presented in table 40.

Table 40 Models' Statistics for the 25 KM instance (S4.2)

25 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	67 234 345	67 242 996
Block of Equations	6	13
Block of Variables	3	6
Single Equations	154,571	387,535
Single Variables (Discrete)	77,563(77,562)	232,409 (77,840)
Iterations	5237	4582
Number of Nodes	80	153
Resource Usage (Seconds)	2.125	3.625
Relative Gap	0.00%	0.00%

Moving to the 50 km covering radius, with table 41 and Annex 6, the lowest number of logistic hubs obtained in the single allocation instances while providing a feasible solution was 8. And with these 8 logistic hubs, the highest number of orders allocated to one hub was 418.515, in hub H97 in Sobral de Monte Agraço. This hub also has the largest area, 15.409 m^2 and is the most expensive, with 16.7M€.

In the MA instance, and using the 8 logistic hubs, a capacity constraint had to be added for the model to provide multiple allocations. This restriction is equal to 415.000 orders (less 3.515 orders), which allows for M195 in Moita to be served by two logistic hubs, H97 and H202, the last one is located in Setúbal. It is worth mentioning that, comparing the capacities of H97 and H202, the capacity of H97 will decrease while the capacity of H202 increases. For both models, the number of orders fulfilled is 1.100.012, the number of municipalities covered is 178, and the hubs' locations are the same.

Table 41 Summarised table with the Hubs' Characteristics for the 50 KM instance (S4.2)

	SA (50KM, 90%) Cap – 419k					MA (50KM, 90%) Cap – 415k				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Orders	Hub Area	Hub Cost
3	H97	22	418515	15408.94	16672664	H97	22	415000	15279.52	16532630
7	H202	6	35278	1298.87	2421110	H202	7	38793	1428.29	2662350

Similar to the analyse in the 25 km radius, with the new capacity constraint, hub H97 will be at full capacity, which forces the model to allocate the remaining 3515 orders to hub H202, which also has a higher cost per square meter than H97. This will impact the total hub cost, increasing by 101k€. In contrast, transportation costs reduce, which is a result of the municipality M195 being closer to H202. In the end, the MA model is the most expensive, costing more than 53k€ than the SA model. The cost per order is cheaper in the SA model.

Table 42 Models' Outputs for the 50 KM instance (S4.2)

50 KM – 90%	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	15408.94	15279.52
Minimum Cap (m^2)	1298.87	1428.29
Cost of Hubs (€)	42 821 626	42 922 832
Total Distance (Km)	31738240	31642600
Cost of Distance (€)	15 869 120	15 821 300
Total Costs (€)	58 690 746	58 744 132
Cost per Order	53.35	53.40

Regarding the models' statistics, in table 43, the MA instance is the one with more iterations, nodes and resource usage. The resource usage almost more 27 seconds in the MA instance compared to the SA instance. And looking at the table 40, the 50 km with Ma takes more 26 seconds then the 25 km with MA. The remaining factors assume the same values for the respective type of allocation.

Table 43 Models' Statistics for the 50 KM instance (S4.2)

50 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	57 920 714	57 974 097
Iterations	19040	40153
Number of Nodes	227	255
Resource Usage (Seconds)	2.750	29.687

Lastly, for this third covering distance, 60 kilometres shown in table 44 and Annex 6, in the single allocation model, the minimum number of logistic hubs to implement while covering 90% of demand and which allows the model to provide a feasible solution, is 6 logistic hubs. For this number, the maximum capacity of a hub is equal to 453k orders, which are allocated in hub H97 in Sobral de Monte Agraço, with a respective area of 16.676 m^2 and a hub cost of 18M€, making this hub the most expensive out of the 6.

Moving to the MA model, the capacity constraint that will be applied to obtain multiple allocations is equal to 443k orders. Hub H97 can serve that number of orders, meaning that the hub will be at full capacity, with an area equal to 16.310 m^2. Also, the municipality M232, located in Salvaterra de Magos, will be served by two hubs, H97 and H162, with the last one located in Entroncamento. In addition, the capacity of H97 will decrease, forcing an increase in orders in H101, in Anadia, and in H162. For both models, the number of orders fulfilled is 1.100.011, the number of municipalities covered is 212, and the hubs' locations are the same.

Table 44 Summarised table with the Hubs' Characteristics for the 60 KM instance (S4.2)

	SA (60KM, 90%) Cap – 453k						MA (60KM, 90%) Cap – 443k				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H21	49	312423	11502.83	10030610		H21	49	312423	11502.83	10030610
2	H97	29	452936	16676.26	18043920		H97	29	443000	16310.43	17648087
3	H101	42	112292	4134.38	2724608		H101	44	113208	4168.11	2746836
4	H171	36	91354	3363.48	2283845		H162	35	100374	3695.58	2952814
5	H186	38	66242	2438.91	1197535		H186	38	66242	2438.91	1197535
6	H211	18	64764	2384.49	1936235		H211	18	64764	2384.49	1936235

In table 45, it is relevant to allude to the fact that the difference between hubs' costs increases by 295k€ when implementing multiple allocation. This is due to several facts. Firstly, with the MA model, the H171 in Vila Nova da Barquinha was replaced by H162 in Entroncamento, which costs more 120€/m^2, but transportation costs have almost no impact since both H171 and H162 are very close to each other. Secondly, since the capacity is restricted to 443k orders, the remaining 22.936 will be distributed throughout the hubs H101 and H162, impacting, yet again, the hub's cost. The transportation costs also increases by 675€, and the main reason may be the switch from H171 to H162. Finally, the total costs are lower for the SA model, with a difference of 296k€ to the MA model. And the cost per order is also lower in the SA by 0.26€.

Table 45 Models' Outputs for the 60 KM instance (S4.2)

60 KM – 90%	Single Allocation	Multiple Allocation
Maximum Cap (m^2)	16676.26	16310.43
Minimum Cap (m^2)	2384.49	2384.49
Cost of Hubs (€)	36 216 752	36 512 118
Total Distance (Km)	40483010	40484360
Cost of Distance (€)	20 241 505	20 242 180
Total Costs (€)	56 458 257 €	56 754 298
Cost per Order	51.33 €	51.59

Regarding the models' statistics in table 46, and similar to the 50 km radius, the MA instance has the highest objective function, more iterations, nodes and resource usage. The remaining factors assume the same values for the respective type of allocation. For the resource usage, the MA instance takes more 41 seconds to be solved, and compared to the 50 km with MA, the difference is equalt to 13.5 seconds.

Table 46 Models' Statistics for the 60 KM instance (S4.2)

50 KM – 90%	Single Allocation	Multiple Allocation
Objective Function	55 688 220	55 984 262
Iterations	12311	43238
Number of Nodes	18	325
Resource Usage (Seconds)	2.187	43.203

Comparing the results obtained in the three different covering distances, overall, the SA models were slightly less expensive than the respective MA models, meaning that, as the number of hubs decreases, multiple allocations are less attractive for the model.

Therefore, figure 16 summarises the most important factors to consider when choosing the most appropriate SA model. These factors are the total costs and the cost per order. And from the figure, one may conclude that the 60 km model is the less expensive one, while the 20 km, which is the most realistic distance, is the most expensive in both factors.

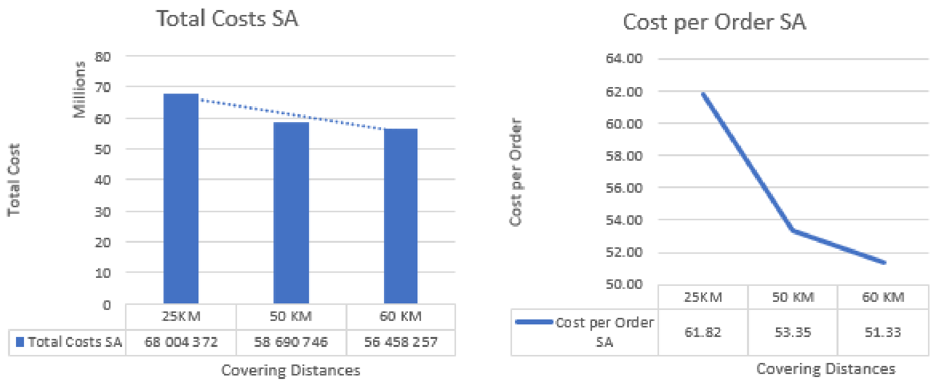

Figure 16 Comparison of Total Costs and Cost per Order for the 3 covering distances (SA)

Scenario 4.1 vs 4.2

Now comparing scenario 4.2 with the previous one, 4.1. In this comparison, the total costs and cost per order of each scenario will be analysed. The comparison will be made using the results from the 4.2 single allocations and the 4.1 multiple allocations, representing the best solutions from each scenario.

Contrarily to what was expected, the second scenario has much higher costs than the first one. In the 25 km radius, in the first scenario, 53 hubs were implemented, whereas in the second were 19 hubs. Regarding the total cost, it is possible to analyse that the 4.2 costs more 18.7M€ than the 4.1 and implements less than 34 logistic hubs. In the 50 km radius, scenario 4.2 only requires 8 hubs instead of the 17 used in 4.1. Despite this, 4.2 costs more than 11.3M€. And for the last radius, 60 km, scenario 4.2 requires 6 fewer hubs than 4.1, but the second scenario remains the most expensive with 56.5M€, more 7.1M€ than scenario 4.1. One reason for this to have happened is that, with the decrease in the number of hubs, the model is required to place the hubs closer to city centres, where most orders are located. Also, the reduction in the number of hubs will impact the area. For scenario 4.1, the maximum capacity for all three models was 4713 m^2, whereas in 4.2, the lowest value for the maximum capacity was 11.934 m^2.

Finally, also in figure 17 is possible to examine the different costs per order, depending on the scenario and respective covering distance. For scenario 4.1, the lowest cost per order is reached in the 50 km instance, whereas for 4.2 is achieved in the 60 km. Comparing the lowest costs of each model, the difference equals 8.28€.

In this scenario 4.2, the primary purpose was to reduce the number of logistic hubs implemented by Worten while providing feasible solutions, assuming that the total cost would decrease. With this in mind, it was also considered a fact that transportation costs would increase, but at a much slower rate when compared to the total costs. But this was not the case. The results obtained were must higher compared to scenario 4.1. One possible solution for scenario 4.2 to improve its performance is incorporating an opening /maintenance cost for each hub. With this, it will be possible to conclude that the most expensive scenario would be 4.1.

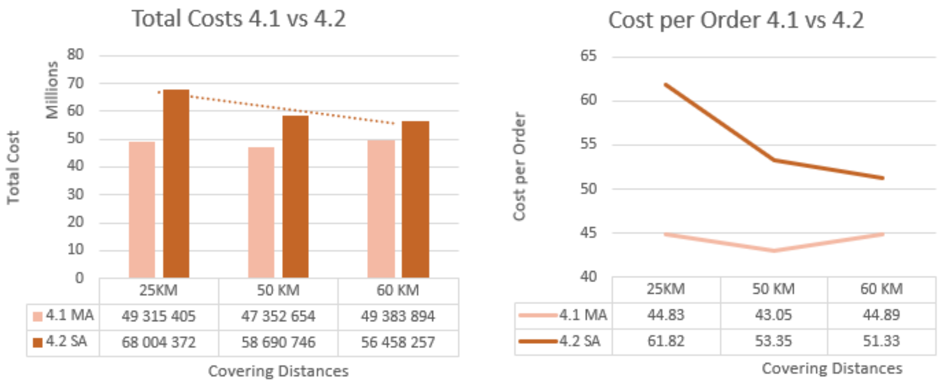

Figure 17 Comparison of Total Costs and Cost per Order between scenario 4.1 and 4.2

5.2.5 Scenario 5 – 5 Logistic Hubs

In this scenario, the model will be run for 5 logistic hubs for the three different radii. This number of hubs reflects a more realistic number of hubs to implement suggested by Worten, and it will compare three maximum hub capacities in each radius, impacting the overall coverage percentage of Worten's orders throughout Portugal's Mainland and hub costs. The allocation will be single for the 25, 50 and 60 km covering distances because the 5 hubs will be located distantly from each other. Therefore, running the model for multiple allocations does not make sense.

For each covering radius, three different maximum capacities will be studied to study their impact on the percentage of demand covered by the hub and analyse the changes in transportation costs and hub costs. The three maximum capacities will be 128k, 200k and 500k orders. With the increase of this restriction, it is expected that the hub costs will increase as well. Regarding the model statistics, throughout the 9 instances that will be analysed, some factors will remain with the same values. Table 47 shows which elements will be constant and the respective values as well.

Table 47 Models Statisctics similar to every instance

Block of Equations	Block of Variables	Single Equations	Single Variables	Relative Gap
7	3	154,849	77,563 (77,562)	0.00%

For the 25 Km distance, in table 48, starting with the 128k restriction, the hub H35 in Santo Tirso has the most municipalities allocated, 13. Regarding the number of orders and area, hub H189 in Amadora is the largest, with the most orders, 4.700 m^2, and almost 128k orders. It also is the most expensive, costing 11.1M€. With these inputs, the instance can cover 51% of Worten's yearly online orders. The hubs cover a total of 38 municipalities. For this instance, the occupancy rate varies between 89.9% and 99.8%. It is worth to mention that in H195, in Moita, only one municipality is covered, which is Lisbon, and in this situation, it would make more sense to transfer that municipality to H189 or H190, in Amadora and Barreiro, respectively. which are also fairly close to Lisbon. This also may impact the hub costs, since H195 has a lower cost per m² compared to the other two hubs. Also, the transportation cost will be reduced, since H189 is much closer to Lisbon (M192) but has the highest cost per m² of the three. Hub H190 e located further away, and it costs more than H195.

Changing the input regarding the capacity constraints and increasing it to 200k orders makes it possible to obtain different results. The highest number of municipalities covered by a hub rises to 15, and H35 is the hub covering them. The highest number of orders is now 199k, which are served by hub H203, in Sintra, with an area of 7.325 m^2. This hub also has the highest cost, with 15.1M€. The orders covered increased to 57% and the municipalities to 46. The occupancy rates decrease compared to the previous capacity.

Finally, testing the model for the maximum capacity restriction of 500k orders. In this instance, H35 is again the hub with more municipalities allocated, with 19. As was expected, the hub with the most orders and a larger area, with 387k orders and an area equal to 14.239 m^2, is H197, located in Odivelas, which costs 34.1M€ and represents 72% of the total hub cost. With this restriction, the orders covered are now 60%, and the municipalities increased to 58. It is worth mentioning that none of the hubs can reach the maximum restriction of 500k orders. Lastly, the occupancy rates assume very low values, reaching 8.3% in H90, and the maximum rate is equal to 77.4% in H197.

Table 48 Hubs' Characteristics for the 25 KM instance for different capacities (S5)

25 KM CAP = 128K	Hub	H31	H35	H189	H190	H195
	Mun	10	13	6	8	1
	Orders	115032	125888	127766	127611	127128
	Occupancy	89.87%	98.35%	99.82%	99.70%	99.32%
	Hub Area	4235.26	4634.96	4704.1	4698.4	4680.62
	Hub Cost	4 603 780	4 885 305	11 054 693	7 818 196	6 824 402
25 KM CAP = 200K	Hub	H31	H35	H101	H190	H203
	Mun	5	16	9	12	4
	Orders	62643	192476	45683	196995	198960
	Occupancy	31.32%	96.24%	22.84%	98.50%	99.48%
	Hub Area	2306.4	7086.61	1681.96	7252.99	7325.33
	Hub Cost	2 636 244	7 469 375	1 108 433	12 069 065	15 104 921
25 KM CAP = 500K	Hub	H34	H35	H90	H101	H197
	Mun	8	19	8	8	15
	Orders	65058	194428	41606	45510	386735
	Occupancy	13.01%	38.89%	8.32%	9.10%	77.35%
	Hub Area	2395.31	7158.48	1531.86	1675.59	14238.86
	Hub Cost	2 737 869	7 545 126	1 787 699	1 104 235	34 144 962

In table 49, comparing the outputs from the three capacity restrictions, it is possible to conclude that the maximum capacity increase with the limitation. This analysis is also essential to study the behaviour of the minimum hub capacity, which decreases as the restriction increase the number of orders. One possible reason can be that when the restriction is equal to 128k orders, the hubs are almost at full capacity (90% - 99.8% of occupancy) and located near city centres Lisbon and Porto. With the increased capacity, city centres can be served by fewer hubs, resulting in new locations for the hubs allowing them to cover other municipalities. This will also increase the percentage of orders covered.

Regarding the cost of the hubs, between the 128k and 200k, there is a difference of 3.2M€, and between 200k and 500k orders differ by 8.9M€. The transportation costs of the orders reach the lowest cost in the 128k instance, and its highest in the 200k, with a difference of 617k€. Now comparing the total costs of each maximum capacity, the difference between the instances goes from 3.82M€ (128K-200K) to 12.6M€ (128k-500k). Also, from the total costs, it is possible to study the cost of 1 percentage point for each instance, where for 128k 1% costs 792k€, for 200k costs 775k€ and finally, the 500k costs 883k€. The lowest cost per order is achieved in the instance of the 200k order.

Table 49 Models' Outputs for the 25 KM instance (S5)

5 Hubs	25 km Radius		
Cap Restriction	128k	200k	500k
Demand Covered	51%	57%	60%
Max Cap (m^2)	4704.1	7325.33	14238.86
Min Cap (m^2)	4235.26	1681.96	1531.86
Cost of Hubs (€)	35 186 376	38 388 037	47 319 892
Total Distance (Km)	10368088	11602760	11271870
Cost of Distance (€)	5 184 044	5 801 380	5 635 935
Total Costs (€)	40 370 420	44 189 417	52 955 827
Cost per Order (€)	64.76	63.42	72.21

Table 50 presents the remaining factors of the model statistics that do not have the same value. The objective function is related with the number of orders covered by the hubs, location, area and travelled distance between hubs and municipalities, resulting in different values for the three capacities. The number of iterations, nodes and resource usage is much higher for the first instance (128k), and decreases gradually.

Table 50 Models' Statistics for the 25 KM instance (S5)

5 Hubs	25 km Radius		
Cap Restriction	128k	200k	500k
Objective Function	39 934 001	43 701 658	52 442 448
Iterations	31463	4233	2816
Number of Nodes	596	110	0
Resource Usage (Seconds)	4.000	1.594	0.609

For the 50 Km distance, in table 51, and starting with the 128k order for the maximum hub capacity, the hub H231 in Rio Maior has the most municipalities allocated, 30, but its capacity is 124k orders. Hub H38 in Vale de Cambra has the most orders to fulfil, 128k, and the largest area, 4.713 m^2. This last hub is also the most expensive, representing a cost of 3.9M€. The occupancy rate for the 5 hubs varies between 96.6% and 100%, meaning that they are at full capacity. With these inputs, the hubs can fulfil 52% of the online orders received and can allocate 104 municipalities to hubs.

Proceeding to the analysis of the maximum hub capacity of 200k for the 50 km covering distance, the maximum number of municipalities covered by one hub increases to 33, and hub H24 in Vizela is the one responsible for it. H24 is also the one with the largest area at 7.346 m^2, but it is not the most expensive hub. The hub H195 in Moita has the highest cost, 10.6M€. The orders served by the hubs increased to 73%, and the municipalities covered to 107. Hub H231 has the lowest number of orders and consequently the lowest occupancy rate as well, while the other vary between 85.8% and 99.8%.

Lastly, by running the model with a hub capacity restriction of a maximum of 500k orders, it is possible to conclude that hub H24 can now cover 42 municipalities, which is the highest number of municipalities allocated to one hub. Following this, the H190 in Barreiro fulfils the most orders, almost 440k, has the largest area, 16.192 m^2 and also is the most expensive hub, costing 26.9M€, representing 58% of the total hub's cost. To conclude this analysis, the percentage of orders covered is now 82%, and the municipality covered also increased to 138. The occupancy rate drops in all hubs, with hub H275 having the lowest one, and highest rate belonging to H190 with almost 88%.

Table 51 Hubs' Characteristics for the 50 KM instance for different capacities (S5)

50 KM CAP = 128K	Hub	H21	H38	H52	H97	H231
	Mun	19	20	27	8	30
	Orders	127997	128000	127998	127904	123659
	Occupancy	100.00%	100.00%	100.00%	99.93%	96.61%
	Hub Area	4712.61	4712.72	4712.65	4709.19	4552.89
	Hub Cost	4 109 454	3 892 765	2 681 556	5 095 402	3 942 859
50 KM CAP = 200K	Hub	H24	H38	H97	H195	H231
	Mun	33	28	10	7	29
	Orders	199533	171688	199161	198250	123592
	Occupancy	99.77%	85.84%	99.58%	99.13%	61.80%
	Hub Area	7346.43	6321.23	7332.74	7299.19	4550.43
	Hub Cost	6 406 178	5 221 414	7 934 115	10 642 309	3 940 729
50 KM CAP = 500K	Hub	H24	H99	H160	H190	H275
	Mun	42	32	30	23	11
	Orders	294203	113999	99305	439786	54938
	Occupancy	58.84%	22.80%	19.86%	87.96%	10.99%
	Hub Area	10832	4197.23	3656.22	16192.1	2022.71
	Hub Cost	9 445 638	3 655 839	1 952 467	26 943 855	4 599 668

Starting by comparing the demand covered, in table 52, as expected, the instance with 128k orders has the lowest percentage, but in contrast, it is the less expensive one. The maximum capacity registered in a hub increases with the restriction while the minimum capacity decrease. As was already mentioned, one possible justification for this is the fact that as the maximum hub capacity increases, city centres which represent most of the orders, need fewer hubs to cover their demand, allowing the hubs to cover other municipalities.

Now focusing on the costs of each instance, since the 128k has the smallest area, the hub costs will be the lowest of the three. And as the restriction increases, so does the maximum capacity, which will have an impact on the hub costs. As the logistic hubs can serve more demand and municipalities, the distance travelled between nodes will increase, corresponding to an increase in transportation costs. The 128k instance has the lowest transportation costs. Regarding the total cost, the 200k instance costs more 16.7M€ than the 128k, and less 12.9M€ compared to the 500k instance. The 128k instance is less expensive than the 500k by 29.6M€, which is equivalent to the instance's total cost for the 128k orders.

Finally, the cost per order, which considers the total costs divided by the total orders served, is cheaper on the first instance.

Another analysis performed in the previous covering distance was the cost of one percentual point for each model, where for the 128k model, 1% costs 570k€, followed by 635k€ for the 200k, and lastly, 723k€ for the model of the 500k orders.

Table 52 Models' Outputs for the 50 KM instance (S5)

5 Hubs	50 km Radius		
Cap Restriction	128k	200k	500k
Demand Covered	52%	73%	82%
Max Cap (m^2)	4712.72	7346.43	16192.1
Min Cap (m^2)	4552.89	4550.43	2022.71
Cost of Hubs (€)	19 722 036	34 144 745	46 597 467
Total Distance (Km)	19803506	24418920	25321320
Cost of Distance (€)	9 901 753	12 209 460	12 660 660
Total Costs (€)	29 623 789	46 354 205	59 258 127
Cost per Order (€)	46.61	51.95	59.13

Table 53 presents the factors which belong to the model statistic that differentiate between instances. The number of iterations and nodes are much higher in the instance of the 128k orders and decrease as the maximum capacity restriction increases. The resource usage follows the same behavior, and the 128k instance takes 27.4 seconds to solve the model, while the remaining two take 12.3 and 3.5 seconds, respectively.

Table 53 Models' Statistics for the 50 KM instance (S5)

5 Hubs	50 km Radius		
Cap Restriction	128k	200k	500k
Objective Function	29 178 881	45 729 625	58 556 536
Iterations	177611	73059	13128
Number of Nodes	21273	634	54
Resource Usage (Seconds)	27.375	12.328	3.516

Moving on to the last covering radius, 60 km, in table 54, and starting again with the 128k orders maximum hub restriction. In this instance, hub H108 in Sever de Vouga serves the most municipalities, 35 in total. Despite this, the hub with the most orders is H52 in Cinfães, with almost 128k orders and a corresponding area of 4.710 m^2. The most expensive hub costs 5.1M€ and belongs to Sobral de Monte Agraço, H97. The orders covered by the logistic hubs represent 52% of the total amount. And the municipalities allocated to hubs are 120. For this capacity restriction, the logistic hubs occupancy rates range between 97.81% and 99.95%.

For the 200k orders, hub H108 remains the one with more municipalities allocated to it, but now the value has increased to 47. Hub H24 in Vizela has the highest number of orders, almost 200k, with an area of 7.361 m^2. Still, it is relevant to point out that 4 of the 5 logistic hubs are almost at full capacity, with an occupancy rate between 99.92%(H1088) and 99.96%(H24), and the hub with the lowest occupancy rate is H231 with 71.54%. The hub with the highest costs is H195, located in Moita, costing 10.7M€. The percentage of orders covered increases to 77% and the number of municipalities to 129.

To conclude, in the third and last restriction, 500k orders, the logistic hub with more municipalities is H144 in Oliveira de Frades, with a total of 55. The hub with the highest number of orders, largest area and the most expensive is H204 in Vila Franca de Xira, with 490k orders, 18.060 m^2 and costing 33.7M€, which represents 60% of the total hubs cost. For this last instance, the percentage of orders fulfilled by the hubs is 88%, and the municipalities covered increased to 190. To conclude, the occupancy rates for the 500k capacity, decrease, reaching the lowest value of the three instances. The smallest value attained was 20.47% in hub H129.

Table 54 Hubs' Characteristics for the 60 KM instance for different capacities (S5)

60 KM CAP = 128K	Hub	H24	H52	H97	H108	H224
	Mun	17	27	8	35	33
	Orders	127626	127933	127477	127330	125200
	Occupancy	99.71%	99.95%	99.59%	99.48%	97.81%
	Hub Area	4698.95	4710.25	4693.46	4688.05	4609.63
	Hub Cost	4 097 543	2 680 191	5 078 382	2 475 348	2 655 204
60 KM CAP = 200K	Hub	H24	H97	H108	H195	H231
	Mun	32	12	47	7	31
	Orders	199922	199387	199834	198898	143082
	Occupancy	99.96%	99.69%	99.92%	99.45%	71.54%
	Hub Area	7360.75	7341.06	7357.51	7323.05	5268.01
	Hub Cost	6 418 665	7 943 118	3 884 856	10 677 098	4 562 162
60 KM CAP = 500K	Hub	H21	H129	H144	H204	H270
	Mun	40	43	55	38	14
	Orders	206285	102358	208630	490485	67801
	Occupancy	41.26%	20.47%	41.73%	98.10%	13.56%
	Hub Area	7595.03	3768.63	7681.37	18058.74	2496.31
	Hub Cost	6 622 960	2 076 562	4 992 985	33 661 715	8 020 675

Based on the table 55, it is easy to conclude that, for the third consecutive time, as the capacity restriction increases, so does the demand covered, maximum capacity, hubs and transportation costs and the cost per order. And as was referred to in the two previous covering distances, the minimum capacity also decreases as the capacity restriction grows, but this only happens between the 200k and 500k instances. When increasing the maximum capacity from 128k orders to 200k, the minimum capacity increases, the hub H24 in Vizela is capable of serving the demand within its radius, allowing to relocate the hub located at H52 in Cinfães to H97 in Sobral de Monte Agraço, which has more demand within the 60 km radius.

It is relevant to point out that regarding the total costs, the 200k instance costs more 20.4M€ than the 128k and less 27.2M€ than the 500k. Also, the difference between the 128k and 500k orders instances equals 47M€. The lowest cost per order belongs to the 128k instances. To conclude, and similar to what was analysed for the 25 and 50 km instances, the cost of one percentual point for each instance is 523k€, 619k€ and 851k€, respectively.

Table 56 shows some factors of the model statistics that do not have a constant value for each instance. The number of iterations and nodes is much higher in the instance of the 200k order, followed by the 128k. Regarding the resource usage, contrarily to what was presented in the previous radii, the 200k instance is the one which takes longer to be solved, around 7 minutes and 17 seconds, the longest time of all the scenarios. The second longest instance for this scenario with the 60 km radius, is the 128k with 1 min and 2 seconds.

Table 55 Models' Outputs for the 60 KM instance (S5)

5 Hubs	60 km Radius		
Cap Restriction	128k	200k	500k
Demand Covered	52%	77%	88%
Max Cap (m^2)	4710.25	7360.75	18058.74
Min Cap (m^2)	4609.63	5268.01	2496.31
Cost of Hubs (€)	16 986 667	33 485 899	55 374 897
Total Distance (Km)	20599640	28358320	39013660
Cost of Distance (€)	10 299 820	14 179 160	19 506 830
Total Costs (€)	27 286 487	47 665 059	74 881 727
Cost per Order (€)	42.93	50.65	69.62

Table 56 Models' Statistics for the 60 KM instance (S5)

5 Hubs	60 km Radius		
Cap Restriction	128k	200k	500k
Objective Function	26 841 585	47 006 251	74 128 778
Iterations	358632	727274	11020
Number of Nodes	944	2214	0
Resource Usage (Seconds)	62.437	436.844	2.203

To conclude this scenario, a comparison will be made for the three covering distances and the three maximum capacities studied in this scenario, reaching some interesting conclusions. Starting with the analysis regarding the total costs and the cost per order, and considering figure 18 and 19, it is possible to conclude that for the 128k restriction, the 25 km radius has the highest total costs and cost per order.

Focusing only on the total costs, for the other two restrictions, 200k and 500k, the 60 km radius is the most expensive. And based on what was already mentioned in the cost per order for the 128k restriction, in the following two, the 25 km radius maintains its position as the most expensive instance.

In terms of demand covered, the 25 km radius for the 128k restriction has the lowest percentage, while the 60 km, for the same capacity, can cover one more percentual point with less 13.1M€. For 200k restriction, the 50 km radius achieves 73% with the lowest total costs of the remaining radius, while the 60 km covers 77%, increasing by 1.3M€. One constant movement through the three graphs, in figures 18 and 19, is that, as the capacity restriction increases, so do the total costs, cost per order and demand covered. The only situation where one of these factors decreases is the cost per order for the 50 km radius. When the restriction increases from 128k to 200k, there is a decrease of 5.34€.

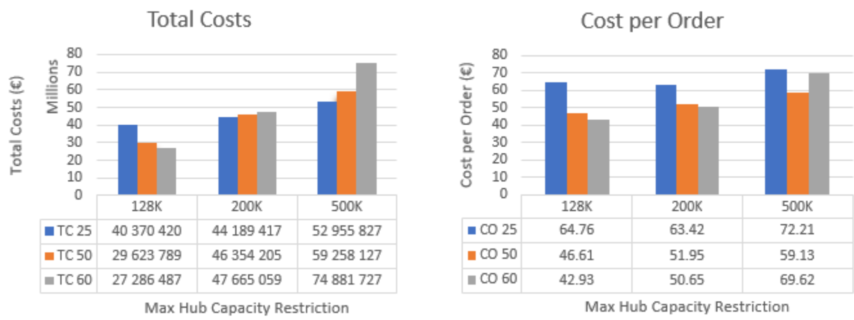

Figure 18 Comparison of Total Costs and Cost per order for the different covering distances and hub capacities

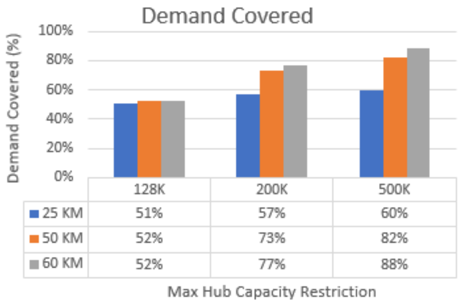

Figure 19 Comparison of demand covered for the different covering distances and hub capacities

The average cost per square meter can also be analysed depending on the covering radius and capacity restriction. Table 57 shows the impact that the covering radius has on the cost of each hub. As the radius increases, the lower average costs get. Another interesting behaviour is that the average cost for 50 and 60 km radii also increases with the capacity restriction. One possible explanation for this is that the hubs will be strategically placed in municipalities which cover the most demand at the lowest cost possible. As seen in the 25 km instance, with 128k orders, the model chooses a hub located further away, but with a lower cost per m^2.

Table 57 Average cost of the square meter depending on the covering distance and order capacity

Av. Cost of m^2	128K	200K	500K
25 KM	1503.6	1297.4	1265.2
50 KM	824	1001.8	1224
60 KM	706.4	942.2	1411

Since Worten may want to cover as much demand as possible, with the most efficient cost and the ability to comply with the two-hour delivery window, the most appropriate choice would be the 200k instance for the 25 km covering distance. This instance has the lowest cost per order compared to the other restrictions, only has 3 hubs at full capacity and has the best cost per percentual point. But if Worten is willing to take the risk and increase the covering distance, by saving 14.6M€, the 128k instance with the 50 km is a good option, with an even lower cost per order but reduces in 5% of coverage. Most attractive for the 128k and 200k instances would be the 60 km and for the 500k the 50 km. And between these last three instances, the ones that should be considered are the 128k and 200k instances, which involve a 23% increase in demand covered and an investment of 20.4M€. The best solution depends on the covering distance that Worten is willing to choose. This will impact the percentage of demand covered, total costs and cost per order.

6 Conclusions, Limitations and Future Work

In this subchapter, an analysis of the results obtained in chapter 5 will be performed, followed by limitations of the models and future work.

6.1 Conclusions

Analysing the first scenario, it is possible to conclude that neither of the values the p assumed, were capable of complying in the maximum covering radius or with the delivery time window, as the lowest maximum distance registered was 80 kilometres, which does not allow Worten to prepare and deliver the order within the time window. Regarding the objective functions used, it was clear that the one that has de objective of minimising the costs related with the hubs and distance provides lower costs.

For scenario 2, with the introduction of a maximum distance between logistic hubs and municipalities, it was possible to reach the necessary number of hubs to implement depending on the covering radius pretended for every logistic hub. It is possible to conclude that scenario 2 is more expensive than scenario 1. Despite this, scenario 2 is the most realistic one of the two.

In scenario 3, the constraint regarding the maximum capacity of order was implemented, with the objective of having logistic hubs with similar areas, eliminating the discrepancies observed in scenario 2 and trying to restrict the maximum areas that the hubs can possess. With the introduction of this new constraint, it was also possible to study the multiple allocations of logistic hubs to municipalities. It was possible to realize that scenario 2 was less expensive than scenario 3, but with this scenario is possible to establish the maximum area that a logistic hub can occupy.

With scenarios 4.1 and 4.2 was possible to study the partial coverage of the online orders, and in scenario 4.2 it was obtained the lowest number of logistic hubs, depending on the covering radius, that provided feasible solutions, and without capacity restrictions. It was also studied the multiple allocation. In the end, although the number of hubs for each covering distance reduced more than 50%, the total costs were lower in scenario 4.1. And in this scenario 4.1, it was the multiple allocations models that provided the lowest total costs.

And finally, scenario 5, which is the one that provides a more realistic scenario. Here, each model depends on the covering radius and maximum capacity defined for each logistic hub, and it was possible to reach interesting results, that allow Worten to cover between 51% and 88% of the online orders, with a much lower investment cost compared to the previously studied scenarios. For this scenario multiple allocation model was not implemented since that as the number of hubs decreases, the distances between them increase, making it less probable to have municipalities located within the covering radius of two hubs. In addition, it is possible to conclude that as the covering radius and capacity increase, the logistic hubs tend to be placed on the outskirts of municipalities with most orders, where the cost per m2 is lower and leading to a rise in the transportations costs and an increase in the percentage of demand covered.

To conclude, it is relevant to mention that the cost per order is relatively high throughout the different scenarios, covering distances and types of allocations. That happens due to the large scale that some logistic hubs assume and the location where the hubs are placed, since the cost per square meter significantly impacts the hubs' cost and the total costs as well.

6.2 Limitations

Fixed Cost of Opening and Maintenance a Logistic Hub – For this work, three types of costs were considered. The first one was the rental costs (€/m^2) for each municipality belonging to Portugal's Mainland, which helped in obtaining a cost per logistic hub depending on the total area and location. The second cost was associated with the distance travelled between logistic hubs and municipalities for each order, with a transportation cost of 0.5€/Km. And lastly, it was also considered an operational cost per order, related with the resources which are needed to prepare each order. The fixed cost assumed by the author was 0.7€/order.

In order to make the different scenarios more realistic, a cost associated with opening and maintaining a logistic hub should have been considered. By not considering it, the real total cost for the 5 scenarios was affected, but mainly the sub-scenarios 4.1 and 4.2 is where it was more noticeable. In 4.2, the number of logistic hubs to serve 90% of the total demand are much lower, but the total cost is much higher compared to 4.1. For example, for the 25 kilometres radius, the 4.1 scenario uses 53 hubs, while the 4.2 uses 19, but in the end, 4.2 costs more 18.7M€.

Location of Demand/Hubs – As was mentioned in chapter 5, the demand was aggregate by municipality and its location was define through coordinates, which represent the centre of the municipality. The logic is applied to the logistic hubs, where if allocated to a certain municipality, it will be located in the center of the municipality.

Distances between nodes - Since the purpose of a logistic hub is also to serve the municipality where is located, plus the municipalities which are allocated to it, a coefficient could be used ($\mathrm{Dist}_{\mathrm{total}}$*1.5) to provide a more realistic representation of the total distance, since that the current distance is linear, and also allow to include the distances travelled within the municipality where each logistic hubs are located. Furthermore, other factors could be considered, such as the time lost due to traffic, that affects the time to deliver, which is different when comparing city centres with small towns.

Based on what was mentioned in above, regarding the distance assumed between nodes, in a real-world model, one must also consider that the coverage radius of a logistic hub must decrease due to the restrictive time windows of 2 hours and the traffic within city centres.

Products to allocate to the Logistic Hubs – It was assumed that each order received by Worten in the year of 2021 represented only one product, and to simplify even more the problem, it was also assumed that each order would have a generic product, with the same physical dimension. This is an assumption that does not reflect the actual reality within Worten's Warehouse in Azambuja, but since there were more than one million orders, this was the path taken. In order to reach an approximation of what should be the dimensions of each hub, it was assumed that if Worten's warehouse, which has 45.000m^2, had previously served all of the orders from 2021, for a specific number allocated to a certain logistic hub, the corresponding area would be obtain based on the indicators already mentioned.

6.3 Future Work

Regarding future work based on this project, there are several subjections to explore the topic further.

Products: Starting with the most important one, the products that will be placed on the Logistic Hubs. It is relevant to consider which product type to place in each logistic hub. One factor which must be considered is that the placement should take into account the popularity of each SKU, the demand all year round and rotation. Regarding this factor, one strategy that can be applied in this situation is the 20/80, which refers to the 20 SKUs representing 80% of the online sales.

The following subject is to study how will the SKU arrive to the logistic hubs. For this project, it was used the online orders that were fulfilled in Worten's warehouse, but a more realistic approach would be to study the average flow of pallets arriving to each hub. This study could focus on the daily number of online orders, as well as the number of SKUs that can be transported in one pallet, on average. With this and considering the physical dimensions and quantities of the SKUs allocated in the hubs, it would be possible to arrive at an estimation for the area needed to store all of the SKUs.

Another important issue that could be discussed is related to the design and layout of the logistic hubs based on the products which will be allocated in them. Mainly, determining the areas associated with the inbound, outbound and consolidation areas, the storage solutions and material handling equipment (MHE). Concerning the storage solutions, one must consider the current storage solutions that are being used in Worten's warehouse, and from here study new solutions that will reduce the logistic hub's floor space while being suitable for a fast-moving operation. The high-density storage solution can also be considered since it uses the space available in a more efficient way. Lastly, the material handling equipment, as mentioned, this will be a fast-moving operation, similar to cross-docking, Worten could explore automation by studying the implementation of a vertical carousel for storing mezzanine's SKUs or the implementation of a conveyor belt, like the one that is being used in the online operation at Azambuja

Purpose of Logistic Hubs: Other study that can be performed is to analyse another objective for the logistic hub. For this project, the purpose was to be able to fulfil all the online orders received by Worten, but they also can have the ability and flexibility of serving some Worten stores, not only to provide inventory but also to store it. There is also the possibility of instead of implementing logistic hubs in new location, it can be studied the possibility of transforming stores such as the ones from Colombo or Cascais Shopping which have higher storage capabilities, into logistic hubs.

Software used: For this project it was used the software GAMS to obtain the best possible location for the logistic hubs, based on demand, cost per square meter and coordinates of each municipality. But there is the possibility of using a more accurate program that takes into consideration real road distances between nodes, which is a very important component for the logistic hubs that operate within a 2-hour delivery window. This program is called Anylogisticx, but to use it at its full potential it would be necessary to buy the pro/paid version.

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5. Appendix

Annex 1 - Characteristics of each Municipality

Municipalities	Hub/Mun	Demand	€/m^2
Arcos de Valdevez	1	1108	930
Caminha	2	850	1146
Melgaço	3	506	655
Monção	4	3450	755
Paredes de Coura	5	5213	566
Ponte da Barca	6	556	906
Ponte de Lima	7	6055	1080
Valença	8	596	819
Viana do Castelo	9	11858	1306
V. N. de Cerveira	10	215	731
Amares	11	259	944
Barcelos	12	9906	1135
Braga	13	24403	1381
Esposende	14	7302	1931
Terras de Bouro	15	149	971
Vila Verde	16	8955	1068
Cabeceiras de Basto	17	834	748
Fafe	18	10352	895
Guimarães	19	15842	1420
Mondim de Basto	20	355	652
Povoa de Lanhoso	21	516	853
Vieira do Minho	22	277	938
V. N. de Famalicão	23	3134	1111
Vizela	24	804	853
Arouca	25	891	758
Espinho	26	71	2043
Gondomar	27	782	1424
Maia	28	11935	1692
Matosinhos	29	25646	2430
Oliveira de Azeméis	30	5178	957
Paredes	31	7096	1068
Porto	32	31908	3066
Povoa de Varzim	33	7941	1814
Santa M. da Feira	34	8625	1124
Santo Tirso	35	4935	1035
S. J. da Madeira	36	8168	959
Trofa	37	4073	1091
Vale de Cambra	38	1199	807
Valongo	39	17137	1785
Vila do Conde	40	10013	1718
Vila Nova de Gaia	41	33478	1947
Boticas	42	531	335
Chaves	43	5767	840
Montalegre	44	508	610
Ribeira de Pena	45	452	560
Valpaços	46	539	654
Vila Pouca de Aguiar	47	474	662
Amarante	48	5928	839
Baião	49	652	632
Castelo de Paiva	50	869	829
Celorico de Basto	51	489	742
Cinfães	52	737	550
Felgueiras	53	366	859
Lousada	54	4336	1012
Marco de Canaveses	55	6217	893
Pacos de Ferreira	56	6890	985
Penafiel	57	7281	892
Resende	58	94	655
Alijo	59	459	592
Armamar	60	435	465
Carrazeda de Ansiães	61	4626	273
Fx. de Espada a Cinta	62	38	200
Lamego	63	3748	742
Mesão Frio	64	1	726
Moimenta da Beira	65	446	534
Murça	66	42	620
Penedono	67	193	346
Peso da Régua	68	2741	744
Sabrosa	69	77	283
Santa Marta Penaguião	70	19	506
S. J. da Pesqueira	71	298	489
Sernancelhe	72	193	462
Tabuaço	73	227	430
Tarouca	74	340	739
Torre de Moncorvo	75	3964	509
Vila Nova de Foz Coa	76	2758	490
Vila Real	77	8760	1077
Alfandega da Fé	78	740	419
Bragança	79	8492	795
Macedo de Cavaleiros	80	1361	627
Miranda do Douro	81	372	559
Mirandela	82	3748	911
Mogadouro	83	445	610
Vila Flor	84	451	579
Vimioso	85	229	358
Vinhais	86	360	492
Alcobaça	87	5160	1297
Alenquer	88	2310	1050
Arruda dos Vinhos	89	930	1311
Bombarral	90	3815	1148
Cadaval	91	413	863
Caldas da Rainha	92	10617	1371
Lourinhã	93	1340	1361
Nazaré	94	3379	2266
Óbidos	95	374	1733
Peniche	96	7255	1622
Sobral de Monte Agraço	97	43	1063
Torres Vedras	98	13653	1370
Águeda	99	5667	852
Albergaria-a-Velha	100	624	776
Anadia	101	5558	640
Aveiro	102	12640	2202
Estarreja	103	870	1077
Ílhavo	104	495	1676
Murtosa	105	346	1095
Oliveira do Bairro	106	792	976
Ovar	107	7194	1326
Sever do Vouga	108	355	509
Vagos	109	392	1101
Arganil	110	491	480
Cantanhede	111	4906	858
Coimbra	112	26898	1628
Condeixa-a-Nova	113	414	920
Figueira da Foz	114	6409	1330
Gois	115	155	495
Lousa	116	36	663
Mealhada	117	930	727

Municipalities	Hub/Mun	Demand	€/m^2
Mira	118	525	1165
Miranda do Corvo	119	298	593
Montemor-o-Velho	120	611	769
Mortágua	121	367	628
Oliveira do Hospital	122	3725	665
Pampilhosa da Serra	123	183	562
Penacova	124	173	455
Penela	125	225	567
Soure	126	417	585
Tabua	127	461	652
Vila Nova de Poiares	128	221	547
Alvaiázere	129	253	532
Ansião	130	458	582
Batalha	131	584	979
Castanheira de Pera	132	213	695
Figueiró dos Vinhos	133	295	552
Leiria	134	12615	1185
Marinha Grande	135	5258	929
Pedrogão Grande	136	214	594
Pombal	137	458	957
Porto de Mos	138	3325	661
Aguiar da Beira	139	916	311
Carregal do Sal	140	331	505
Castro Daire	141	444	532
Mangualde	142	3103	623
Nelas	143	463	550
Oliveira de Frades	144	391	631
Penalva do Castelo	145	149	327
Santa Comba Dão	146	431	518
São Pedro do Sul	147	441	795
Satão	148	297	560
Tondela	149	3763	542
Vila Nova de Paiva	150	115	523
Viseu	151	14273	1221
Vouzela	152	283	517
Castelo Branco	153	9610	762
Idanha-a-Nova	154	397	500
Oleiros	155	107	430
Penamacor	156	276	403
Proença-a-Nova	157	302	524
Vila Velha de Rodão	158	160	345
Abrantes	159	5394	611
Alcanena	160	554	515
Constância	161	155	627
Entroncamento	162	944	780
Ferreira do Zêzere	163	375	572
Mação	164	351	557
Ourem	165	5254	1028
Sardoal	166	142	462

Municipalities	Hub/Mun	Demand	€/m^2
Sertã	167	3011	666
Tomar	168	6700	837
Torres Novas	169	7673	785
Vila de Rei	170	221	583
Vila Nova da Barquinha	171	67	660
Almeida	172	484	510
Belmonte	173	228	536
Celorico da Beira	174	317	470
Covilhã	175	7718	689
Fig. Do Castelo Rodrigo	176	137	422
Fornos de Algodres	177	167	400
Fundão	178	4365	665
Gouveia	179	220	589
Guarda	180	11002	805
Manteigas	181	257	651
Meda	182	302	360
Pinhel	183	459	276
Sabugal	184	465	554
Seia	185	3809	670
Trancoso	186	355	472
Alcochete	187	1357	2005
Almada	188	20885	2284
Amadora	189	29893	2331
Barreiro	190	13698	1645
Cascais	191	26810	3988
Lisboa	192	127128	5047
Loures	193	25593	2515
Mafra	194	11265	2166
Moita	195	6133	1439
Montijo	196	11592	1762
Odivelas	197	12343	2379
Oeiras	198	24919	3212
Palmela	199	8674	1751
Seixal	200	22073	1961
Sesimbra	201	12240	2884
Setúbal	202	8952	1845
Sintra	203	33757	2043
Vila Franca de Xira	204	19716	1845
Alcácer do Sal	205	1043	2939
Grândola	206	3339	3764
Odemira	207	2199	1720
Santiago do Cacem	208	1250	1270
Sines	209	5938	1803
Aljustrel	210	910	669
Almodôvar	211	770	793
Alvito	212	239	505
Barrancos	213	315	155
Alvito	212	239	505
Barrancos	213	315	155

Municipalities	Hub/Mun	Demand	€/m^2
Beja	214	9501	851
Castro Verde	215	3062	635
Cuba	216	361	709
Ferreira do Alentejo	217	683	700
Mértola	218	605	505
Moura	219	1583	638
Ourique	220	494	732
Serpa	221	930	657
Vidigueira	222	509	536
Almeirim	223	3563	828
Alpiarça	224	318	557
Azambuja	225	1576	1164
Benavente	226	5822	1202
Cartaxo	227	4771	883
Chamusca	228	552	620
Coruche	229	385	1089
Golegã	230	232	809
Rio Maior	231	4139	847
Salvaterra de Magos	232	1821	1224
Santarém	233	9282	845
Alter do Chao	234	279	523
Arronches	235	212	373
Avis	236	398	490
Campo Maior	237	1166	559
Castelo de Vide	238	217	462
Crato	239	200	492
Elvas	240	4195	674
Fronteira	241	364	461
Gavião	242	54	482
Marvão	243	74	618
Monforte	244	243	529
Nisa	245	493	434
Ponte de Sor	246	3095	622
Portalegre	247	5980	619
Sousel	248	383	510
Alandroal	249	216	792
Arraiolos	250	301	803
Borba	251	342	697
Estremoz	252	2955	721
Évora	253	8381	1735
Montemor-o-Novo	254	2127	1151
Mora	255	453	806
Mourão	256	33	605
Portel	257	368	725
Redondo	258	587	624
Reguengos de Monsaraz	259	1996	811
Vendas Novas	260	1030	908
Viana do Alentejo	261	334	726
Vila Viçosa	262	707	660

Municipalities	Hub/Mun	Demand	€/m^2	Municipalities	Hub/Mun	Demand	€/m^2	Municipalities	Hub/Mun	Demand	€/m^2
Albufeira	263	9030	2788	Lagos	269	8779	3114	Silves	275	2964	2255
Alcoutim	264	205	743	Loulé	270	12189	3194	Tavira	276	7123	2461
Aljezur	265	1015	2724	Monchique	271	349	2158	Vila do Bispo	277	765	2742
Castro Marim	266	608	2146	Olhão	272	4726	2308	V. R. S. António	278	1631	2188
Faro	267	7206	2212	Portimão	273	11554	2254				
Lagoa	268	317	3013	São Brás de Alportel	274	378	2090				

Annex 2- Scenario 1

53 Hubs

	O.F. Dist Min						O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H5	8	17699	651.64	381218		H5	14	56719	2088.29	1221675
2	H9	2	12708	467.88	619947		H18	1	10352	381.14	348367
3	H12	3	20342	748.95	864298		H21	3	25178	927.01	808364
4	H13	5	34282	1262.2	1767096		H24	5	25081	923.44	805251
5	H19	6	28475	1048.4	1508661		H37	3	22027	810.99	900209
6	H29	2	37581	1383.66	3388601		H42	7	8908	327.98	116109
7	H36	7	31610	1163.82	1138230		H49	2	6580	242.26	157714
8	H39	3	22854	841.44	1517968		H52	15	155297	5717.74	3253465
9	H40	3	22027	810.99	1408700		H61	6	15845	583.38	170354
10	H41	3	65457	2410	4738090		H69	13	17827	656.36	198229
11	H43	4	7345	270.43	232303		H78	3	2546	93.74	41059
12	H57	9	40006	1472.95	1341876		H85	2	601	22.13	8343
13	H75	12	17700	651.68	344095		H86	2	8852	325.91	166544
14	H77	17	19159	705.4	773127		H88	2	22026	810.96	866926
15	H79	5	10814	398.15	324099		H91	6	26850	988.57	871931
16	H92	8	35152	1294.23	1798996		H97	11	313566	11544.91	12491736
17	H98	3	15036	553.6	768957		H101	4	7805	287.37	189380
18	H101	6	18220	670.83	442085		H108	16	52498	1932.88	1020585
19	H102	7	15892	585.11	1299537		H124	10	33728	1241.8	588629
20	H112	12	29600	1089.82	1794947		H126	5	8309	305.92	184780
21	H114	3	7437	273.82	369387		H133	6	1658	61.04	34855
22	H122	8	9894	364.28	249172		H138	6	30321	1116.36	759139
23	H134	6	22493	828.15	997103		H139	8	3002	110.53	36476
24	H151	12	24368	897.18	1112514		H140	4	4948	182.18	95465
25	H153	5	10576	389.39	304118		H145	10	23179	853.41	295290
26	H159	9	12798	471.2	296862		H149	1	3763	138.55	77728
27	H169	8	21976	809.12	650542		H156	4	1366	50.29	21223
28	H175	6	13064	480.99	340547		H158	5	10672	392.92	143028
29	H180	7	13249	487.8	401953		H160	8	29480	1085.4	579617
30	H189	1	29893	1100.6	2586424		H166	8	13392	493.07	237173
31	H191	1	26810	987.09	3955282		H167	1	3011	110.86	75940
32	H192	1	127128	4680.62	23712079		H174	2	11319	416.74	203791
33	H193	2	37936	1396.73	3539331		H175	1	7718	284.16	201189
34	H194	1	11265	414.76	906256		H178	1	4365	160.71	109928
35	H196	3	19082	702.56	1251268		H183	5	1420	52.28	15423
36	H198	1	24919	917.47	2964357		H195	3	41904	1542.83	2249465
37	H200	3	56656	2085.97	4130246		H210	3	8098	298.15	205131
38	H201	1	12240	450.65	1308243		H211	5	25270	930.39	755488
39	H202	4	19699	725.28	1351931		H212	7	16146	594.47	311510
40	H203	1	33757	1242.87	2562813		H213	4	2861	105.34	18330
41	H204	6	32175	1184.62	2208146		H215	1	3062	112.74	73733
42	H209	4	12726	468.55	853704		H218	8	22482	827.75	433751
43	H214	9	14489	533.46	464117		H220	7	25155	926.16	695558
44	H215	5	5841	215.05	140645		H222	4	10739	395.39	219446
45	H233	5	18319	674.47	582750		H224	11	41039	1510.98	870343
46	H240	7	9964	366.86	254238		H235	4	1900	69.95	27421
47	H247	10	8460	311.48	198728		H238	4	6471	238.25	114601
48	H253	8	14212	523.26	917805		H240	1	4195	154.45	107036
49	H263	1	9030	332.47	933247		H246	1	3095	113.95	73043
50	H267	2	11932	439.31	980106		H248	6	4854	178.72	94545
51	H270	2	12567	462.69	1486629		H259	1	1996	73.49	60998
52	H273	7	25743	947.81	2154384		H260	4	30896	1137.53	1054504
53	H276	4	9567	352.24	873560		H262	4	1852	68.19	46302

12 Hubs

	O.F. Dist Min						O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H13	29	129549	4769.75	6677711		H5	19	90115	3317.87	1940995
2	H30	20	55034	2026.25	1977644		H52	28	215634	7939.24	4517526
3	H32	16	171989	6332.31	19535254		H61	36	52123	1919.07	560392
4	H66	36	54273	1998.23	1276894		H97	19	404098	14878.13	16098321
5	H88	20	92143	3392.53	3626659		H108	17	53290	1962.04	1035981
6	H112	24	50869	1872.9	3084691		H124	26	51600	1899.82	900538
7	H165	27	63631	2342.77	2452914		H145	25	53367	1964.87	679869
8	H185	27	67725	2493.51	1718058		H158	16	28294	1041.73	379203
9	H192	18	398342	14666.21	74299201		H160	30	107943	3974.26	2122304
10	H214	20	31702	1167.21	1015485		H211	21	75969	2797.04	2271231
11	H252	24	35364	1302.04	963523		H212	24	71037	2615.45	1370528
12	H263	17	71603	2636.29	7400094		H235	17	18754	690.49	270681

17 Hubs

	O.F. Dist Min					O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Orders	Hub Area	Hub Cost
1	H13	25	118583	4366	6112454	H5	15	56978	2097.82	1227251
2	H30	14	52644	1938.25	1891756	H24	10	72027	2651.9	2312490
3	H32	10	142984	5264.4	16240739	H52	16	155949	5741.75	3267127
4	H55	22	58033	2136.67	1948669	H69	33	60278	2219.32	670262
5	H82	23	36210	1333.18	1239874	H85	8	12037	443.18	167084
6	H88	20	92143	3392.53	3626657	H97	14	362990	13364.61	14460673
7	H112	23	50762	1868.96	3078200	H108	17	53290	1962.04	1035981
8	H151	19	26784	986.14	1222826	H124	26	51600	1899.82	900538
9	H165	26	63471	2336.88	2446743	H145	26	53970	1987.07	687551
10	H175	17	43599	1605.23	1136522	H158	16	28294	1041.73	379203
11	H192	10	289481	10658.15	53994320	H160	21	79853	2940.04	1570018
12	H202	9	48599	1789.32	3335314	H212	16	32048	1179.95	618308
13	H203	3	71832	2644.72	5453445	H218	11	35916	1322.36	692933
14	H214	15	19927	733.67	638302	H220	14	48146	1772.65	1331282
15	H252	24	35364	1302.04	963526	H228	14	63518	2338.61	1494401
16	H270	10	43866	1615.06	5189208	H235	16	18301	673.81	264142
17	H273	8	27942	1028.77	2338407	H260	5	37029	1363.34	1263833

Annex 3 - Scenario 2

53 Hubs – 25 km

	O.F. Dist Min					O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Orders	Hub Area	Hub Cost
1	H4	3	4552	167.6	129724	H4	4	9765	359.53	278281
2	H7	10	35218	1296.66	1425045	H7	6	20642	760	835249
3	H12	6	62699	2308.46	2663991	H12	7	47304	1741.64	2009874
4	H18	11	40099	1476.37	1349420	H21	10	62391	2297.12	2003117
5	H27	12	152030	5597.46	8077204	H27	9	128716	4739.08	6838551
6	H36	8	31681	1166.44	1140793	H38	11	33841	1245.96	1029178
7	H42	4	1965	72.35	25613	H42	4	7258	267.23	94603
8	H43	2	6306	232.18	199445	H46	1	539	19.84	13353
9	H58	10	14993	552.01	372062	H48	10	32721	1204.73	1033673
10	H69	8	14924	549.47	165947	H67	7	5163	190.09	69385
11	H72	6	2165	79.71	38342	H69	11	18158	668.54	201907
12	H78	6	10709	394.29	172704	H78	6	10709	394.29	172704
13	H79	2	8852	325.91	265295	H85	2	601	22.13	8343
14	H81	2	601	22.13	12791	H86	2	8852	325.91	166544
15	H90	8	41606	1531.86	1787699	H90	8	41606	1531.86	1787699
16	H102	9	22351	822.92	1827716	H106	7	25417	935.81	931142
17	H110	8	6144	226.21	112882	H124	12	36019	1326.15	628612
18	H112	10	39659	1460.17	2404918	H126	7	8992	331.07	199970
19	H126	5	8353	307.54	185758	H136	6	1265	46.57	28548
20	H131	6	30321	1116.36	1114141	H138	7	35575	1309.8	890680
21	H151	9	23163	852.82	1057507	H141	8	6202	228.35	125824
22	H153	3	10167	374.33	292356	H143	6	26364	970.67	552323
23	H167	9	4991	183.76	125878	H153	3	10167	374.33	292356
24	H169	9	22131	814.82	655125	H156	2	741	27.28	11513
25	H174	5	12061	444.06	217151	H170	5	10609	390.6	235146
26	H175	5	16377	602.97	426910	H175	3	12311	453.27	320921
27	H176	5	3876	142.71	62937	H176	4	1118	41.16	18152
28	H184	2	741	27.28	15632	H177	8	15512	571.12	239306
29	H197	10	292681	10775.97	25840909	H190	14	325480	11983.56	19940792
30	H200	9	105604	3888.14	7698565	H197	4	71875	2646.3	6345860
31	H206	2	4382	161.34	610351	H205	1	1043	38.4	113588
32	H207	1	2199	80.96	140791	H207	1	2199	80.96	140791
33	H209	2	7188	264.65	482196	H208	3	10527	387.58	499596
34	H213	1	315	11.6	2019	H213	1	315	11.6	2019
35	H215	4	5236	192.78	126081	H215	4	5236	192.78	126081
36	H216	7	11995	441.63	321512	H216	7	11995	441.63	321512
37	H218	2	810	29.82	15626	H218	2	810	29.82	15626
38	H221	1	930	34.24	23147	H221	1	930	34.24	23147
39	H232	6	31630	1164.56	1447562	H228	10	23340	859.34	549129
40	H233	4	17934	660.3	570507	H232	8	37331	1374.46	1708471
41	H237	3	5573	205.19	118602	H237	3	5573	205.19	118602
42	H238	5	6964	256.4	123332	H238	5	6964	256.4	123332
43	H241	5	1667	61.38	29463	H241	6	4622	170.17	81684
44	H242	5	9036	332.69	166682	H242	5	9036	332.69	166682
45	H252	5	4807	176.98	130967	H250	3	10809	397.97	327136
46	H253	2	8682	319.65	560670	H255	1	453	16.68	13761
47	H254	2	3157	116.23	135991	H256	3	3612	132.99	82987
48	H255	1	453	16.68	13761	H260	1	1030	37.92	35152
49	H256	3	3612	132.99	82987	H262	4	1852	68.19	46302
50	H265	2	1364	50.22	137754	H270	3	28425	1046.56	3362610
51	H269	5	24379	897.59	2812161	H271	6	24978	919.64	2002068
52	H270	4	28803	1060.47	3407303	H276	5	14466	532.61	1320879
53	H276	4	14088	518.69	1286358	H277	1	765	28.17	77778

17 Hubs – 50 km

	O.F. Dist Min					O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Orders	Hub Area	Hub Cost
1	H7	25	128916	4746.45	5216407	H7	19	111069	4089.35	4494246
2	H38	35	223605	8232.72	6800329	H25	33	203938	7508.62	5834291
3	H47	21	46190	1700.63	1158150	H45	27	64818	2386.48	1381801
4	H85	7	11999	441.78	166557	H76	20	21229	781.61	397849
5	H87	24	91484	3368.27	4432685	H85	6	11259	414.54	156287
6	H112	25	55541	2044.92	3368008	H111	21	68827	2534.08	2222420
7	H157	18	28020	1031.64	560193	H157	22	28882	1063.38	577429
8	H175	15	36344	1338.12	947405	H175	19	37944	1397.03	989114
9	H182	21	17351	638.83	242125	H195	17	397312	14628.28	21328213
10	H192	25	443183	16317.17	82662985	H208	4	10430	384.01	494994
11	H208	4	11570	425.99	549106	H217	10	19432	715.45	514417
12	H217	9	16093	592.51	426022	H231	32	137355	5057.15	4379555
13	H219	6	5225	192.37	126390	H235	15	17533	645.53	253056
14	H244	16	18120	667.14	365601	H255	8	16170	595.35	491171
15	H255	8	16170	595.35	491171	H256	7	5812	213.99	133532
16	H266	7	15276	562.43	1217668	H266	8	22482	827.75	1792089
17	H275	12	57137	2103.68	4783794	H275	10	47732	1757.4	3996349

12 Hubs – 60 km

	O.F. Dist Min					O.F. Costs Min				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Orders	Hub Area	Hub Cost
1	H11	43	236051	8690.96	8204266	H11	38	197538	7272.98	6865693
2	H80	16	31648	1165.22	730593	H80	14	23058	848.95	532292
3	H89	33	459271	16909.5	22168355	H88	37	477767	17590.49	18470015
4	H102	33	171228	6304.29	13882047	H108	38	203623	7497.02	3815983
5	H139	36	55822	2055.26	639186	H137	30	65808	2422.93	2318744
6	H165	33	65545	2413.24	2480811	H139	42	72321	2662.72	828106
7	H178	18	33040	1216.47	808953	H178	11	24069	886.18	589310
8	H205	12	53547	1971.5	5794239	H205	8	27650	1018.02	2991961
9	H221	14	21061	775.43	509458	H218	12	26217	965.26	487456
10	H241	22	22914	843.65	388923	H234	23	27451	1010.69	528591
11	H270	10	44155	1625.7	5192486	H256	13	15629	575.43	348135
12	H273	8	27942	1028.77	2318848	H275	12	61093	2249.33	5072239

Annex 4 - Scenario 3

17 Hubs – 50 km

	Single Allocation					Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Hub Cap	Hub Area	Hub Cost
1	H7	19	111069	4089.35	4494246	H7	19	111069	4089.35	4494246
2	H25	33	203938	7508.62	5834291	H25	33	203938	7508.62	5834291
3	H45	27	64818	2386.48	1381801	H45	27	64818	2386.48	1381801
4	H76	20	21229	781.61	397849	H76	20	21229	781.61	397849
5	H85	6	11259	414.54	156287	H85	6	11259	414.54	156287
6	H111	21	68827	2534.08	2222420	H111	21	68827	2534.08	2222420
7	H157	22	28882	1063.38	577429	H157	22	28882	1063.38	577429
8	H175	19	37944	1397.03	989114	H175	19	37944	1397.03	989114
9	H195	16	388360	14298.69	20847667	H195	17	390000	14359.07	20935702
10	H206	4	17183	632.65	2393323	H206	4	15543	572.26	2164867
11	H217	10	19432	715.45	514417	H217	10	19432	715.45	514417
12	H231	32	137355	5057.15	4379555	H231	32	137355	5057.15	4379555
13	H235	15	17533	645.53	253056	H235	15	17533	645.53	253056
14	H255	8	16170	595.35	491171	H255	8	16170	595.35	491171
15	H256	7	5812	213.99	133532	H256	7	5812	213.99	133532
16	H266	8	22482	827.75	1792089	H266	8	22482	827.75	1792089
17	H275	11	49931	1838.37	4180476	H275	11	49931	1838.37	4180476

12 Hubs – 60 km

	Single Allocation					Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost	Hubs	Mun	Hub Cap	Hub Area	Hub Cost
1	H11	45	301437	11098.35	10687848	H11	45	301437	11098.35	10687848
2	H80	14	23058	848.95	548432	H80	14	23058	848.95	548432
3	H97	25	379536	13973.81	15119835	H97	25	380000	13990.89	15138316
4	H99	31	102153	3761.08	3275947	H99	31	102153	3761.08	3275947
5	H139	46	77199	2842.32	938001	H139	46	77199	2842.32	938001
6	H165	35	97169	3577.58	3745771	H165	35	97169	3577.58	3745771
7	H178	13	24690	909.04	621795	H178	13	24690	909.04	621795
8	H205	12	91956	3385.65	10014795	H205	13	91492	3368.56	9964242
9	H221	14	20824	766.7	518299	H221	14	20824	766.7	518299
10	H241	23	31295	1152.22	553080	H241	23	31295	1152.22	553080
11	H264	8	16046	590.78	450182	H264	8	16046	590.78	450182
12	H275	12	56861	2093.52	4760690	H275	12	56861	2093.52	4760690

53 Hubs – 25 km

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H4	4	9765	359.53	278281		H4	4	9765	359.53	278281
2	H7	6	20642	760	835249		H7	6	20642	760	835249
3	H12	7	47304	1741.64	2009874		H12	7	47304	1741.64	2009874
4	H21	10	62391	2297.12	2003117		H21	10	62391	2297.12	2003117
5	H27	9	128716	4739.08	6838551		H27	9	128716	4739.08	6838551
6	H38	11	33841	1245.96	1029178		H38	11	33841	1245.96	1029178
7	H42	4	7258	267.23	94603		H42	4	7258	267.23	94603
8	H46	1	539	19.84	13353		H46	1	539	19.84	13353
9	H48	10	32721	1204.73	1033673		H48	10	32721	1204.73	1033673
10	H67	7	5163	190.09	69385		H67	7	5163	190.09	69385
11	H69	11	18158	668.54	201907		H69	11	18158	668.54	201907
12	H78	6	10709	394.29	172704		H78	6	10709	394.29	172704
13	H85	2	601	22.13	8343		H85	2	601	22.13	8343
14	H86	2	8852	325.91	166544		H86	2	8852	325.91	166544
15	H90	8	41606	1531.86	1787699		H90	8	41606	1531.86	1787699
16	H106	7	25417	935.81	931142		H106	7	25417	935.81	931142
17	H124	12	36019	1326.15	628612		H124	12	36019	1326.15	628612
18	H126	7	8992	331.07	199970		H126	7	8992	331.07	199970
19	H136	6	1265	46.57	28548		H136	6	1265	46.57	28548
20	H138	7	35575	1309.8	890680		H138	7	35575	1309.8	890680
21	H141	8	6202	228.35	125824		H141	8	6202	228.35	125824
22	H143	6	26364	970.67	552323		H143	6	26364	970.67	552323
23	H153	3	10167	374.33	292356		H153	3	10167	374.33	292356
24	H156	2	741	27.28	11513		H156	2	741	27.28	11513
25	H170	5	10609	390.6	235146		H170	5	10609	390.6	235146
26	H175	3	12311	453.27	320921		H175	3	12311	453.27	320921
27	H176	4	1118	41.16	18152		H176	4	1118	41.16	18152
28	H177	8	15512	571.12	239306		H177	8	15512	571.12	239306
29	H190	7	198898	7323.05	12185646		H190	11	200000	7363.63	12253171
30	H197	11	198457	7306.82	17521845		H197	8	197355	7266.24	17424533
31	H205	1	1043	38.4	113588		H205	1	1043	38.4	113588
32	H207	1	2199	80.96	140791		H207	1	2199	80.96	140791
33	H208	3	10527	387.58	499596		H208	3	10527	387.58	499596
34	H213	1	315	11.6	2019		H213	1	315	11.6	2019
35	H215	4	5236	192.78	126081		H215	4	5236	192.78	126081
36	H216	7	11995	441.63	321512		H216	7	11995	441.63	321512
37	H218	2	810	29.82	15626		H218	2	810	29.82	15626
38	H221	1	930	34.24	23147		H221	1	930	34.24	23147
39	H228	10	23340	859.34	549129		H228	10	23340	859.34	549129
40	H232	8	37331	1374.46	1708471		H232	8	37331	1374.46	1708471
41	H237	3	5573	205.19	118602		H237	3	5573	205.19	118602
42	H238	5	6964	256.4	123332		H238	5	6964	256.4	123332
43	H241	6	4622	170.17	81684		H241	6	4622	170.17	81684
44	H242	5	9036	332.69	166682		H242	5	9036	332.69	166682
45	H250	3	10809	397.97	327136		H250	3	10809	397.97	327136
46	H255	1	453	16.68	13761		H255	1	453	16.68	13761
47	H256	3	3612	132.99	82987		H256	3	3612	132.99	82987
48	H260	1	1030	37.92	35152		H260	1	1030	37.92	35152
49	H262	4	1852	68.19	46302		H262	4	1852	68.19	46302
50	H270	3	28425	1046.56	3362610		H270	3	28425	1046.56	3362610
51	H271	6	24978	919.64	2002068		H271	6	24978	919.64	2002068
52	H276	5	14466	532.61	1320879		H276	5	14466	532.61	1320879
53	H277	1	765	28.17	77778		H277	1	765	28.17	77778

Annex 5 - Scenario 4.1

17 Hubs – 50 km

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Hub Cap	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H5	16	57255	2108.02	1233218		H5	15	56978	2097.82	1227253
2	H24	13	114915	4230.96	3689449		H24	13	110328	4062.07	3542175
3	H52	14	123413	4543.84	2585501		H52	15	128000	4712.72	2681596
4	H69	27	43236	1591.87	480764		H69	26	43217	1591.17	480553
5	H86	5	16209	596.79	304967		H86	5	16209	596.79	304967
6	H88	1	127128	4680.62	5003641		H88	5	128000	4712.72	5037956
7	H91	10	65963	2428.63	2142082		H91	8	39607	1458.26	1286203
8	H97	6	127435	4691.92	5076715		H97	5	128000	4712.72	5099221
9	H108	17	53744	1978.75	1044805		H108	18	53815	1981.37	1046188
10	H128	24	50614	1863.51	1054770		H128	24	50614	1863.51	1054770
11	H145	23	52747	1942.05	671973		H145	23	52747	1942.05	671973
12	H158	13	18160	668.62	243386		H158	13	18160	668.62	243386
13	H160	25	94308	3472.24	1854219		H160	25	94308	3472.24	1854219
14	H195	6	83055	3057.93	4458500		H195	8	104247	3838.18	5596114
15	H211	5	25545	940.52	763714		H211	8	29492	1085.84	881716
16	H212	14	28965	1066.44	558828		H212	14	28965	1066.44	558828
17	H235	14	17316	637.54	249924		H235	14	17316	637.54	249924

53 Hubs – 25 km

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H5	8	18043	664.31	375999		H5	8	18043	664.31	388630
2	H9	1	11858	436.59	570187		H9	1	11858	436.59	578487
3	H12	2	17208	633.57	719102		H12	2	17208	633.57	731148
4	H20	5	12396	456.4	297573		H20	5	12396	456.4	306250
5	H21	6	34559	1272.4	1085357		H21	6	34559	1272.4	1109549
6	H24	5	29051	1069.6	912369		H24	5	29051	1069.6	932705
7	H37	5	81151	2987.83	3259723		H37	5	81151	2987.83	3316528
8	H38	2	15819	582.43	470021		H38	2	15819	582.43	481094
9	H42	4	7258	267.23	89522		H42	4	7258	267.23	94603
10	H52	11	26862	989.01	543956		H52	11	26862	989.01	562759
11	H56	3	50733	1867.89	1839872		H56	3	50733	1867.89	1875385
12	H57	3	25015	921.01	821541		H57	3	25015	921.01	839051
13	H61	5	12097	445.39	121591		H61	5	12097	445.39	130059
14	H69	9	13234	487.25	137892		H69	9	13234	487.25	147156
15	H78	4	6294	231.73	97095		H78	4	6294	231.73	101501
16	H86	2	8852	325.91	160348		H86	2	8852	325.91	166544
17	H88	2	22026	810.96	851508		H88	2	22026	810.96	866926
18	H90	1	7255	267.12	306654		H90	1	7255	267.12	311732
19	H91	7	34351	1264.74	1091471		H91	7	34351	1264.74	1115516
20	H97	5	50174	1847.31	1963691		H97	5	50174	1847.31	1998812
21	H100	2	13135	483.61	375281		H100	2	13135	483.61	384476
22	H101	5	12578	463.1	296384		H101	5	12578	463.1	305189
23	H108	10	23081	849.8	432548		H108	10	23081	849.8	448705
24	H124	8	28639	1054.43	479766		H124	8	28639	1054.43	499813
25	H126	7	8992	331.07	193676		H126	7	8992	331.07	199970
26	H136	7	4276	157.43	93513		H136	7	4276	157.43	96507
27	H138	6	30321	1116.36	737914		H138	6	30321	1116.36	759139
28	H140	5	8711	320.72	161964		H140	5	8711	320.72	168061
29	H145	9	19703	725.43	237216		H145	9	19703	725.43	251008
30	H158	4	10565	388.98	134198		H158	4	10565	388.98	141594
31	H160	6	14724	542.11	279187		H160	6	14724	542.11	289493
32	H166	8	13392	493.07	227798		H166	8	13392	493.07	237173
33	H174	2	11319	416.74	195868		H174	2	11319	416.74	203791
34	H175	3	12311	453.27	312303		H175	3	12311	453.27	320921
35	H183	4	1435	52.83	14581		H183	4	1435	52.83	15586
36	H185	2	4066	149.7	100299		H185	2	4066	149.7	103145
37	H190	6	117601	4329.85	7122603		H190	6	117601	4329.85	7204924
38	H195	1	127128	4680.62	6735412		H195	1	127128	4680.62	6824402
39	H196	1	11592	426.8	752022		H196	1	11592	426.8	760136
40	H199	2	17626	648.96	1136329		H199	2	17626	648.96	1148667
41	H203	1	33757	1242.87	2539183		H203	1	33757	1242.87	2562813
42	H208	3	10527	387.58	492227		H208	3	10527	387.58	499596
43	H215	4	5236	192.78	122415		H215	4	5236	192.78	126081
44	H222	6	11312	416.49	223239		H222	6	11312	416.49	231157
45	H224	5	18486	680.62	379105		H224	5	18486	680.62	392046
46	H227	3	9219	339.43	299717		H227	3	9219	339.43	306170
47	H237	3	5573	205.19	114701		H237	3	5573	205.19	118602
48	H238	4	6471	238.25	110072		H238	4	6471	238.25	114601
49	H241	6	4622	170.17	78448		H241	6	4622	170.17	81684
50	H246	1	3095	113.95	70877		H246	1	3095	113.95	73043
51	H250	3	10809	397.97	319570		H250	3	10809	397.97	327136
52	H256	3	3612	132.99	80459		H256	3	3612	132.99	82987
53	H262	4	1852	68.19	45005		H262	4	1852	68.19	46302

12 Hubs – 60 km

	Single Allocation						Multiple Allocation				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H5	17	81658	3006.49	1758834		H5	17	74738	2751.71	1609784
2	H24	16	121446	4471.41	3899125		H24	16	128000	4712.72	4109550
3	H69	40	77099	2838.64	857304		H69	41	77465	2852.12	861375
4	H88	8	127536	4695.64	5019697		H88	5	128000	4712.72	5037956
5	H91	10	127914	4709.55	4153881		H97	8	128000	4712.72	5099221
6	H97	2	127171	4682.2	5066198		H108	24	128000	4712.72	2488374
7	H108	19	127804	4705.5	2484562		H124	35	73699	2713.46	1286214
8	H124	37	73449	2704.25	1281848		H156	13	38831	1429.68	603343
9	H156	13	38831	1429.68	603343		H160	33	105831	3896.5	2080779
10	H160	31	101603	3740.83	1997650		H195	9	121250	4464.2	6508859
11	H211	13	62300	2293.77	1862570		H211	15	62966	2318.29	1882480
12	H212	17	33192	1222.07	640380		H212	18	33225	1223.28	641014

Annex 6 - Scenario 4.2

25 KM – 19 Hubs

	SA (25KM, 90%) Cap – 326k						MA (25KM, 90%) Cap – 325k				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H7	10	35218	1296.66	1425045		H7	10	35218	1296.66	1425045
2	H12	6	62699	2308.46	2663991		H12	6	62699	2308.46	2663991
3	H26	10	132985	4896.26	10096149		H26	10	132985	4896.26	10096149
4	H54	15	92778	3415.91	3521846		H54	15	92778	3415.91	3521846
5	H60	12	17644	649.62	314424		H60	12	17644	649.62	314424
6	H84	6	16287	599.66	358604		H84	6	16287	599.66	358604
7	H90	7	37467	1379.46	1609847		H90	7	37467	1379.46	1609847
8	H106	11	32884	1210.73	1204691		H106	11	32884	1210.73	1204691
9	H126	8	35890	1321.4	798142		H126	8	35890	1321.4	798142
10	H138	8	36129	1330.2	904553		H138	8	36129	1330.2	904553
11	H143	10	30297	1115.48	634722		H143	10	30297	1115.48	634722
12	H161	10	22234	818.61	528832		H161	10	22234	818.61	528832
13	H173	5	19670	724.21	401946		H173	5	19670	724.21	401946
14	H190	14	325480	11983.56	19940792		H190	14	325000	11965.89	19911389
15	H197	5	92478	3404.87	8164920		H197	6	92958	3422.54	8207293
16	H216	7	11995	441.63	321512		H216	7	11995	441.63	321512
17	H227	9	33602	1237.16	1115934		H227	9	33602	1237.16	1115934
18	H274	5	31622	1164.26	2455439		H274	5	31622	1164.26	2455439
19	H275	5	32644	1201.89	2733113		H275	5	32644	1201.89	2733113

50 KM – 8 Hubs

	SA (50KM, 90%) Cap – 419k						MA (50KM, 90%) Cap – 415k				
	Hubs	Mun	Orders	Hub Area	Hub Cost		Hubs	Mun	Orders	Hub Area	Hub Cost
1	H35	34	288032	10604.8	11177590		H35	34	288032	10604.8	11177590
2	H66	26	44515	1638.96	1047316		H66	26	44515	1638.96	1047316
3	H97	22	418515	15408.94	16672664		H97	22	415000	15279.52	16532630
4	H99	32	113999	4197.23	3655839		H99	32	113999	4197.23	3655839
5	H160	30	99305	3656.22	1952467		H160	30	99305	3656.22	1952467
6	H178	15	42853	1577.77	1079214		H178	15	42853	1577.77	1079214
7	H202	6	35278	1298.87	2421110		H202	7	38793	1428.29	2662350
8	H275	13	57515	2117.59	4815426		H275	13	57515	2117.59	4815426