Logistics Challenges in a New Distribution Paradigm: Drone Delivery

Connect Robotics Case Study

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“It always seems impossible until it's done.” - Nelson Mandela

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Abstract

This dissertation analyses a new paradigm imposed by the integration of unmanned aerial vehicles (UAV), commonly referred to as drones, in logistics and distribution processes. This work is motivated by a real case-study, where the company Connect Robotics, the first drone delivery provider in Portugal, wants to implement drone deliveries in their client, “Farmácia da Lajeosa”, which requires tackling the logistics challenges brought by the drones’ characteristics.

To understand how to approach these challenges, the national and international outlook of drone deliveries is scrutinised, as well as the new trends in the logistics and transportation industry, the future role of drones in delivery and the several approaches to delivery problems with drones. Interestingly, the literature highlights the relevance of the problem studied since the researched studies consider that drones will eventually be adopted in the future for the last-mile deliveries in rural areas. Regarding the approaches reviewed for drone delivery problems, the parallel drone scheduling travelling salesman problem (PDSTSP) was considered the most similar to the problem of Farmácia da Lajeosa since its formulation considers the drone integration concurrently with a road vehicle.

Therefore, this work proposes the parallel drone scheduling vehicle routing problem (PDSVRP), which is based on the PDSTSP but allows for multiple road vehicle routes. Four variants of this problem were modelled and implemented with real data to support analyses and decisions. Finally, the results obtained suggest that it is possible to obtain savings in the cost and transportation time of the deliveries.

Keywords: *drone deliveries, unmanned aerial vehicles, drones, last-mile deliveries, vehicle routing problem, transportation trends, logistics trends.*

Resumo

Esta dissertação analisa um novo paradigma imposto pela integração de veículos aéreos não tripulados, comummente apelidados de drones, em processos logísticos e de distribuição. Este trabalho é motivado por um caso de estudo real, onde a empresa Connect Robotics, o primeiro operador de transporte por drones em Portugal, quer implementar entregas por drone no seu cliente, a Farmácia da Lajeosa, o que requer lidar com desafios logísticos causados pelas características dos drones.

Para compreender como abordar estes desafios, o panorama nacional e internacional das entregas por drone é escrutinado, tal como as novas tendências da indústria da logística e transporte, o futuro dos drones para entregas e as várias abordagens a problemas de entregas com drones. Curiosamente, a literatura realça a relevância do problema estudado visto que os estudos pesquisados consideram que os drones serão eventualmente adotados para as entregas de última milha em zonas rurais. Em relação às abordagens revistas na literatura para os problemas de entrega com drones, o Parallel Drone Schedulling Travelling Salesman Problem (PDSTSP) foi considerado o mais semelhante ao problema da Farmácia da Lajeosa tendo em conta que a sua formulação considera a integração do drone paralelamente a veículos rodoviários.

Assim sendo, este trabalho propõe o Parallel Drone Scheduling Vehicle Routing Problem (PDSVRP) que é baseado no PDSTSP mas permite múltiplas rotas de veículos rodoviários. Quatro variantes do problema foram modeladas e implementadas com dados reais para apoiar análises e decisões. Finalmente, os resultados obtidos sugerem que é possível reduzir custos e tempos de entrega.

Palavras-chave: *entregas por drone, veículos aéreos não tripulados, drones, entregas de última milha, problemas de rotas de veículos, tendências de transporte, tendências logísticas.*

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List of abbreviations and acronyms

2E-VRP – *Two-echelon vehicle routing problem*

2E-GU-RP – *Two-echelon ground vehicle and unmanned aerial vehicle cooperated routing problem*

ANAC – *Portuguese National Civil Aviation Authority*

AGV – *Autonomous ground vehicle*

B2B – *Business-to-business*

BSS–EV–LRP – *Electric vehicles battery swap stations location routing problem*

BVLOS – *Beyond visual line of sight*

CEO – *Chief executive officer*

CTO – *Chief technology officer*

CTT – *Postal Services of Portugal*

DCVRP – *Distance-constrained capacitated vehicle routing problem*

DDP – *Drone delivery problems*

E2EVRP – *Electric two-echelon vehicle routing problem*

EVRP – *Electric vehicle routing problem*

E-VRPTW – *Electric vehicle routing problem with time windows and recharging stations*

FAA – *Federal Aviation Administration*

FLP – *Facility location problem*

FSTSP – *Flying sidekick traveling salesman problem*

GA – *Genetic algorithm*

GAMS - *General Algebraic Modeling System*

GPS – *Global positioning system*

GRASP – *Greedy randomized adaptive search procedure*

GUTMA – *Global UTM Association*

G-VRP – *Green vehicle routing problem*

HDP – *Heterogenous delivery problem*

INE – *Instituto Nacional de Estatística*

IoD – *Internet of Drones*

IoT – *Internet of Things*

KSE – *Kernel Sequence Enumeration*

LAANC – *Low Altitude Authorization and Notification Capability*

MC-DDP – *Minimum cost drone delivery problem*

MDVRP – *Multi-depot vehicle routing problem*

MILP – *Mixed integer linear programming*

MST – *Minimum spanning tree*

MT-DDP – *Minimum time drone delivery problem*

MTVRP – *Multiple trips vehicle routing problem*

MWDP – *Multiple warehouse delivery problem*

PDSTSP – *Parallel drone scheduling traveling salesman problem*

PDSVRP – *Parallel drone scheduling vehicle routing problem*

PMS – *Parallel machine scheduling*

SA – *Simulated annealing*

SCM – *Supply Chain Management*

SDDPHF – *Same-day delivery routing problems with heterogeneous fleets*

TSP – *Traveling salesman problem*

TSP-D – *Traveling salesman problem with drone*

UAV – *Unmanned aerial vehicles*

UGV – *Unmanned ground vehicles*

USAF – *United States Air Force*

UTM – *Unmanned traffic management*

VDRPTW – *Vehicle drone routing problem with time windows*

VRP – *Vehicle routing problem*

VRD – *Vehicle routing with drones*

VRPD – *Vehicle routing problem with drones*

VRPDR – *Vehicle routing problem with drone resupply*

VRPTW – *Vehicle routing problem with time windows*

1. Introduction

This chapter's purpose is to explain the background and motivation of the problem, define the dissertation's objectives, detail the methodology followed and present the outline of the dissertation.

1.1. Problem background and motivation

Unmanned aerial vehicles (UAV), commonly referred to as drones, have been growing rapidly in popularity while also breaking traditionally impenetrable barriers for technological innovation across different industries. Although they are still in an early stage of mass adoption, drones' capability to reach remote areas autonomously with minimum effort, time and energy has been proven useful for various applications, from military to commercial sectors (Joshi, 2018). Consequently, drones were labelled a disruptive technology (Bamburry, 2015).

One of the most promising drone application is the delivery of packages to previously hard to access areas due to the drones' potential to improve lead times, decrease costs and reduce emissions. Additionally, recent technology advancements contribute for the feasibility of drone deliveries with longer flight times, automated navigation systems and improved payloads, which is the maximum amount of weight a drone can carry outside its weight (Shavarani et al., 2017). Hence, multiple delivery and logistics providers have already started to introduce this technology in their operations, such as DHL, SwissPost, Google and Amazon, either by developing their drone technology or by partnering up with drone manufacturers (Dorling et al., 2017). However, the regulatory issues and the airspace management still represent a concern for the implementation of drone deliveries, which is being surpassed with the drafting of regulations across different countries and the development of Unmanned Traffic Management (UTM) platforms by several companies and associations to manage the increased presence of autonomous vehicles in the air, especially in cities (Mendes, 2017). Therefore, since the existing barriers are fading, there is a new distribution paradigm that must be studied.

As a matter of fact, Connect Robotics, the first drone delivery operator in Portugal, already offers a drone delivery service to interested customers and this dissertation's motivation is precisely the logistics challenges presented by the implementation of deliveries by drone at their first customer, Farmácia da Lajeosa. These logistics challenges are caused by the drones' specific characteristics, such as the limited range and carrying capacity, when compared to other transportation modes. Consequently, the ambition of this dissertation is to develop models that are able to analyse the impact of drones and also support the day-to-day drone delivery planning of Farmácia da Lajeosa.

1.2. Thesis objectives

The present work aims to develop and implement models that approach the logistics challenges of the problem presented by Connect Robotics, which concerns a new distribution paradigm where drones are employed in the delivery of small packages in their customer, Farmácia da Lajeosa. Therefore, several objectives were defined and are described below.

- Study the environment surrounding drones by researching drone’s technology and technical features, as well as investigate relevant companies in the drone industry and the companies introducing or planning to introduce drones in delivery.
- Describe the first drone delivery operator in Portugal, the company Connect Robotics, as well as their target market for drone deliveries, the regulations concerning the utilisation of airspace in Portugal and the public demonstrations of their delivery service.
- Characterise the drone delivery service provided by Connect Robotics, identifying the options and features of the service, the characteristics of the drones and its components, and estimating the cost savings that can be obtained with drone deliveries.
- Detail the conditions surrounding the customer Farmácia da Lajeosa, since the problem proposed by Connect Robotics concerns the implementation of deliveries by drone in this customer.
- Clarify the new logistics challenges brought by drone deliveries and what can be the contribution of the dissertation to help face these challenges regarding the particular case of Connect Robotics and Farmácia da Lajeosa.
- Study recent trends in the transportation and logistics industry, from the new technologies driving change to the other relevant trends that are emerging alongside drone deliveries.
- Investigate the future of drone deliveries, to establish the sustainability of this delivery model and how it is positioned in future scenarios.
- Research concepts and current methodologies related to drones’ application in delivery and find delivery models created to provide answers for this new distribution paradigm.
- Explore other transportation problems that address constraints similar to those present in drone deliveries which can help to understand how to model these constraints
- Link the challenges presented in the problem characterisation with fitting contributions of authors for drone delivery problems in the existing literature to develop a mathematical model for the drone delivery problem of Connect Robotics and Farmácia da Lajeosa that can provide decision support regarding drone deliveries and vehicle routes.
- Study the potential impact of drones in the daily delivery operations of Farmácia da Lajeosa, concerning the cost and time savings that can be obtained in a significant period.
- Analyse different scenarios featuring single delivery operations to draw conclusions regarding the decisions related with the assignment of drones to customers, as well as the most cost-efficient vehicle routes.

1.3. Research methodology

To accomplish the objectives established, the methodology followed along the dissertation was divided in several steps. The two first steps are related to the study of the problem and the relevant literature which required different approaches due to the nature of the information. The following steps concern the development and implementation of the model, as well as the results obtained, which is the aim of the dissertation. Furthermore, the methodology followed for approaching each step is detailed in the subsequent paragraphs and the ordered steps are portrayed in Figure 1.

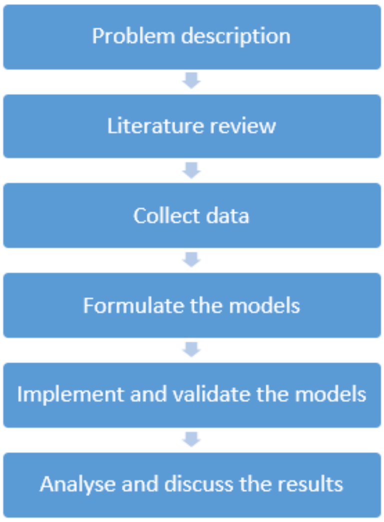


Figure 1 - The main steps for the dissertation's methodology

- **Problem description:** For the characterisation of the problem, several meetings with the chief executive officer (CEO) of Connect Robotics, Raphael Stanzani, were held to discuss the company's history, the service offered by Connect Robotics, the customer Farmácia da Lajeosa and the logistics challenges faced by Connect Robotics to implement deliveries by drone at this customer's operations. Additionally, the customer Farmácia da Lajeosa was visited to witness a drone flight test. Furthermore, other relevant information available regarding Connect Robotics and their activities was researched and compiled. The sources for this information were Connect Robotics' official website, websites of other entities related to their activities, as well as newspaper and magazine articles that covered Connect Robotics' activities. Moreover, several papers, articles and web pages were researched regarding drone technology and the current companies in the drone market. Additionally, research of newspaper and magazine articles was performed to complement the data gathered. These articles were found through different search databases such as Google Scholar and Mendeley with the keywords: drone delivery, UAV, drone technology and drone industry. Finally, the information gathered was processed, clarifying the logistics challenges, the problem at hand and the potential contributions of the dissertation.
- **Literature review:** Regarding the review of relevant literature, the primary sources for information on trends in the transportation industry and the future of drones were journal and magazine articles. However, this information was complemented with relevant newspaper articles covering the most recent developments. As for the drone delivery problems and other related work, only journal articles were consulted, and it was possible to find several recent articles modelling drone-related problems. Various search engines were utilised to find the articles, such as Mendeley, ScienceDirect, B-on, ResearchGate and Google Scholar, with the keywords: transportation trends, logistics trends, disruptive trends, last-mile delivery, drone, UAV, drone delivery and vehicle routing.
- **Collect data:** The next step refers to the data collection and processing. For the validation of the model, it will be necessary to define within the model the drone's characteristics and test it with customers' locations and historical demand. Hence, it will be necessary to gather real data from Connect Robotics and Farmácia da Lajeosa.

- **Formulate the models:** The optimisation model parallel drone scheduling vehicle routing problem (PDSVRP) will be created by adapting the parallel drone scheduling travelling salesman problem (PDSTSP) formulation to the situation presented by Connect Robotics and Farmácia da Lajeosa. This model should be able to assign the products' demanded by each client to be delivered by drone or car while considering the possibility of several car routes. Two variants will be developed and presented to study the benefits in daily delivery operations and single delivery operations. The objective of the models will be to either minimise costs or time, considering the costs and the time of transportation by drone and car.
- **Implement and validate the models:** The proposed mathematical models will be implemented on a GAMS software and tested with the collected data.
- **Analyse and discuss the results:** The results provided by the models will be interpreted and debated to judge the suitability of the provided solutions.

1.4. Outline

The dissertation is divided into the following chapters:

- **Introduction:** This chapter presents the background and motivation behind this dissertation, the thesis objectives, the research methodology followed to fulfil these objectives and an outline of the dissertation, which is the current section.
- **Problem description:** The problem under study is characterised by describing and analysing the drone's current technology, the relevant drone companies, the Portuguese drone delivery operator Connect Robotics, their first customer Farmácia da Lajeosa and the logistics challenges presented by this new distribution paradigm. After framing the problem within the particular case of the customer Farmácia da Lajeosa, it is defined how the dissertation can contribute to aid Connect Robotics and Farmácia da Lajeosa in the successful implementation of drone deliveries.
- **Literature review:** Definitions, concepts and methodologies related to the problem at hand are introduced by exploring how and what trends are shaping transportation and logistics, how drones fit in future delivery scenarios and how the scientific community is approaching drone delivery problems. The study of these delivery problems also has the purpose of inspiring possible approaches for the problem identified in the previous chapter.
- **Mathematical model for the drone delivery problem:** the problem statement was summarised and the different model variants of the PDSVRP were characterised and formulated.
- **Results:** the resolution of the problem is presented. First the data collection and treatment of the necessary inputs for the model is described while clarifying all the assumptions and estimations. Then, the approach utilised to analyse the current situation is described and its rationale explained. Moreover, the results obtained in the study of the daily delivery operations are presented for both cost and time minimisation. Finally, the results of the single delivery operation models are portrayed, and the potential benefits are analysed.
- **Conclusions and future work:** The dissertation's conclusions are discussed, and possible future research in this field is proposed.

2. Problem description

The goal of this chapter is to characterise the problem under study, through the detailed description of its various elements. Hence, the conditions and the environment around drones and the first drone delivery operator in Portugal, Connect Robotics, will be portrayed, as well as their delivery service. At last, some context regarding Farmácia da Lajeosa, a Connect Robotics' customer that wants to implement drone deliveries in their operations, will be provided and the logistics challenges regarding the utilisation of drones in delivery will be discussed and analysed.

2.1. Drones' environment

The following paragraphs focus on the drones' environment with the purpose of understanding the technology evolution and who are the current players in this expanding market.

2.1.1. State of drone technology

Nowadays, drones have been commonly adopted for three different purposes: military, personal and commercial. However, drones' technologies diverge significantly from military to personal and commercial (Hassanalian and Abdelkefi, 2017).

Military drones are the more technologically advanced and can fulfil many military operations, such as combat and reconnaissance, due to their capability for executing high profile and time-sensitive missions while reducing losses. Consequently, they are also much more expensive (Brar et al., 2015). For example, the Northrop Grumman, a large-scale UAV at the service of the United States Air Force (USAF) and known as Global Hawk, costs 104 millions of dollars, has a maximum speed of 650 kilometres per hour and a range of 22,224 kilometres. Currently, there are 46 Global Hawks in the USAF and one at the service of German forces (Military factory, 2017).

Personal drones, on the other hand, are the most affordable and thereby have a shorter range and a higher susceptibility to weather conditions. Photography and video recording are the most common functions. Meanwhile, these drones come in different sizes and shapes, from cheap single-rotor devices to quadcopters equipped with cameras, a global positioning system (GPS) module and first-person control, that cost more than 1 thousand dollars (Joshi, 2018). The drone Phantom 3, one of the models for sale from the manufacturer DJI, costs in Portugal 500 euros, has a maximum speed of 57,6 kilometres per hour, a range of 500 metres and a maximum flight time of 25 minutes. Additionally, it includes a camera with a resolution of 12 megapixels (DJI, 2018).

Meanwhile, commercial drones have been employed in several applications, such as monitoring crops and forest fires, keeping track of animal populations, inspecting remote infrastructures and delivering packages (Rao et al., 2016). Therefore, drone technology has improved consistently. This evolution can be represented along seven different generations of drone technology. Presently, most of the current technology sits in the sixth generation, although top professional drones are already crossing into the next generation (Air Drone Craze, 2018). These generations are represented in Figure 2.

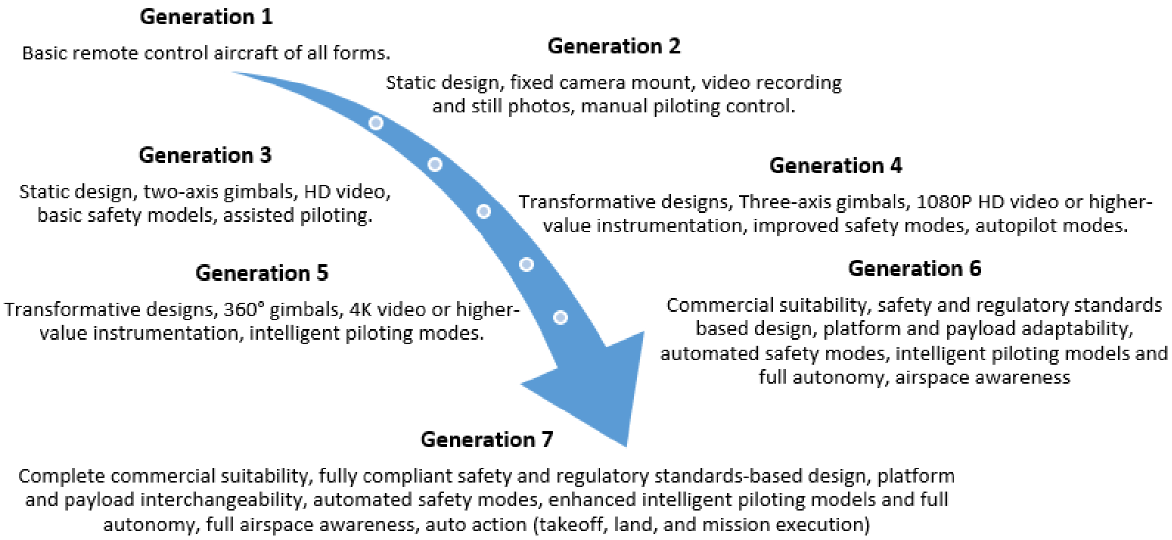


Figure 2 – Generations of drone technology. Adapted from Air Drone Craze (2018).

Furthermore, commercial drones have also been improving their quality, technical functionalities and cost efficiency by partnering with disruptive technologies like 3D printing. In fact, this technology provides easy access to customised drone components (Bamburry, 2015). Moreover, the potential of 3D printing could already be seen back in 2014 when researchers from the University of Sheffield in England printed a working drone in less than 24 hours (O'Toole, 2014).

2.1.2. Most prominent players in the drone industry

Before developing the particular case of Connect Robotics, it is essential to understand what else is out there. In this perspective, it is possible to discover at least one thousand active organisations that have been driving the drone industry. Moreover, these players operate in different areas, such as drone manufacturing, software developing, services, components and systems, constituting a diverse ecosystem (Drone Industry Insights, 2018). From this comprehensive environment, some companies with relevant contributions in the drone industry, and for drone deliveries specifically, can be identified. These organisations were divided into the two categories depicted in Figure 3, and further information about each one will be given in Table 1 and Table 2.

Figure 3 – Relevant companies in the drone industry

The first category is the drone manufacturers and software developers since they have been responsible for the improvement of the drones' technology and the addition of new functionalities. Therefore, these companies' inputs are described in Table 1.

Table 1 - Manufacturers and software developers in the drone industry

Company	Description and contributions
Matternet	Based in California, Matternet is a drone manufacturer that focuses on drone delivery technology (Taylor, 2013). Back in 2015, they produced the Matternet One, a drone designed for transportation, and tested their delivery system in a partnership with the Swiss postal service, Swiss Post (Biggs, 2015). As a part of this partnership, they announced an autonomous delivery network with drones for transporting medical items between hospitals in Switzerland (Ong, 2017). This network included their latest drone, the Matternet M2 Drone, that can fly over distances of 20 kilometres carrying a payload of 2 kilogrammes and their Matternet Station, an interface that automatically verifies and attaches a package to the drone and upon the drone's return also swaps its battery (Matternet, 2018). On another note, Matternet also partnered with Mercedes-Benz to create a new delivery concept using vans as mobile landing stations for drones (Daimler, 2017).
DJI	Mostly known due to their Phantom drones, DJI is a Chinese manufacturer that operates mainly in the consumer drone market. Their Phantom drones purpose is aerial photography and video recording (Glaser, 2017). However, their success and technological improvement drive the industry forward. In fact, their last generation drone, the Phantom 4 Advanced released in April 2017, has a maximum flight time of 30 minutes, a range of 7 kilometres and autonomous flight modes (Feist, 2018). Meanwhile, after dominating the consumer market, DJI is expanding into the enterprise and industrial market with hardware and software tools that allow the development of customised solutions by businesses on DJI drones (Terdiman, 2018).
3DR	Which stands for 3D Robotics, is a pioneer in the drone industry. This American company founded in 2009 started by manufacturing consumer drones. In 2015, they introduced their Solo drone, which included onboard computers on both the remote controller and the drone (Newton, 2015). However, the Solo drone was not the success the company expected. Lagging behind the market leader DJI, which kept improving their drones while reducing prices, 3DR decided to quit the hardware market to focus only on enterprise software (Mac, 2016). Therefore, being unable to beat DJI in the consumer drone market, they partnered with them in the commercial market by integrating 3DR's Site Scan software with DJI drones (Murphy, 2017). This software was developed specifically for architecture, construction and engineering teams. It allows a drone with a high-resolution camera to survey a construction site to capture and process data, creating 2D and 3D maps compatible with Autodesk software (Sartori, 2017).
Parrot	Originally a manufacturer of wireless components for tablets and smartphones, the American Parrot decided to diversify and started designing and producing drones in 2010. Therefore, they established a partnership with Dassault Systémes to create drone designs in their software application Solidworks Industrial Design (Dassault Systèmes, 2015). However, their AR.Drone differentiated itself by offering augmented reality gaming alongside the camera functionalities (Meige, 2015). After the success of the AR.Drone, they launched the Bebop drone which competed directly with DJI and 3DR in the aerial photography and recording market. This drone was cheaper than the alternatives and can be piloted through a smartphone or tablet (Phillips, 2014). Currently, the second version of Bebop has a maximum flight time of 30 minutes (Parrot, 2018).
Skyward	Not all major players in the drone industry focus on the hardware, this company from Portland offers a flight operations management platform designed for both small and large drone operators. Their software solution was launched back in 2015 and allows for efficient planning, managing and tracking of flight operations with drones (sUAS News, 2015). Meanwhile, in early 2017, the telecommunications company Verizon acquired Skyward as a part of their strategy to simplify the drone industry by streamlining connectivity and certification of wireless drones (Burns, 2017). Later that year, the American Low Altitude Authorization and Notification Capability (LAANC) granted Skyward an authorisation to give commercial drone operators instant access to controlled airspace, automating a process that previously required 2 to 3 months (Skyward, 2017).

Delivery and logistics providers is the second category as these companies have been investing in deliveries by drone, although regulatory barriers still restrain some of these companies' efforts. Consequently, the contributions of these companies are described in Table 2.

Table 2 – Delivery and logistics providers in the drone industry

Company	Description and contributions
Amazon	In 2013, this American online retailer announced their drone delivery project, the Amazon Prime Air, whose goal was to serve customers by drone in 30 minutes or less (Brar et al., 2015). However, since there were still no regulations for UAVs, Amazon still had to persuade the Federal Aviation Administration (FAA) to authorise testing. In June 2016, the new regulations finally authorised commercial drones to operate Beyond Visual Line of Sight (BVLOS), which made delivery drones feasible in the United States. Regardless, Amazon had already been testing its technology in countries with favourable regulations (Digital Trends, 2017). Therefore, the first delivery demonstrations occurred first in England (BBC News, 2016) and then later in the U.S. (Rubin, 2017). Since these public demonstrations, Amazon continued working on their drone technology and recently issued a patent for a drone that recognises human gestures and voices, which would allow delivery recipients to communicate with the drones (Shaban, 2018). Nevertheless, Amazon will still require some time before their service is fully operational. The current forecasts suggest a soft launch for 2020 (Midrack, 2018).
Zipline	By partnering up with the government of Rwanda, this company has launched a national drone delivery system in 2016 to serve health facilities in remote areas (Zipline, 2018). These deliveries are performed with fixed-wing autonomous drones that fly to their destination, release the packages attached to parachutes without landing and return (Simmons, 2016). Upon returning the drones are ready to fly again after switching their battery. Moreover, doctors can request their orders by using the mobile app WhatsApp Messenger (Ackerman & Strickland, 2018). In an emergency, the supplies can be delivered within 15 minutes (Baker, 2018). After the success in Rwanda, Zipline partnered with the government of Tanzania to create the most extensive drone delivery network in the world (Walcutt, 2017). Meanwhile, Zipline developed a delivery drone with a speed of 128 kilometres per hour and a maximum payload of 1,75 kilograms. Moreover, it can make a round trip of 160 kilometres (Giles, 2018).
UPS	UPS has been testing a delivery truck that launches a drone since 2017. This solution is similar to the one spawned from the partnership of Matternet and Mercedes-Benz in 2016. Instead of replacing drivers, the drones only deal with the last-mile in hard to reach places. These drones can fly for 30 minutes, with a maximum payload of four kilogrammes, and then recharge at the truck (Perez, 2017). However, the current negotiations with a labour union that demands the ban of drone deliveries represent an obstacle for the company (Zhao, 2018).
Flirtey	Founded as an independent drone delivery service in 2013, this Australian company has the mission of creating a fast and efficient delivery service centred on the customer (Flirtey, 2018). Therefore, after conducting successful autonomous drones tests in Sydney, they relocated to the United States in 2014 following a partnership with the University of Nevada, Reno, to develop drone technology and logistics systems (Wolterbeek, 2014). In July 2015, Flirtey conducted the first FAA-approved drone delivery in the United States (Lim, 2015). Later, they also made the first fully autonomous FAA-approved urban delivery with a drone in the United States in March 2016 (Vanian, 2016). In July 2016, they teamed up with the company 7-Eleven to make the first fully autonomous FAA-approved household delivery via drone (Soper, 2016). Later that year, Flirtey formed a partnership with Domino's Pizza in New Zealand to create a drone delivery model where drones are fully integrated into online orders and GPS systems (Dominos, 2016). Finally, REMSA Health, a provider of ambulance and emergency health services, has partnered up with Flirtey to have portable defibrillators delivered by a drone (Kolodny, 2017).
JD.com	The Chinese online retailer JD.com started their drone delivery program in October 2015 by developing drone technology in their logistics innovation lab, the JD X. Consequently, in June 2016, JD.com started making the first test flights (Meredith & Kharpal, 2017). The goal of their program was to reach remote areas in China by establishing drone routes from their regional warehouses to drone landing platforms in rural villages. Subsequently, local distribution channels were responsible for making the last-mile delivery. By May 2017, JD.com's drones had already delivered thousands of packages in the outskirts of Beijing and other four provinces (Aleem, 2017). Meanwhile, the China Civil Aviation Administration recently allowed JD.com to set up drone landing platforms across China (Borak, 2018). According to JD.com, there are currently seven different drone models. Their maximum payload varies from 5 kilos to 30 kilos, their maximum range from 7 to 100 kilometres and their maximum speed from 54 to 100 kilometres per hour. Furthermore, JD.com is already testing heavy-load drones capable of carrying more than 1 ton in the future (JD.com, 2018).

Company	Description and contributions
DHL	In 2014, DHL announced a delivery service that used the second generation of the parcelcopter, an autonomous drone designed in a DHL's research project. The objective was to deliver small parcels to the German island of Juist which had a population of two thousand people (Hern, 2014). Given the success of this endeavour, DHL has continued to develop and test their parcelcopter in Germany. The third generation of the parcelcopter was able to carry payloads of almost two kilogrammes to their destination in eight minutes, whereas the same trip took a car thirty minutes to complete (Burgess, 2016). With the new parcelcopter, DHL also introduced the Skyport, a station where the drone can pick up and drop off its cargo. Moreover, DHL tested its drone under the harsh weather conditions of the alpine region, proving the drones suitability to overcome meteorological challenges (Chua, 2017).
Flytrex	Based in Israel and founded in 2013, this software-focused drone company developed the first delivery drone connected to the cloud (UAV Coach, 2018). Moreover, they also designed a cloud-based drone management system for companies interested in delivering with autonomous drones that establishes routes by combining real-time data extracted from the cloud with their position, battery and other flight information (Blum, 2017). The data in the cloud is obtained from the connected devices built in-house for drones (Rabinowitz, 2016). In 2016, they announced a pilot program with the Ukrainian Postal Service to deliver packages with the Flytrex Mule drone, an octocopter in carbon-fibre, with a maximum payload of 3 kilos, a speed of 70 kilometres per hour and a range of 23 kilometres (Woollaston, 2016). Afterwards, in 2017, Flyxtrex deployed a fully operational drone delivery system in Reykjavik, Iceland, to deliver packages autonomously across the river that divides the city (Macaulay, 2017).
Alphabet	The Google's parent company Alphabet has been investing in drones for delivery through its research and development subsidiary Google X since 2012. Back then, this subsidiary started Project Wing with the goal of working toward a new commerce system by exploring and developing autonomous delivery drones (Project Wing, 2018). Although it started in 2012, this drone delivery program was only announced by Alphabet in 2014, when it was attempting to move from research to product. Having considered several methods for delivery, Project Wing settled on a fishing line to gradually lower the package to customers (Rushe, 2014). Hence, they began testing their single-wing drone by delivering small packages in Australia, due to tolerant regulations towards UAVs (Stevens, 2018). Meanwhile, another critical element of Project Wing was the development of a UTM platform to enable their drone fleet to share the sky with other UAVs. In 2017, this platform was already able to manage complex flight paths of multiple drones at the same time (Burgess, 2017).

It's important to mention that the company Connect Robotics is a delivery and logistics provider just as the companies described in Table 2. However, since their drone delivery service is behind the motivation for this dissertation, the company will be characterised with more detail in the following section.

2.2. Connect Robotics

The company Connect Robotics is introduced in this topic by going through their origins and covering all the subjects that sent the company in the current direction. Subjects such as the current market, the flights' regulations and the events surrounding the first drone deliveries demonstrations', will be detailed given their significance for the problem at hand.

2.2.1. First drone delivery operator in Portugal

By bringing together expertise in UAVs and Supply Chain Management (SCM), Connect Robotics was founded in January 2015. The company's vision is "A connected world, where everyone can access what they need, wherever they are, whenever they want" and they wish to contribute by making their mission to "Support the on-demand economy growth by providing drone delivery service wherever it is needed". Therefore, Connect Robotics is currently making deliveries Beyond Visual Line of Sight (BVLOS) with autonomous drones in Portugal, while also being committed to the integration of drones safely into the international airspace (Connect Robotics, 2018). Located in UPTEC, a place for Science and Technology in the University of Porto, Connect Robotics is, at the moment, the only Drone Delivery Operator in Portugal. The solution offered by Connect Robotics consists of drones that fit the specifications of each customer and an autonomous navigation and control system that includes traffic management capabilities. This solution is flexible, safe, trustworthy, and can be integrated into the delivery and transportation processes of logistics operators (third-party logistics), retailers and manufacturers (Mendes, 2017).

However, to better understand how a start-up such as Connect Robotics begun, it helps to know its founders' background and motivations, as well as the first steps of the company. Starting from the very beginning, Connect Robotics derived from the PhD project of Eduardo Mendes, who was at the time a PhD candidate in Electrical Engineering at the Engineering Faculty of the University of Porto. His project concerned the developing of algorithms to control and navigate UAVs in an autonomous way. Subsequently, Eduardo asked Raphael Stanzani, an enthusiast for innovation in technology and business management practices, to join the venture as the CEO of Connect Robotics, while Eduardo assumed the role of chief technology officer (CTO). From then on, Eduardo and Raphael started working together, and by February 2015 they were both working full time on the project (Connect Robotics, 2018). Initially, their idea was to sell hardware and software kits for drones, that would enable a drone to be multi-purpose. Additionally, by creating an online software store, it would be possible to update their software and sell new programs, increasing the drone's functionalities. However, while undertaking an acceleration program in July 2015, the founders received much feedback from investors and experienced entrepreneurs. Consequently, it was then decided that Connect Robotics would focus only on a vertically integrated software for transportation to optimise efforts and reduce the business risk. This software was considered the one that most benefits from the automation of flights, not to mention it is a market in its very early stages with wide-open opportunities. During the second half of 2015, they prepared a business plan and made two applications for the ESA BIC Portugal (European Space Agency Business Incubation Centre) and, through the accelerator SOUL-FI, the European project FIWARE (Platform for Future Internet and Internet of Things). Both applications were a success. The first, from ESA BIC Portugal, granted a value of 50.000€ for two years of product development. Meanwhile, the second application, from the FIWARE project, resulted in 100.000€, funded at 75% of co-participation, to develop the software component of the product for six months. Similarly, Connect Robotics also obtained support from the acceleration program Building Global Innovators, promoted by the MIT-Portugal program (Connect Robotics, 2018). Consequently, in the first half of 2016, the team grew to four employees and two interns and started investing in the creation of a system of UTM, a cloud server to manage and generate routes, while centralising all the flights to be managed. The UTM ensured that an unlimited number of drones could fly with coordination and without conflicts. For the same purpose the team also developed collision-preventing algorithms onboard (Mendes, 2017).

2.2.2. The current market for drone deliveries and flight regulations

Connect Robotics considered that last-mile deliveries to regions with difficult access, as well as a low population density, was the market that better matched the technologies' restrictions and the still undeveloped regulation. In fact, the drones currently being employed by Connect Robotics, which are the more economically accessible, have a payload of 3 kilos. Hence, a drone can carry packages up to 3 kilos. Furthermore, their maximum flight time is 35 minutes and they have a maximum range longer than 5000 metres. Finally, these drones require a landing site with at least 3 square metres, considering their landing precision of 3 metres around the location defined. Therefore, by operating in rural areas and doing last-mile deliveries, Connect Robotics could overcome some of these limitations. For example, the maximum allowable weight limitations are not an issue for these types of deliveries. The problem in rural areas is mainly the problematic access and not the volume since potential recipients are spread across a considerable area. Consequently, these routes are expensive for last-mile deliveries with regular vehicles. Moreover, the landing space would not be an issue in rural areas. Last but not least, regulation challenges are harder to handle in cities considering the airspace is crowded, while in rural areas there are not as many obstacles.

To validate the viability of this market, Connect Robotics resorted to the data available on the website PORDATA, a Portuguese database of official and certified statistics, to estimate the potential market profit. According to these data, Portugal has a population of approximately 10,4 million, with 2,6 individuals per household, on average. Considering a "low population density" for regions with values below 300 individuals per square kilometre, counties such as Ponta Delgada, Albufeira, Viana do Castelo, Leiria, Viseu, Amarante, Penela, Vila Real, Baião, Tomar, Santarém, among many others, are included. Hence, this category represents about 44 percent of the Portuguese population, which means around 1,75 million households. However, due to battery limitations, drones cannot reach everywhere. Still, only 5% of these households would represent 87,5 thousand delivery destinations. If each one of these households makes three online purchases in a month with the delivery being handled by a drone, then this would potentially generate a business volume of approximately 3,15 million deliveries per year. If the estimate for the contribution margin of one delivery is 5 euros, then the potential yearly profit of this market is around 15,75 million euros. Regardless, there are still other possibilities for the employment of drones, like carrying out inbound transportation within a logistics operators' supply chain. Drones could, in this scenario, deliver packages from a distribution centre to a store, transfer packages between distribution sites, or even transfer packages between trucks in different routes.

As aforementioned, the lack of regulation was a concern for Connect Robotics. In fact, this matter generates discussions all around the globe, with some countries at a more advanced stage than others. However, in January 2017, a new regulation for drones came into force through the Portuguese National Civil Aviation Authority (ANAC), which defined the limits of operation for drones in Portugal. Furthermore, ANAC also proposed a process for people and businesses to request approval for commercial activities that operate beyond the proposed limits. Essentially, Connect Robotics started to have a standard procedure to get an approval for the needed flight routes. Thus, all flights performed by Connect Robotics have been approved previously by ANAC, as well as all the routes BVLOS where Connect Robotics operates. Nevertheless, the air traffic control is still a vital concern for the drone industry, and one that cannot be addressed individually by each company or institution that handles drones, but in a coordinated and united endeavour. Global standards must be established and followed by all entities involved to allow for the sharing of information. Therefore, in a joint effort, many international companies and institutions of this sector created the Global UTM Association (GUTMA) with the goal of developing such standards. As a matter of fact, Connect Robotics is one of the founding members (Mendes, 2017)

2.2.3. Package delivery's demonstrations

In December 2016, Connect Robotics made their first public demonstration of package delivery by drone. The goal of this demonstration was to evaluate the viability of drone transportation as an alternative to truck transportation and resulted in the first food delivery by drone to an elderly person in the Countryside of Portugal, more specifically in the municipality of Penela. Mr Joaquim dos Reis, a septuagenarian living in Podentinhos, a small village in the middle of Portugal, was the first beneficiary of this service and continues to receive his meals by drone nowadays. In Figure 4, the drone utilised for the demonstration can be observed in mid-air with a purple container attached, containing the meal, and after leaving the container on the ground for Mr Joaquim dos Reis to pick it up (Jornal de Notícias, 2016).

Figure 4 – The drone carrying the meal of Mr Joaquim dos Reis (left) and the drone taking off after leaving the meal (right). Retrieved from Jornal de Notícias (2016).

This initiative received a significant national coverage at the time and came into being from partnerships made with Penela's Town Hall and "Santa Casa da Misericórdia de Penela", a public institution that provides healthcare and other services to people in need. For Connect Robotics, this project was a turning point from the development stage to the product launching stage (Mendes, 2017). At that moment, Connect Robotics' Drone Delivery Service was already ready to be commercialised. However, there was still the need to convince others of the viability and advantages of this new transportation mode. Therefore, during 2017, there were two delivery demonstrations for the CTT, the Postal Services of Portugal. The first one in Penela, since a permit was granted by ANAC for Connect Robotics to fly BVLOS in the entire region, and another one in the urban area of Lisbon, from the CTT's distribution centre at Cabo Ruivo to the sidewalks in front of the CTT's headquarters at Parque das Nações.

Naturally, ANAC also authorised the demonstration in Lisbon and the drone flown at an altitude of 30 metres, as can be seen in Figure 5 (Connect Robotics, 2018).

Figure 5 - Drone flying at an altitude of 30 meters. Retrieved from Connect Robotics (2018).

These demonstrations generated a lot of media attention and attracted many potential clients from diverse industries, such as food, mechanical components, publicity materials and books. In addition, they also promoted the start of a relationship between Connect Robotics and the Municipality of Lisbon, mainly through the Smart Open Lisboa program, a start-up implementation program that is supported by several Portuguese and European institutions and companies (Connect Robotics, 2018).

2.3. Connect Robotics' drone delivery service

To provide an insight on how Connect Robotics is positioned in the Portuguese distribution market, their drone delivery service is detailed in the following paragraphs. This description focuses on the options and features of the service currently being offered to their customers, as well as the characteristics of the drones and the cost reduction that can be obtained through drone deliveries.

2.3.1. Options and features of the delivery service

Nowadays, it is already possible for a business to have its transportation needs handled by Connect Robotics' drones. In fact, this delivery service is made available through the company's website, where Connect Robotics offers two different possibilities for drone deliveries. One for distributors, to utilise drones in their daily operations, and another one for regular sellers and consumers as a third-party distributor. However, since Connect Robotics is only starting their business, the option for distributors is currently the only short-term possibility for any business interested in drones for deliveries. Hence, distributors are prompted to contact Connect Robotics to implement transportation by drone in their operations. After signing a delivery service contract, Connect Robotics studies and evaluates the needs of the distributor. Subsequently, dedicated drones are made available on site, and the client's personnel also receives training on how to handle the aircraft. Furthermore, every concern with legal authorisations, regular maintenances and updates is dealt by Connect Robotics. Regarding the option for sellers and consumers, interested parties can register in Drone2.me to let Connect Robotics know where the drone deliveries are needed. This service will be offered according to the number of individuals in each region that registered their address, as well as their preferred location for the drone-port, where drones would be allocated. This location would have to be validated before initiating any operations. Moreover, sellers will be able to have a dedicated drone or a shared one, depending on their operations' demand. From there, they can start offering drone deliveries to their clients (Connect Robotics, 2018; Mendes, 2017).

However, delivering by drone is still not very familiar among regular business owners. Therefore, Connect Robotics seeks a close relationship with its clients and offers a personalised service, according to each client's requirements. Furthermore, the main features of the delivery service, shown in Figure 6, also promote a smoother integration of this new transportation mode into the clients' operations.

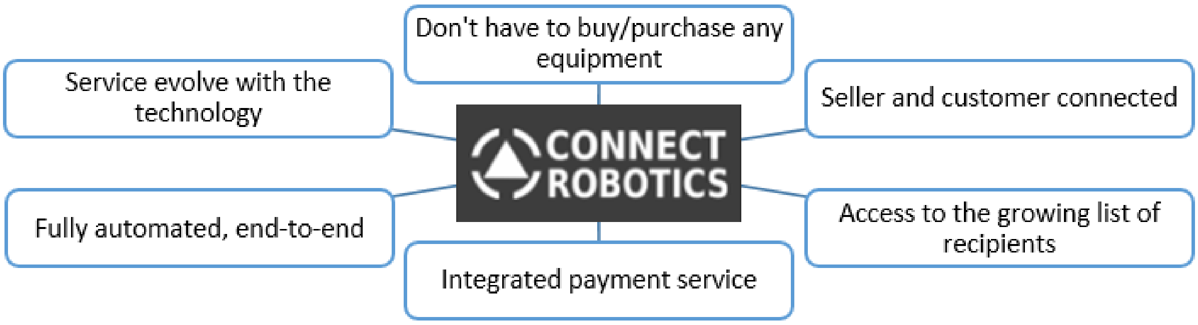


Figure 6 - Announced features in Connect Robotics website. Adapted from Connect Robotics (2018).

First, there is no need for purchasing any equipment. Clients will pay the ride, while the drone is still Connect Robotics' property. Consequently, Connect Robotics is responsible for the setup of the drone, which includes the required customisations to add all the service's functionalities. Additionally, and since Drone Deliveries demand the customer's readiness to receive the package, seller and customer are connected at the critical steps of the delivering process; thus, the customer will receive an e-mail to confirm when he or she is ready to receive the package. Regarding legitimate privacy concerns, the customer's coordinates are not available to the seller. Instead, they are automatically sent to the drone following the client's authorisation. Moreover, clients will have access to Connect Robotics' web service and their growing list of recipients, which is a list of customers prepared and willing to receive their packages through drones. Therefore, this list allows for the seller to automatically check if a customer is available for drone deliveries. Considering how recent the technology is and the intrinsic characteristics of drone deliveries, not every customer will want drone deliveries, hence the importance of this list of recipients. Furthermore, an integrated payment service is included. For example, it is possible for the drone to take off only after Connect Robotics' software application processes the payment. In fact, the delivery process is fully automated since the software does everything end-to-end, such as flight planning, weather check, collision avoidance and piloting the drone. Finally, since there are no purchases, the service evolves with technology. In fact, Connect Robotics' continuously upgrades their fleet of drones and clients also benefit from any future software updates (Connect Robotics, 2018).

To provide these features, Connect Robotics' drone delivery service resorts to an IoD developed in-house, which contains all the different elements of the logistics process in an autonomous way. This system works through the Cloud, follows European standards and was develop through the funding, support and technology of the Internet of Things (IoT) technology of the FIWARE project. The elements of the logistics process handled by the IoD are the following:

- **Route Creation Module**: creates the flight route by combining current traffic information and the airspace regulation.
- **Climatic Module**: verifies if the climate conditions are safe for the equipment's utilisation.
- **Recipient Module**: sends an e-mail to the recipient, who needs to confirm that he/she is available to receive the package.
- **Sender Module**: a mobile interface is operated by the sender to confirm that the package was correctly attached to the drone.
- **Drone**: informs the central system automatically of its current state, as well as its conformity for the prompted flight.
- **Administrative Panel**: all the flights are displayed and tracked in real-time through a web interface, from where an administrator can manually approve or reject a flight.

In fact, for the drone to lift off to make a delivery, it must receive authorisation from every element in the network independently (Mendes, 2017). In Figure 7, the flight's approval process for a delivery is reproduced since it is an excellent example of the application of this system.

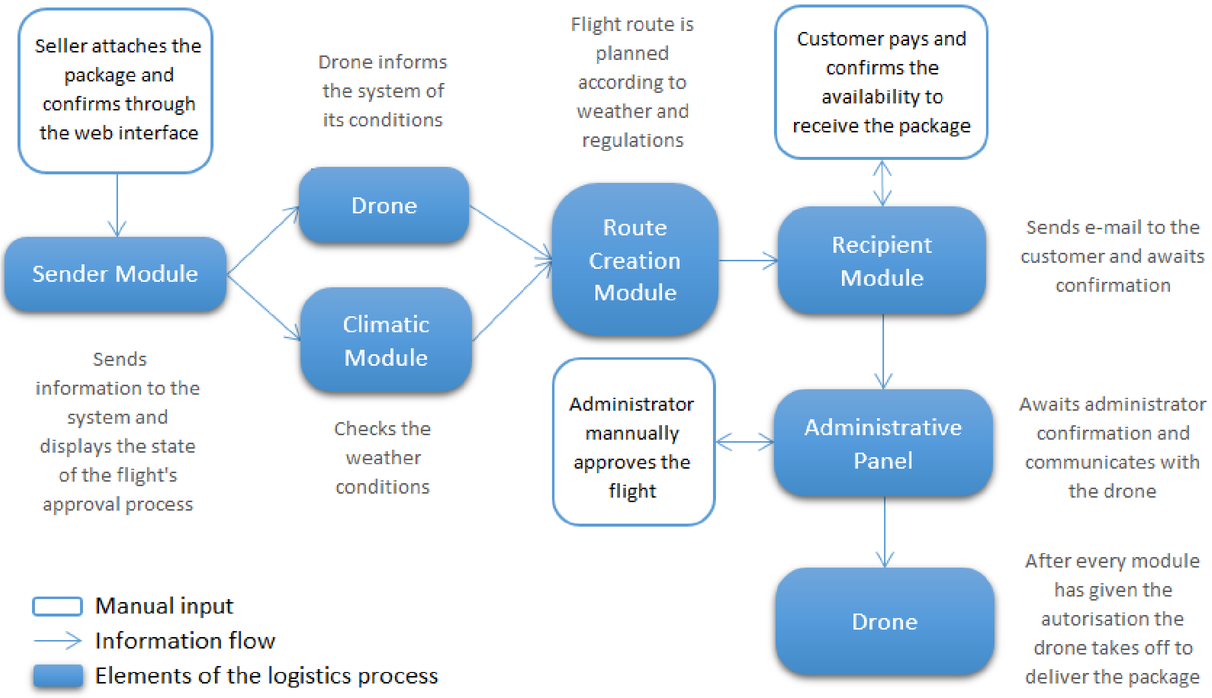


Figure 7 - Example of a flight's approval process for a delivery in Connect Robotics' system.

2.3.2. Characteristics of the drone and its components

The drones Connect Robotics is adopting nowadays can travel 5000 metres, while carrying a package, in approximately 5 minutes, which translates to a moving speed of 1 kilometre per minute. Although, in urban areas, due to the increased number of obstacles, a drone can take twice this time. As previously mentioned, they have a maximum range of 5000 meters and their batteries enable a maximum flight time of 40 minutes. An example of a drone utilised by Connect Robotics is depicted in Figure 8.

Figure 8 – Example of Connect Robotics' drones. Retrieved from Connect Robotics (2018).

These drones are designed and manufactured by Sleeklab, a drone manufacturer from Coimbra, which produces them according to Connect Robotics' specifications to fit each customer's operations demand. Comparing with the Sleeklab's standard drones, Connect Robotics' drones have additional 3D printed elements installed to attach packages and increase the drones' stability. Furthermore, the software in the onboard computer is developed by Connect Robotics. This software implements autonomous piloting, weather checking capacity and collision-preventing algorithms. More importantly, it also connects the drone to the IoD, which allows for the deliveries to be managed through a user-friendly and intuitive web interface that contains multiple functionalities. In Figure 9, the functionalities of the web interface are portrayed.

Figure 9 - Web interface's functionalities. Adapted from Connect Robotics (2018).

First, and since the drones fly autonomously and BVLOS, this web interface includes a real-time tracking system, allowing for the drones to be tracked throughout the entire process. In addition, the delivery status can be followed by both the sender and the receiver. Naturally, security approvals can also be checked through the interface. Moreover, it is possible to define new deliveries, as well as setup warehouses, consumers and destinations. Finally, there is also the possibility to abort flights (Connect Robotics, 2018).

2.3.3. Cost savings from drone delivery

Connect Robotics states that delivering with a drone in a remote area can translate to a significant saving in transportation costs. In this respect, the cost simulation represented in Figure 10 can demonstrate how much there is to gain from this new transportation mode. Since Connect Robotics' automated drones do not require an operator, this simulation only considered energy costs.

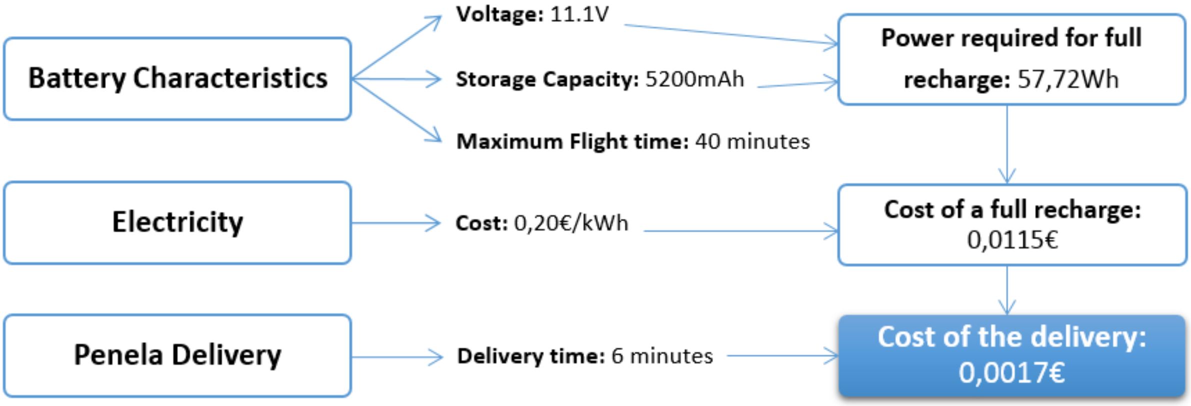


Figure 10 - Cost simulation of the drone delivery in Penela.

This simple cost simulation represents the situation from the aforementioned demonstration in Penela, where an elderly person, Mr Joaquim dos Reis, used to receive his meals by car from "Santa Casa da Misericórdia de Penela", a healthcare institution. In this demonstration, the drone took 6 minutes to deliver the meal and return. Considering that a regular drone battery usually has a voltage of 11.1V and an approximate capacity to store energy of 5200mAh, it allows for a maximum flight time of 40 minutes. Conversely, this battery requires a power of 57,72Wh to recharge fully. According to official statistics, available in the website PORDATA, the cost of electricity in Portugal is around 0,20 euros per KWh. Consequently, the battery costs 0,0115 euros in Portugal to be recharged to its maximum capacity (PORDATA, 2017). Therefore, for a 6-minute flight, the cost is 0,0017 euros in electricity. On the other hand, before the meals started being delivered by drone, it took 30 minutes for a car to make that delivery and return. Considering a cost of 1 euro per kilometre and an average speed of 40 kilometres per hour due to poor roads conditions, it cost 20 euros to make the same delivery by car.

2.4. Farmácia da Lajeosa

This topic provides some context regarding the background and motivations of the customer Farmácia da Lajeosa, a drugstore located in Viseu, since they were the first customer to sign a delivery service contract with Connect Robotics to implement deliveries by drone in their daily operations. Thus, Connect Robotics response to the new regulation barriers will be portrayed, considering the specific conditions entailed by the transportation of medicines. Finally, the arising logistics challenges related to the drones employment in distribution, which are the focus of the dissertation, will be analysed and approaches on how these challenges can be dealt with will be discussed, since Connect Robotics must face them to implement drone deliveries successfully in the customer Fármacia da Lajeosa.

2.4.1. Context and motivation

Back in April 2017, the primary focus of Connect Robotics was the registry of potential clients in the service Drone2.me, along with the creation of partnerships for the implementation of distribution sites, mainly in regions with a low population density. At the time, some demonstrations for big distribution companies in the Portuguese market were already in motion, such as the previously mentioned CTT, the Portuguese Postal Services (Mendes, 2017). Unfortunately, a country-wide distributor like CTT was still reluctant to abandon old practices to adopt such a recent technology with undeveloped regulations. Hence, Connect Robotics made an effort to establish partnerships with smaller distributors. Consequently, in June 2017, the first delivery service contract was signed with Farmácia da Lajeosa, a drugstore in the countryside of Portugal, to deliver medicines.

Farmácia da Lajeosa is located in the District of Viseu; this drugstore mainly serves the population of the parish Lajeosa do Dão, but also some surrounding populations. Data gathered from Instituto Nacional de Estatística (INE), the National Statistical Institute of Portugal, indicated there was a living population in this parish of 1940 inhabitants in 2011. Given that Lajeosa do Dão has an area of 24,31 square kilometres, this corresponds to a population density of around 79,8 individuals per square kilometre. Therefore, it fits the market identified by Connect Robotics for the first steps in the implementation of drone deliveries (INE, 2018). The reasoning behind the interest in drone deliveries is rather ordinary. In fact, Farmácia da Lajeosa brings medicines to five nursing homes every day, since the nursing homes' staff is not able to go to the drugstore to retrieve these medicines. And, even though the daily orders of each one of these homes are variable, they all order medicines regularly and sometimes more than once in the same day. Consequently, Farmácia da Lajeosa has an average of five deliveries per day which they achieve by aggregating some of the orders. However, this is a service that causes some problems in the drugstore's daily operations considering it requires an available vehicle, as well as an employee leaving their station. Moreover, rural road networks do not always enable a fast delivery and, unfortunately, car accidents are not unprecedented either. To sum up, drone deliveries came as a potential answer to these issues. In essence, there would be no need for an employee to leave the pharmacy. Additionally, drones are not affected by road conditions and are overall less costly, as the previous cost simulation demonstrated.

2.4.2. New regulation barriers

However, although the contract was already signed, the operation did not start right away, since the transportation and storage of medicines require authorisation from Infarmed, the National Authority of Medicines and Health Products. Infarmed is a Government agency under the tutelage of the Health Ministry whose principal objective is to guarantee the quality, efficacy, safety and performance of medicines and health products, for ensuring adequate standards and protection of Public Health. Therefore, this new requirement raised a new challenge since the regulations for operating in health segments are stricter than for regular transportation. Furthermore, a relationship was established in the meantime with Fundação Champalimaud, a Portuguese institution that demonstrated an interest in delivering biological samples with drones. These additional circumstances, and an understanding of what was necessary to overcome these new regulatory barriers, lead to the decision of Connect Robotics to deepen their focus on this concern (Infarmed, 2018).

As a result, during the second half of 2017, Connect Robotics' team prepared a container to transport medicines following the requirements and best practices of Infarmed. Subsequently, Connect Robotics' convened with Infarmed to show their container, along with the support documents for its utilisation and maintenance, with the purpose of obtaining the approval for testing the delivery of medical samples for a major clinical analysis laboratory from Porto. Finally, Connect Robotics' team ended 2017 with face-to-face meetings with ANAC. These meetings had the purpose of understanding which improvements should be made in the drone and the supporting documentation to enable the authorisation to fly in the routes needed for their clients.

2.4.3. Logistics challenges introduced by the drones' employment

Despite the issues with regulation, there are still logistics challenges to be tackled in the implementation of a drone-based distribution operation. Planning and managing the day-to-day logistics of an operation using conventional vehicles, such as cars and trucks, is pretty straightforward and there is no need for significant effort in small-scale businesses. Regular folks have been doing it for the last decades. However, the logistics involved in delivering with drones is still uncharted territory and decidedly not common knowledge. As a matter of fact, the employment of drones introduces new restrictions that make the logistics concepts and methodologies commonly applied for transportation in last-mile deliveries unprepared to deal with drone deliveries properly. In this respect, there are three significant constraints on current drone technology:

- **Battery limitations**: drones have a limited battery and, as a consequence, the maximum flight time is of 40 minutes. Furthermore, if there are no substitute batteries, the drones will also be unavailable until their batteries are fully recharged, which takes around 85 minutes (Suzuki, 2012).
- **Low maximum payload**: a drone's payload is a balance between power, size, and weight. It takes into account several factors, like the motor power, the type of battery, the weight of the frame of the drone, the size of the propellers and the number of propellers (Flynt, J., 2017). Considering a regular commercial drone, it can only carry a package with a maximum weight of 3 kilos.
- **Affected by adverse weather conditions**: drones are exposed to weather conditions. High wind speeds, rain or snow, will affect the drone's trip and can even damage the drones' frame and its electronics.

These limitations uncover some logistics challenges derived from delivering with drones, which are depicted in Figure 11.

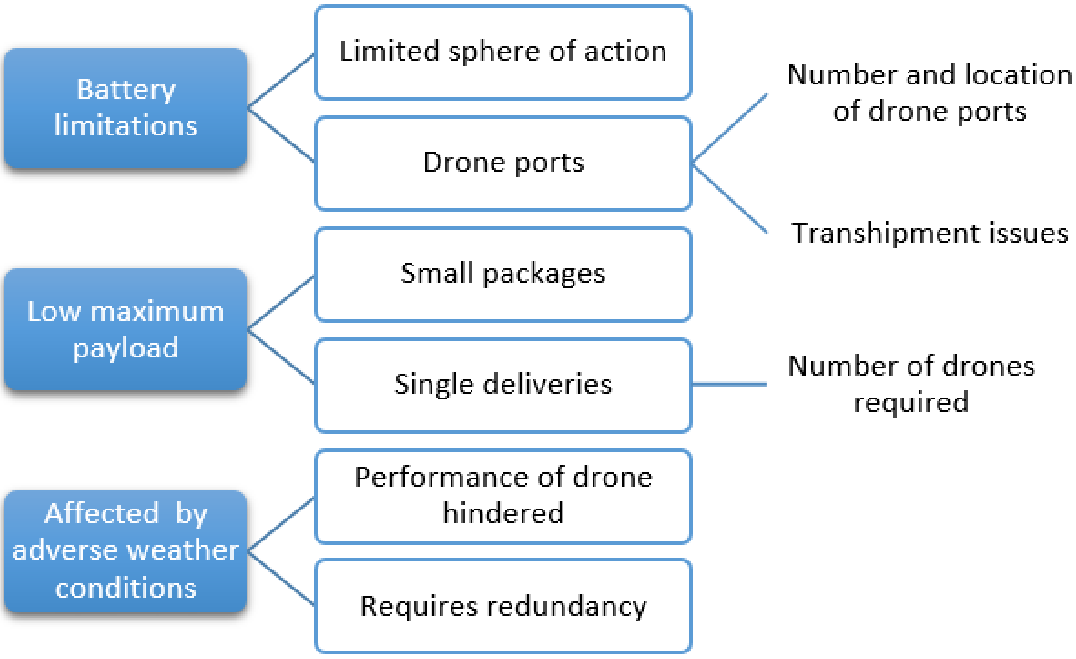


Figure 11 - Logistics challenges introduced by the drones' employment.

Battery limitations affect the area a drone can cover before it has to make the returning trip. Thus, leading to either one of two possibilities: the drones can only be used in a limited sphere of action or a small drone-port must be built as a secondary hub. Therefore, if a distributor must cover an area with multiple recipients more extensive than the sphere of action of a drone, a network of drone-ports must be created to reach all these customers. These drone-ports would serve as landing platforms, where drones could recharge or change batteries. Additionally, these drone-ports not only have to be able to ensure all customers are served but also should be cost-effective concerning their number and location. Thus, potential locations must be tested by computing the most efficient routes that reach all customers. Regarding the need for secondary hubs, there are also different possibilities for how the transhipment would work: recharge the drone, have another drone pick the package or replace the batteries in the drone. Waiting for the drone to fully recharge is time-inefficient, thereby a second drone stationed is a possible solution. However, it could imply a meagre utilisation rate, arguably not justifying the drone's cost. Instead of a drone, there could be substitute batteries allocated at the drone-ports. According to Lee (2017), substituting batteries in the drones can minimise delivery times, since it improves the drones' readiness. Nevertheless, all these possibilities for transhipment are not mutually exclusive. Another concern with transhipment relates to the automation of the process since it may include the detachment and reattachment of packages or the changing of batteries which is not simple to automate. Additionally, maintenance needs must also be considered. Therefore, these drone-ports may require a human operator on site.

Regarding the drone's payload, its current maximum in commercial drones limits the market for drone deliveries to small packages, at least in the current stage of the technology. Moreover, it does not allow deliveries to be aggregated. As a consequence, drones can only make one delivery each time and will not be able to start a new delivery until return. This situation leads to another issue: the number of drones required for each client; this must consider not only cost but also service levels.

Finally, drones are particularly affected by adverse weather conditions due to their relatively low power and exposed structure. Consequently, if the weather is not favourable, the drone's performance might be hindered. For example, the drone will require more power to counter an unfavourable wind. In the worst-case scenario, the drone might not be able to make the delivery. In fact, in the case of Connect Robotics' drones, they will not even take off if certain weather conditions are met. Moreover, that is not a very unlikely scenario since the drones cannot fly under rain or snow, for example. Therefore, a distribution operation cannot rely solely on drones. The delivery operations require some redundancy, with alternatives in place to substitute drones.

2.5. Chapter conclusions

The current chapter's purpose was to provide a context to the problem under study, regarding the drones' environment, the company Connect Robotics, the customer Farmácia da Lajeosa and the logistics challenges related to a new distribution paradigm: the delivery of packages with drones.

All things considered, it is apparent this paradigm requires a careful examination, given how the drones' unique characteristics add new constraints that create different logistics challenges. These challenges diverge significantly from common logistics problems and the existing methodologies that currently handle these problems. Moreover, every potential client of Connect Robotics will have distinct needs concerning routes and drone fleet requirements, which concerns the number of batteries and the number of drones. Eventually drone-ports may also be a part of the solution. Additionally, the distribution would be handled by drones alongside other road vehicles, since transportation needs cannot rely solely on drones. Therefore, it was possible to conclude that Connect Robotics, and more specifically Farmácia da Lajeosa, would benefit from an optimisation models for decision support that is capable of aiding in the implementation of drone deliveries.

The goal of this model would be to study the financial viability of drones and the potential time savings in the situation presented by Connect Robotics and Farmácia da Lajeosa by utilising historical demand data, customers locations, as well as estimate the transportation costs and times. The model would consider the existence of two possible transportation modes: car and drone. Furthermore, it would also provide the most cost-efficient routes in single delivery operations where a set of customers must be served.

3. Literature review

Given the new distribution paradigm and challenges derived from the delivery of packages by drone, it is necessary to discuss existing literature regarding concepts and methodologies related to the transportation industry and the drone's role in delivery. Therefore, recent trends will be analysed to understand how the industry has been evolving and how drones are positioned regarding the future of transportation. Finally, some scientific contributions related to drones and deliveries will be analysed, since they could provide insights on how to deal with the case presented in the previous chapter.

3.1. Trends shaping the transportation industry

To understand the evolution of the industry and the potential role of drones in the future of transportation, the recent trends in this industry are discussed, starting from the technologies driving that change and followed by the current trends in transportation and logistics. Finally, the focus will be on the trends that concern the last-mile delivery, which was identified as Connect Robotics' market for drone deliveries.

3.1.1. New technologies as drivers of innovation

Nowadays, the transportation industry is changing, and the key drivers of innovation are the new technologies. Hence, being a technology-driven innovation. This change is noticeable through the investments being made in transportation businesses that offer new options for either short and long distances. Therefore, six technologies that are contributing to innovation in the transportation industry will be discussed. These technologies are represented in Figure 12.

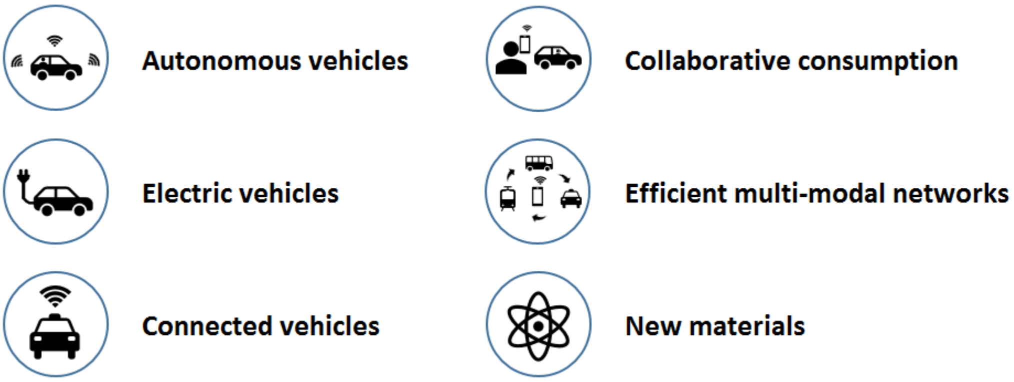


Figure 12 - Technologies driving innovation in the transportation industry. Adapted from Speranza (2018).

Autonomous vehicles: they are a reality and UAVs are but one example. There are also smaller vehicles like droids designed for delivery (Perry, 2016) or even larger autonomous ground vehicles (Joerss et al., 2016). Moreover, cars with hands-free technology have already been announced (Koetsier, 2017) and there are also companies researching on autonomous boats (Lindeman, 2018). In fact, fully autonomous vehicles have significant benefits. For instance, on-demand services and deliveries would be more common, fuel efficiency would improve, traffic congestion and the number of parking spaces needed would be reduced, elderly people would gain a once lost mobility and people's safety would increase (Porter et al., 2015). Consequently, these vehicles would lead to higher travelling comfort at lower prices and a leap in accessibility (Meyer, 2017).

Electric vehicles: although it is not exactly a new technology, the reliability of electric vehicles is increasing due to these vehicles ability to travel longer without recharging, as exemplified by Tesla's electric trucks range of 800 kilometres (Tung, 2017). Furthermore, the cost of electric vehicles is also decreasing, and electric vehicles are already cost-competitive with fuel-driven vehicles (Weldon et al., 2018). In fact, the investments in battery technology will continue to reduce the cost of electric batteries (Berckmans et al., 2017). Regarding drones, lithium batteries are rapidly improving which will allow drones to fly further on a charge (D'Andrea, 2014). In the future, low-carbon electricity will continue to get more economical, whereas fossil fuels will get costlier. Therefore, it is only natural that the utilisation of electric vehicles for transportation will continue to increase.

Connected vehicles: nowadays, vehicles are equipped with internet connectivity. The telecommunications company AT&T that provides internet wirelessly in the U.S. added in the third quarter of 2014 to their network 500 thousand car subscribers. This number of subscriptions was higher than the new smartphone subscribers, with 466 thousand, and tablet subscribers, with 342 thousand. By the second quarter of 2016, AT&T claimed they had around 9,4 million car subscribers connected in 200 countries and territories. At the end of 2017, these numbers almost doubled with 17,8 million car subscribers around the world (AT&T, 2018). The company's data plans connect the cars to the network, delivers traffic data to the navigation system and allows for software updates to the vehicle, as well as internet connectivity to the passengers. Therefore, vehicles are connected between them and with infrastructures, allowing for the reduction of traffic congestion and car accidents. Moreover, they enable car manufacturers to develop features for predicting and preventing maintenance needs. Another benefit of the connectivity can be observed in commercial vehicle fleets. Companies can use location and vehicles data to manage the vehicles, make efficient routes and also plan for vehicle purchases (Jadaan et al., 2017).

Collaborative Consumption: on-demand collaborative options for transportation are currently being offered by companies such as Uber, GrabTaxi, BlaBlaCar, Lyft and Zipcar. Even though the majority of people owns a private vehicle, which remains the dominant mode of transportation, these new alternatives are now being preferred by several young consumers, that end up delaying the acquisition of a car and even of the driver's license (Speranza, 2018). These services allow for passengers to not worry about purchasing the vehicle, navigating traffic, getting speeding tickets, parking, putting fuel and paying for the car insurance. In fact, according to Clewlow and Mishra (2017), the main reason for adopting car-sharing services seems to be parking.

Efficient multi-modal networks: at first companies like BMW, and its ConnectedDrive services, incorporated real-time traffic information to calculate the fastest routes (Adcock, 2011). Then, country-wide route planners for public transportation were developed. One example is the 9292 service in the Netherlands that determines the routes according to the users' preferences. Through the service's website or mobile application, multiple efficient trip alternatives are automatically suggested, which use and combine different public transportation modes (McAllister, 2017). Now, several companies are also trying to create efficient intermodal networks that integrate cars and ride-hailing services. By crowdsourcing transit data, car-sharing services and other public transportation modes will also adapt to the passenger's needs. Furthermore, the prices for all the transportation options will be automatically calculated, and ticketing will be conveniently available through smartphones (Porter et al., 2015)**.**

New materials: manufacturers are nowadays motivated to reduce vehicle’s weight to achieve fuel efficiency standards, reduce the battery size required in electric vehicles and extend their range. Hence, higher demand for lightweights and the employment of new materials. This demand was accompanied by a cost decrease of carbon fibre car parts over the years. In fact, BMW’s first electric vehicle was produced with plastic-reinforced carbon fibre (Peterson, 2013). Moreover, 3D printing is also one of the new trends in automotive manufacturing technologies. This technology can potentially increase the performance of vehicles, reduce their weight and change how they are designed and assembled (Sevcik, 2018)

Bringing together these trending technologies will produce autonomous fleets of shared electric vehicles that are connected between them, to the internet, to the road infrastructure and also to a network of public transportation options. In this perspective, drones take advantage of at least three of these technologies, since they are autonomous, electric and connected. Meanwhile, the introduction of new and lighter materials could enhance the drones’ performance. A lighter drone could travel faster, longer and carry more extra weight, i.e. increase the payload limit.

3.1.2. Current trends in transportation and logistics

Other than drones, more trends are shaping this industry. Therefore, five relevant trends that may drive a shift in the landscape of the transportation and logistics industry will be discussed. These trends were identified by the Business Insider Intelligence (2017) and are represented in Figure 13.

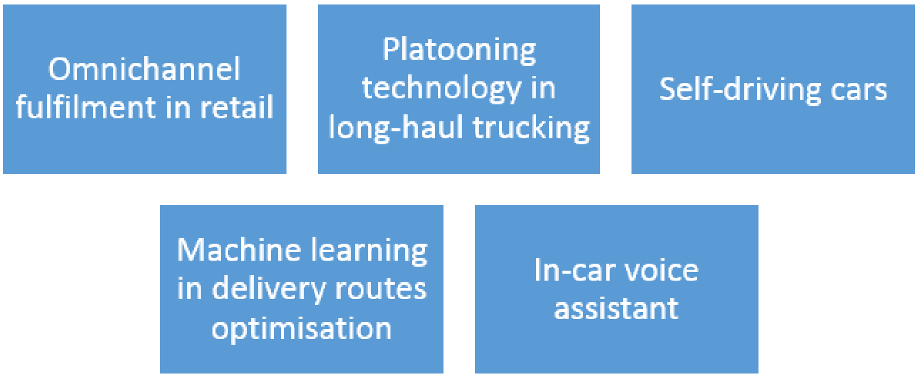


Figure 13 – Five disruptive trends in transportation.

Omnichannel fulfilment in retail: recently, Amazon acquired Whole Foods, a supermarket chain. Whole Foods’ store network provided Amazon hundreds of locations to execute deliveries on-demand (Thompson, 2017). By getting closer to its customers, Amazon will be able to offer same-day deliveries and even deliveries within one or two hours to more customers. In fact, Amazon has already announced a two-hour delivery service for Whole Foods groceries (Kharpal, 2018). Therefore, Amazon’s competitors will be pressured to improve their delivery times and accelerate omnichannel fulfilment strategies. For example, the retailer Target announced recently the acquisition of Grand Junction to improve their local delivery capabilities and expedite their efforts to transform the supply chain. Grand

Junction is a transportation technology company with a network of more than 700 carriers. Their integrated software platform allows retailers, distributors and third-party logistics providers to offer local deliveries (Target, 2017). Another competitor, Walmart, expanded their services to include new in-store pickup options (Rushing, 2018).

Platooning technology in long-haul trucking: truck platooning is the linking of trucks in convoy. Platooning trucks face less wind resistance hence reducing the fuel consumption, which is the most significant cost for trucking fleets. In fact, several truck manufacturers have the technology to allow platooning (Bhoopalam et al., 2018). Furthermore, automated platooning software has been developed by Peloton to allow for multiple trucks to autonomously follow each other (Peloton Technology, 2016). Regarding the technologies' differences across diverse truck brands, the European ENSEMBLE consortium is currently planning to implement multi-brand truck platooning in Europe to ensure safe platooning when using trucks of various brands. For this endeavour contributed six truck manufacturers: Volvo Group, MAN, Daimler, DAF, Iveco and Scania (Volvo Group, 2018). Hence, considering the improved fuel efficiency, the demand for this technology by commercial long-haul trucking is expected to increase in the next years.

Self-driving cars: Tesla already stated their intent to offer full self-driving cars at a future time. As a matter of fact, the cars being manufactured by Tesla nowadays are equipped with an advanced driver-assistance system named Enhanced Autopilot. This system includes features like lane centring, adaptive cruise control, self-parking, ability to automatically change lanes without requiring the driver to steer, and finally the ability to summon the car to and from a garage or parking spot. To sum up, these cars are already capable of attaining full self-driving, it is just not an available feature yet (Tesla, 2018). However, Tesla is not alone in the race for achieving self-driving car technology. There are other major companies, like Apple, Uber and Waymo, developing this technology (Fortune, 2018). In 2016, Tesla acknowledged that, besides the technical challenges, there are legal and regulatory barriers to be overcome first (The Verge, 2016). Nevertheless, Tesla expects that their 'Fully Self-Driving Capability' can be demonstrated in 2018 and possibly released as well (Lambert, 2018). Regarding the legal and regulatory hurdles, there has been some progress in the United States. Self-driving car legislation has been introduced since legislators acknowledged the importance of addressing this issue quickly. However, due to the testing required, the National Highway Traffic and Safety Administration (NHTSA) will take a few years to release self-driving car regulations. Still, several states already drafted state regulations for self-driving cars, which allowed the companies developing this technology to start acquiring permits to test self-driving cars. Consequently, there is already a significant amount of self-driving cars on the streets (Fortune, 2018).

Machine learning in delivery routes optimisation: logistics companies rely on route optimisation to make deliveries efficiently. Considering the trend for on-demand deliveries, these companies are now required to generate optimised routes faster to improve their speed and fuel consumption. Therefore, machine learning technologies can enable the aggregation and analysis of not only real-time data, like weather, traffic and construction delays, but also historical data regarding demand for deliveries and pick-ups (Zimberoff, 2018). Nowadays, several companies already started to implement machine learning in their route optimisation for deliveries, since it allows for quicker on-demand routing that reduces operational costs. For example, the package delivery company UPS has been developing the fleet management system ORION which includes a route optimisation algorithm that resorts to machine learning to generate efficient paths on-road for its delivery trucks (Samuels, 2017).

In-car voice assistant: connected cars access to internet facilitated the introduction of services such as Google's Android Auto and Apple's CarPlay that enabled voice as an interface for apps with Google Assistant and Siri, respectively (Greenough, 2015). To further this trend, the car manufacturer Ford has already implemented Amazon's Alexa assistant, another competitor of Google and Apple, in their most recent models (Hawkins, 2017). Nevertheless, the utilisation of voice assistants is still rather low, and drivers prefer to interact with apps through touch. Therefore, these companies are working on improving the experience of consumers with voice assistant technology on other fronts first, like smartphones and home speakers (Gibbs, 2018). Consequently, by providing these voice assistants with a more significant role and getting users more comfortable with them, it will also translate to increased utilisation on cars.

Regarding the employment of drones in transportation and logistics, it was possible to verify that none of these trends represents a direct alternative to drone deliveries. In fact, potential synergies can be identified. For example, drone deliveries can be a useful asset for achieving omnichannel fulfilment in retail. Moreover, Amazon has already patented a speech interacting technology for drones, which can lead to drones equipped with Alexa (Nickelsburg, 2017).

3.1.3. The future of last-mile parcel deliveries

Until today, parcel deliveries were performed by dedicated employees, usually driving delivery vehicles such as large vans, that would pick up the parcels at a consolidation point and deliver them directly to the recipients. However, different models are now being introduced to deliver parcels in the last-mile, and one of them is drone deliveries. In fact, the research performed by Joerss et al. (2016) lead to six operational models that diverge from the traditional model. These delivery models are depicted in Figure 14 and will be characterised further in the following paragraphs.

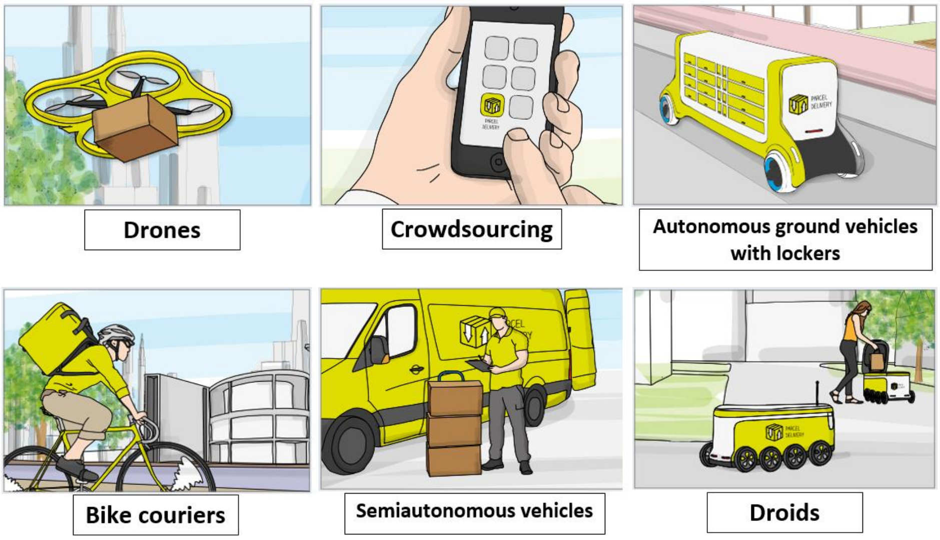
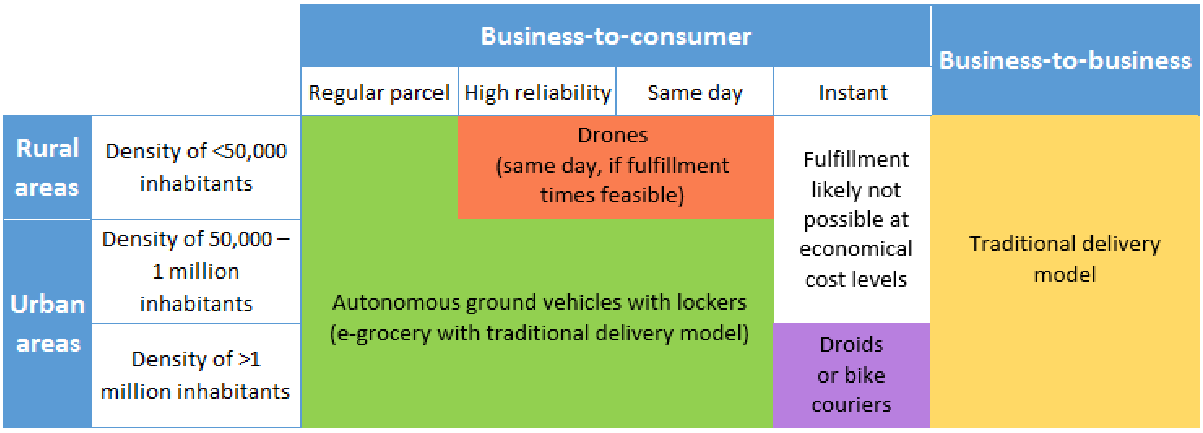


Figure 14 - Delivery models for last-mile deliveries. Adapted from Joerss et al. (2016)

- **Drones**: these unmanned vehicles are equipped to deliver small packages autonomously to a chosen destination along the most direct route and at a reasonable speed.
- **Crowdsourcing**: a courier service that matches registered drivers with delivery orders through an online network, enabling same-day deliveries with high flexibility and low investment by the delivery companies.
- **Autonomous ground vehicles (AGV) with lockers**: an AGV can deliver multiple parcels in the same route without the need for a human carrier. Upon notification that the AGV has arrived, the clients can go and pick their parcel from a locker.
- **Bike couriers**: reliable for short distances in areas with a considerable population density, due to their ability to avoid traffic congestion easily, bike couriers can deliver a small number of parcels.
- **Semiautonomous vehicles**: the incoming self-driving vehicles offer a more time-efficient alternative to the traditional model by liberating the delivery person for other tasks, like sorting the parcels or expedite administrative tasks, during the driving time.
- **Droids**: for delivering to the doorstep, this autonomous vehicle can offer a solution that does not require much supervision. Although, they move at only 5 to 10 kilometres per hour and can only carry one package at a time.

Nevertheless, consumers are who will ultimately dictate the success of these different models. In that regard, consumers' demand for faster home deliveries is growing, although the price remains as a decisive criterion. Customers' general preferences for delivery fall into four categories: regular parcel, high reliability (e.g. time window), same-day and instant delivery. Hence, to understand the suitability of each delivery model for a given category, there needs to be a balance between the cost efficiency and the performance of the model chosen for the delivery. Moreover, the cost efficiency of any given option also changes according to the population density. Therefore, it is expected that last-mile parcel deliveries will be executed through the delivery models in Figure 15, according to consumers' preferences and population density.



		Business-to-consumer				Business-to-business
		Regular parcel	High reliability	Same day	Instant	
Rural areas	Density of <50,000 inhabitants	Autonomous ground vehicles with lockers (e-grocery with traditional delivery model)	Drones (same day, if fulfillment times feasible)		Fulfillment likely not possible at economical cost levels	Traditional delivery model
Urban areas	Density of 50,000 – 1 million inhabitants		Autonomous ground vehicles with lockers (e-grocery with traditional delivery model)			
	Density of >1 million inhabitants				Droids or bike couriers	

Figure 15 – Last-mile deliveries future according to population density. Adapted from Joerss et al. (2016).

As illustrated in Figure 15, AGVs with parcel lockers will substitute current forms of delivery in urban areas, being capable of same-day and time-window deliveries, and also in rural areas for regular parcels. However, traditional delivery will still be preferred for business-to-business (B2B) and e-grocery due to their higher volume capacity. Meanwhile, droids and bike couriers can both offer instant deliveries in areas densely populated. Droids' dominance over bike couriers will depend on how its technology and costs evolve. Regarding crowdsourcing, it is likely to only play a minor role in the delivery of parcels and the recent shut down of Uber's crowdsourcing delivery service, the UberRush, points in that direction (McKay, 2018). Finally, drones will be adopted for high reliability and same-day parcel deliveries in rural areas. Given that drone deliveries are the focus this dissertation, the reasoning behind this vision will be the topic of the following paragraphs.

According to Joerss et al. (2016), drones have two disadvantages. The first is the maximum payload. Even considering a raise in the payload limit to 15 kilos, a drone delivery operator would still require an alternative model to deliver the remaining items. The second is the area required for landing since current drones have significant size. In fact, even small drones are difficult to land in tight urban areas. However, by delivering small parcels in rural areas, both these disadvantages are diminished. Moreover, delivering in rural areas within a specific time-window, or even in the same day, with other delivery models can be quite expensive due to the vast distances that have to be covered. Hence, drone delivery might as well be the only cost efficient or even feasible alternative to offer remote recipients high reliability and same-day deliveries. Regarding economic feasibility, the estimation of same-day deliveries in rural areas is of 500 million parcels in Germany in 2025, which is a significant market segment with no access to this delivery service otherwise (Joerss et al., 2016).

Nevertheless, the rate at which drone delivery is implemented will still vary according to factors like technology, regulation and public acceptance (Anbarolu, 2017). For example, it is expected an earlier adoption of autonomous delivery models in developed countries compared to developing countries, considering how the return on investment will be more significant due to the higher labour costs. Concerning the regulation for autonomous vehicles in general, the pressure from car manufacturers is helping in overcoming these challenges and regulation is being drafted at a steady pace in the United States (Fortune, 2018). Meanwhile, drone deliveries have already been approved officially in eastern China (Quartz, 2018) and the U.S. recently announced the UAV Integration Pilot Program to test drones across the country aiming to integrate drones in the airspace and accelerate their acceptance for commercial use (Dellinger, 2018). Regarding the public opinion, it has already started to shift around the globe, with a majority of consumers in favour of drone deliveries, or at least not against them (Joerss et al., 2016).

3.2. Drone delivery problems

The acknowledgement of the potential advantages of employing drones in transportation have already generated considerable research efforts focused on the strategic and operational challenges associated with drones. Therefore, the following paragraphs will describe the contributions of several authors for delivery problems involving drones. Furthermore, some additional work, not directly related to drones, will also be explored given how it deals with similar challenges to the ones presented in deliveries by drone.

3.2.1. Different approaches to delivering problems with drones

Most of these studies explore variants of the travelling salesman problem (TSP) and the vehicle routing problem (VRP), which is a generalisation of the TSP that considers a fleet of vehicles. The generic definitions and models of the VRP and its extensions were covered by Toth and Vigo (2002). However, they cannot be applied directly to drone deliveries. Hence, the following authors developed new models to address situations where drones are employed in transportation.

The authors Murray and Chu (2015) presented two problems for delivering with drones, where the drones work in collaboration with a traditional vehicle. The first problem, portrayed in Figure 16 (on the left), is the flying sidekick travelling salesman problem (FSTSP), where a drone is allocated to a truck to deliver parcels to customers. The truck follows a route, that starts at a depot, serves customers along the route and finishes at the depot. Meanwhile, at each customer, the drone may be dispatched to make a delivery to another customer, returning to the truck at a following customer. All the customers must be served by either the truck or the drone. Note that, in the example below the customers are numbered from 1 to 9. Additionally, the customers 2 and 9 were considered ineligible to be served via drone, hence they were coloured red and represented in a circle.

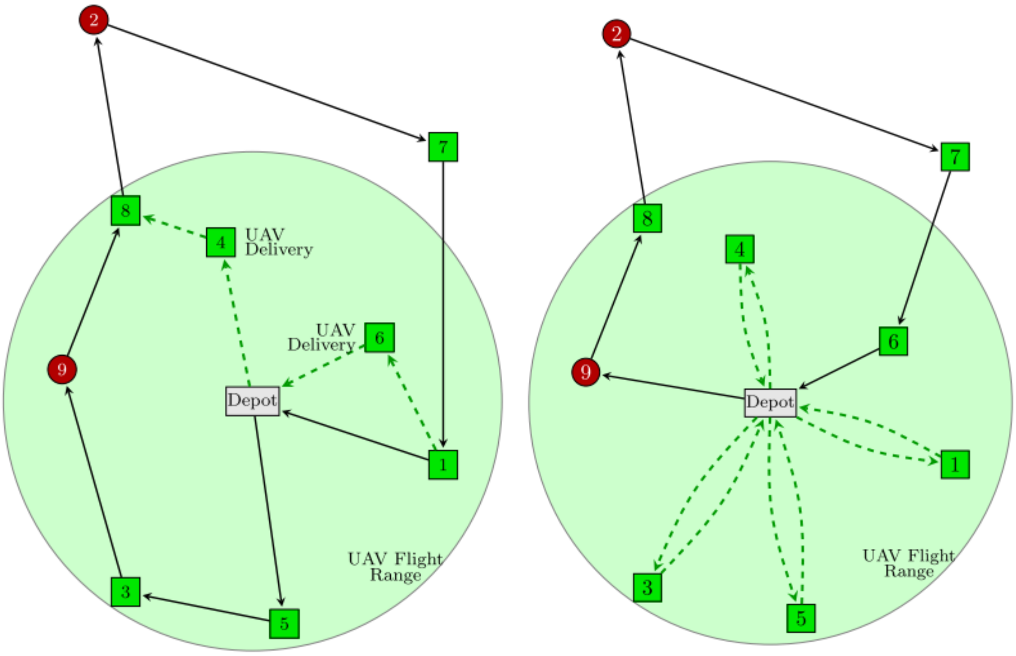


Figure 16 – Two optimal solutions for the same delivery problem: FSTSP solution (left) and PDSTSP (right). Retrieved from Murray and Chu (2015).

The second problem, also represented in Figure 16 (on the right), is the parallel drone scheduling traveling salesman problem (PDSTSP). Contrarily to the situation in the FSTSP, this problem considers that the drone(s) and the truck perform deliveries independently. Hence, some customers will be served by the drone directly, while the remaining customers will be served by the truck along its route. For both problems, a mixed integer linear programming (MILP) formulation was presented, which minimises the time required to serve all the customers. Furthermore, two heuristic approaches were proposed for solving problems with a practical size since MILP solvers required several hours to solve the formulation for problems with only ten customers. Regarding the FSTSP, the heuristic proposed creates a route for the truck first by solving a TSP where the truck visits all the customers. Then, it starts an iterative procedure to reassign customers to the drone. In each iteration of this procedure, the time savings gained from removing each customer individually from the truck's route are calculated and the modification with the maximum savings is implemented. This procedure stops when there are no more improving moves. For the PDSTSP, the heuristic assumes that the drones will serve all the customers within their maximum range and the truck will serve the remaining customers, dividing the customers into two sets. The set of customers served by the drones are then scheduled by minimising the makespan of a parallel machine scheduling (PMS) problem, where each customer represents a "job" and the "processing time" is given by the flight time required to serve the customer and return. In the next step of the procedure, the set of customers served by the truck are sequenced with a TSP and the time required for the truck to complete its route is considered the "makespan" of the truck. Finally, if the makespan of the drone is longer, the makespans of both the drones and the truck are balanced by moving customers to the truck's set. To find the customer to move, a local search is performed and the customer whose move represents the greatest savings in the overall makespan is chosen. If there are no improving moves or the truck's makespan is determining the overall makespan, a swap of customers between sets is considered and all possible exchanges are locally searched. The swap with greatest savings is performed and the process is repeated until no improving moves are possible. Meanwhile, in his dissertation, Ponza (2016) proposes an improved model formulation for the FSTSP. Moreover, he presented a heuristic approach based on the simulated annealing (SA) metaheuristic for solving the problem. Later, Freitas and Penna (2018) also explored the FSTSP and developed a hybrid heuristic to obtain a solution for the problem. First, a initial solution is generated by creating an optimal TSP route, then a general variable neighbourhood search (GVNS) creates routes for the drones. Ferrandez et al. (2016) suggests a variation of the FSTSP where the truck carries multiple drones. In this scenario, the truck follows a route and at each stop it launches drones to perform deliveries. The objective is to determine the location and number of stops along the truck's route that minimise time. To generate a solution for this problem, the author proposes a procedure based on the genetic algorithm (GA) metaheuristic to calculate the TSP for the truck's route and a K-means clustering to determine the truck's stops.

Agatz et al. (2015) introduced a similar problem to the FSTSP, referred to as the traveling salesman problem with drone (TSP-D). One of the differences is the possibility for the drone to return to the truck, after making a delivery, at a later customer or the depot, instead of mandatorily returning at a following customer. Furthermore, the truck can visit the same customer location twice, allowing for the deployment or return of the drone in the second visit. The problem was modelled as a MILP formulation, which minimises the time required to serve all customers, and developed a heuristic for solving the problem that, similarly to the solutions proposed by Murray and Chu (2015), is also divided into truck and drone. First, a TSP route for the truck is found, where the truck visits all customers. Since an optimal TSP will not necessarily generate the optimal TSP-D, a faster alternative to the optimal TSP is the Kruskal's minimum spanning tree (MST). Then, a TSP-D route, where some of the customers in the truck's route are reassigned to the drone, is built from this TSP. Two approaches were proposed for generating the TSP-D: the greedy partitioning heuristic, that obtains a fast solution with local search, and the exact partitioning heuristic, which is based on dynamic programming. Later, Bouman et al. (2017) presented an exact approach based on dynamic programming for solving the TSP-D with larger instances.

Ha et al. (2015) presented a new variant of Murray and Chu's FSTSP problem under the name TSP-D. Even though this problem shares the same name as the previous problem, it's important to notice that this problem is not the same problem as the TSP-D proposed by Agatz et al. (2015). In this TSP-D a drone can be launched from either the depot, if a customer is within range, or the truck. After making the delivery, the drone may return to the depot or to the truck at the next customer. To solve the problem, two heuristic approaches are proposed: cluster first - route second and route first - cluster second. The difference between the two heuristics is the order in which the steps, cluster and route, are performed. The cluster step finds the drone routes and to solve it a MILP was introduced. Meanwhile, the route step, which generates the truck route, is solved by a TSP. In the heuristic cluster first - route second, the cluster step finds the drone routes and then, given these fixed clusters, the route step constructs the truck route. On the other hand, in the route first - cluster second heuristic, the route step generates an initial truck-only route by solving a TSP and then, in the cluster step, that route is rearranged to include drone routes. In a subsequent paper, Ha et al. (2017) formulated another variant of the problem, the min-cost TSP-D. The objective is to minimise the operational costs of both drone and truck. Two algorithms were proposed to solve the min-cost TSP-D: the TSP-LS, based on the solution approach from Murray and Chu (2015), and the Greedy Randomized Adaptive Search Procedure (GRASP), which contains a split procedure and local search.

Mathew et al. (2015) formulated a problem slightly different than the FSTSP and the TSP-D, the heterogeneous delivery problem (HDP). This problem characterises a situation where the truck does not make deliveries directly. Instead, the truck transports the drone to locations where customers are within the drone's flight range. From these locations, the drone is launched to perform a delivery and returns to the truck, which remains in the same location. The problem's objective is to find the routes for both vehicles that minimises cost. Their proposed solution is to reduce the HDP to a generalised travelling salesman problem (GTSP) which enables the application of existing solvers. Furthermore, a variant for the HDP is also defined, the multiple warehouse delivery problem (MWDP), which only considers drones and warehouses. The truck is replaced by static warehouses from where a drone is launched and must return to after each delivery. At the end of the route, the drone must return to the depot. The warehouses' locations are already defined, and the problem attempts to find the most cost-efficient drone route. To solve this problem the HDP solution above can be used, but the authors also suggest a simplified transformation algorithm from MWDP into TSP and an exact algorithm able to solve problems with few warehouses, the Kernel Sequence Enumeration (KSE) algorithm.

Wang et al. (2017) described a general problem named vehicle routing problem with drones (VRPD), which considers a fleet of trucks equipped with drones. Both vehicles can deliver the packages and the trucks must wait for the drone when it has been deployed for a delivery. The objective is to serve all customers in the minimum time. The problem notations are defined by the authors and can be considered a variation of the distance-constrained capacitated vehicle routing problem (DCVRP) with heterogeneous vehicles, according to the classification of Toth and Vigo (2002). Consequently, an analysis of worst-case scenarios is performed to study the potential of employing trucks equipped with drones. Poikonen et al. (2017) reviewed and extended these models. Two of the improvements were to consider battery limitations and cost minimisation. Later, Schermer et al. (2018) developed two heuristics for solving the VRPD with large instances. First, a two-phase heuristic (TPH) that initially creates the VRP for the truck and then inserts drones. Then, a single-phase heuristic, which computes routes that already include drones.

Dorling et al. (2017) introduced the drone delivery problem (DDP), which represents a scenario with several delivery drones where each drone can make multiple trips. The DDP is formulated as a multiple trips vehicle routing problem (MTVRP), and two MILP models are proposed to solve the DDP for different objectives: the minimum cost drone delivery problem (MC-DDP) and the minimum time drone delivery problem (MT-DDP). These models generate an optimal number of drones in the fleet, as well as the routes for each customer by considering the drones reutilisation and their energy consumption, which is computed as a function of battery and payload weight. Furthermore, an algorithm based on the SA metaheuristic is proposed to solve practical scenarios with a large number of locations.

Scott and Scott (2017) considered a facility location problem (FLP) where a remote area is not served by good roads and is too far for drone deliveries. The solution is a drone port to be installed in that area. Therefore, a truck transports packages from a warehouse to this location and then a drone delivers to the final destination. In this situation, a decision is required regarding the position of both the warehouse and the drone port. Consequently, the problem was modelled for two different objectives. The first model minimises the total delivery time with a budget constraint. The second model minimises the maximum delivery time, also subject to a budget, to balance delivery times between packages. Furthermore, the models are solved with the software MINOS, a solver for optimisation problems.

Hong et al. (2017) explored another FLP for a delivery service with drones in an urban environment, where a network of recharging stations supports the fleet of drones. Therefore, a distance-restricted maximal coverage location model was formulated to construct a feasible network that covers the whole area, by finding the locations for the recharging stations, while computing the routes for the drones. This model was solved with a heuristic approach that combined the SA metaheuristic with a greedy algorithm.

Jiang et al. (2017) presented a problem where a fleet of drones makes deliveries to customers with time-window constraints. Therefore, a MILP was developed by adapting the vehicle routing problem with time windows (VRPTW) to drone deliveries. The authors propose their modified version of the particle swarm optimisation algorithm to achieve a solution for the drone routing and assignment of customers.

Kim et al. (2017) study a delivery service with drones in rural areas since there are customers that must visit health facilities regularly for routine health examinations or to refill medicine. Therefore, a fleet of drones would make pick-ups and deliveries of medicine and test kits. To approach this situation, two distinct models are proposed that combine provided locations for the drone ports, the number of drones and their routes. The first model is an FLP that finds the locations of drone ports with a set covering approach to ensure all customers are served. The second model is an adapted multi-depot vehicle routing problem (MDVRP) that determines the number of drones assigned to each drone port that minimises the drones operating costs. Moreover, the authors also develop a preprocessing algorithm, a partition method and a lagrangian relaxation method to improve computational performance.

Carlsson and Song (2017) explored the advantages of drones working in collaboration with trucks to make deliveries. As an intermodal instance of the VRP, the horsefly routing problem was defined. Moreover, analytical formulas for the expected delivery cost and time were derived with continuous approximation models that assumed customers were evenly distributed across the serviced area. Later, Campbell et al. (2017) developed mathematical expressions for the problem with continuous approximation modelling techniques. Furthermore, their models provided insights regarding the benefits of employing trucks equipped with drones in delivery instead of only trucks.

Luo et al. (2017) introduced the two-echelon ground vehicle and unmanned aerial vehicle cooperated routing problem (2E-GU-RP), which is similar to the FSTSP variant purposed by Ferrandez et al. (2016). Similarly to that scenario, the truck does not deliver directly to customers. Instead, it makes strategic stops to deploy the drone to make the deliveries. The MILP model of the 2E-GU-RP was formulated and two heuristics, based on the GA metaheuristic, were developed to provide feasible solutions. The first heuristic generates routes to all customers and then splits it by truck routes. Then, the second heuristic assigns the drones to each customer.

Daknama and Kraus (2017) formulated another problem where trucks carry a drone for deliveries, which was named, the vehicle routing with drones (VRD). Even though this problem has a similar name to the VRPD introduced by Wang et al. (2017), it is a different approach on drone deliveries. In this scenario, both vehicles perform deliveries, but the drone must always return to the truck after each delivery. A heuristic based on local search is provided to obtain schedules for the trucks and the drones.

Ulmer and Thomas (2017) presented the same-day delivery routing problems with heterogeneous fleets (SDDPHF), where drones and trucks make deliveries independently, and the demand is not known beforehand. The parametric policy function approximation, which is an approximate dynamic programming approach, is proposed to decide which vehicles make the incoming deliveries.

A different scenario is introduced by Dayarian et al. (2017) with trucks making the same-day deliveries, while drones resupply them in real-time. The problem was called the vehicle routing problem with drone resupply (VRPDR). Some algorithms were developed to obtain solutions, which include a VRPTW for generating the truck’s route.

Yu et al. (2017) studied a route planning of drones that considered the possibility of installing stationary or mobile recharging stations. These mobile recharging stations are small unmanned ground vehicles (UGV) that continue travelling while the drone recharges. Three scenarios were considered: multiple stationary stations, a single mobile station or multiple mobile stations. A problem formulation is presented to compute the route for the drone. Moreover, it also determines the UGVs routes or the location to place stationary recharging stations. An algorithm based on the GTSP was proposed to solve the two first scenarios and an algorithm based on integer linear programming for the third.

Shavarani et al. (2017) studied an FLP for a drone delivery service. To support a fleet of drones, the instalment of launch and recharge stations is required. Therefore, the problem was formulated to identify these locations with the objective of minimising the total cost of the system. Two heuristic algorithms were proposed to solve the problem based on the GA metaheuristic, including a hybrid GA and local search.

Pugliese and Guerriero (2017) proposed a variant of the VRPTW, where trucks carry drones, and both vehicles perform last-mile deliveries. However, unlike similar problems involving the collaboration of trucks and drones, the customers must be served within specific time-windows. Therefore, the problem was named vehicle drone routing problem with time windows (VDRPTW). An integer programming formulation that minimised the transportation cost was proposed and solved with optimisation solvers.

Finally, these authors and their contributions to drone delivery problems are summarised in Table 3. Additionally, the present work was also introduced in the table for comparison.

Table 3 - Summary of authors and contributions for delivery problems with drones

Authors	**Problem**	**Drones**	**Other vehicles**	**Vehicles synchronised**	**Mathematical formulation**	**Solution approach**	**Real application**
Murray and Chu (2015)	FSTSP	1 drone	1 truck	Yes	Yes	Yes	No
	PDSTSP	Several drones	1 truck	No	Yes	Yes	No
Ponza (2016)	FSTSP	1 drone	1 truck	Yes	Yes	Yes	No
Freitas and Penna (2018)	FSTSP	1 drone	1 truck	Yes	No	Yes	No
Ferrandez et al. (2016)	FSTSP variant	Several drones	1 truck	Yes	No	Yes	No
Agatz et al. (2015)	TSP-D	1 drone	1 truck	Yes	Yes	Yes	No
Bouman et al. (2017)	TSP-D	1 drone	1 truck	Yes	No	Yes	No
Ha et al. (2015)	TSP-D (based on FSTSP)	1 drone	1 truck	Yes	Yes	Yes	No
Ha et al. (2017)	min-cost TSP-D (based on FSTSP)	1 drone	1 truck	Yes	Yes	Yes	No
Mathew et al. (2015)	HDP	1 drone	1 vehicle	Yes	No	Yes	No
	MWDP (variant of the HDP)	1 drone	-	No	No	Yes	No
Wang et al. (2017)	VRPD	Several drones	Several trucks	Yes	No	No	No
Poikonen et al. (2017)	VRPD	Several drones	Several trucks	Yes	No	No	No
Schermer et al. (2018)	VRPD	Several drones	Several trucks	Yes	No	Yes	No
Dorling et al. (2017)	DDP (adapted MTVRP)	Several drones	-	No	Yes	Yes	No
Scott and Scott (2017)	FLP	Several drones	1 truck	No	Yes	Yes	No
Hong et al. (2017)	FLP	Several drones	-	No	Yes	Yes	Yes
Jiang et al. (2017)	VRPTW variant	Several drones	-	No	Yes	Yes	No
Kim et al. (2017)	FLP and MDVRP variant	Several drones	-	No	Yes	Yes	Yes
Carlsson and Song (2017)	VRP variant	1 drone	1 truck	Yes	No	Yes	No
Campbell et al. (2017)	VRP variant	Several drones	1 truck	Yes	No	Yes	No
Luo et al. (2017)	2E-GU-RP	1 drone	1 truck	Yes	Yes	Yes	No
Daknama and Kraus (2017)	VRD	Several drones	Several trucks	Yes	Yes	Yes	No
Ulmer and Thomas (2017)	SDDPHF	Several drones	Several trucks	No	No	Yes	No
Dayarian et al. (2017)	VRPDR	Several drones	Several trucks	Yes	No	Yes	No
Yu et al. (2017)	TSP variant	1 drone	Mobile charging stations	No	No	Yes	Yes
Shavarani et al (2017)	FLP	Several drones	-	No	Yes	Yes	Yes
Pugliese and Guerriero (2017)	VDRPTW	Several drones	Several trucks	Yes	Yes	Yes	No
This work	**PDSVRP**	**Several drones**	**Several cars**	**No**	**Yes**	**Yes**	**Yes**

By analysing Table 3, it is important to observe that all these contributions are very recent, ranging from 2015 to 2018, which was expected given that drone delivery is currently trending. Nevertheless, the number of contributions related to drone delivery problems was still substantial for such a short period, with 18 new papers only in the last year. Regarding the approaches to the problem, most of the contributions analysed considered a drone being deployed from a truck, which required a vehicle synchronisation. This scenario is different from the one present in the problem of Connect Robotics. In fact, the only contribution that represents the situation considered in this dissertation's problem is the PDSTSP from Murray and Chu (2015). However, the models introduced in this paper are only tested with artificial instances. Furthermore, only four of the other papers analysed applied their models to real applications, although always based on assumptions since no official data was retrieved from any drone delivery company.

3.2.2. Other related work

Many other transportation problems address challenges and constraints similar to those present in drone-related problems. Therefore, it can be useful to explore these problems to understand how these constraints were modelled.

One of the limitations of the drone is its low maximum payload. In that regard, weight capacity is a vehicle characteristic that has already been explored with the capacitated vehicle routing problem (CVRP) and its variants (Braekers et al., 2015). Another characteristic of the drone is its ability to perform several trips each day. A generic formulation, the multiple trips vehicle routing problem (MTVRP), has already been developed and several algorithms to solve it have been proposed (Brandão and Mercer, 1998; Cattaruzza et al., 2014). Furthermore, drones may require drone-ports as secondary hubs to expand their range and reach all customers, which is a challenge addressed by the two-echelon vehicle routing problem (2E-VRP). This routing problem determines the best location for secondary hubs (Crainic et al., 2010). Due to its applicability in logistics, the 2E-VRP has been widely researched, and several variants have been created to include other constraints (Breunig et al., 2016). For example, a two-echelon capacitated vehicle routing problem was explored by Perboli (2011).

A problem that shares some of its characteristics with drone-related problems is the green vehicle routing problem (G-VRP) formulated by Erdoĝan and Miller-Hooks (2012). The G-VRP considers a fleet of vehicles powered by alternative fuels, which includes electric vehicles. Therefore, a fuelling network would be required to support these vehicles given their limited range without refuelling. Although this problem does not mention drones specifically, they face a similar challenge since batteries limit their range and drone ports can be installed for recharging purposes. In this perspective, other authors also attempted to address similar problems but related only to electric vehicles. Breunig et al. (2017) introduced the electric two-echelon vehicle routing problem (E2EVRP), which explores a scenario where large vehicles deliver to intermediate facilities and electric vehicles deliver from these facilities to customers. Adler and Mirchandani (2014) modelled a situation where vehicles with swappable batteries are routed through stations with substitute batteries available. Their model also computes battery reservations at each station that minimise delays. Lin et al. (2015) introduced a general electric vehicle routing problem (EVRP) for finding delivery routes that minimised costs and number of vehicles dispatched while considering charging stations and the effect of the packages' weight on energy consumption. Meanwhile, Yang and Sun (2015) presented a similar situation, the electric vehicles battery swap stations location routing problem (BSS–EV–LRP), where electric vehicles make deliveries to customers and go through stations for swapping batteries if needed. The model generates routes for each customer and identifies locations for these stations. Finally, Schneider et al. (2014) studied a delivery problem named electric vehicle routing problem with time windows and recharging stations (E-VRPTW) that determined locations for the recharging stations while also considering time windows and vehicle capacity constraints. However, most of these problems consider larger vehicles than drones. Hence, to address situations with drones, those models would need to be adapted for vehicles with a limited carrying capacity. A potential answer could be to improve these models with capacity constraints already studied in the CVRPs mentioned above.

3.3. Chapter conclusions

By exploring the existing literature, it was possible to clarify and discuss the prospects for the transportation logistics industry according to relevant trends, a plausible positioning of drones in the future of parcel deliveries and how drone delivery problems have been tackled in recent studies.

Most of the technologies driving change in transportation are present in drones. Therefore, autonomous vehicles, electric batteries and lighter materials have several favourable stakeholders, which provides drone technology a required sustainability. Moreover, other trends in the transportation and logistics industry do not represent an alternative for deliveries by drone and can even be synergetic. Furthermore, research shows that drones are the most suitable delivery model for last-mile deliveries in rural areas.

Several contributions for drone delivery problems had interesting mathematical formulations which were tested with artificial instances or applied to real locations with no official data from companies. Therefore, adapting some of these models to the real case of Connect Robotics and Farmácia da Lajeosa would be an interesting contribution to the related literature. Possible adaptations of the models could be inspired in the related work since several similar constraints were modelled successfully in those transportation problems.

4. Mathematical model for the drone delivery problem

The current chapter introduces the drone delivery mathematical model that was developed to portray the situation of Farmácia da Lajeosa, the parallel drone scheduling vehicle routing problem (PDSVRP). However, before characterising this model, the problem statement is summarised to understand the different issues, regarding the existent literature that the model needed to address. Then, the variants of the model considered to approach the problem are explained. Lastly, the model formulation is presented and explained, including the changes required to obtain its variants.

4.1. Problem statement and model variants

Due to the several possible applications, drone technology has been evolving in a fast and sustained way. Consequently, the drone industry is growing alongside it. Currently, there are already several companies making deliveries by drone all around the world. However, drones are not replacing other transportation modes. Instead, drones reach remote areas that would otherwise be insufficiently served or not served at all. Nevertheless, the potential for performing fast last-mile deliveries for all types of customers has already been identified, which justifies the investments being made by large companies in drone deliveries. The trend for fast on-demand deliveries and omnichannel fulfilment in the transportation and logistics industry is one plausible reason for these companies' interest in drones. Regardless, real companies and researches performed already demonstrate at least the viability of the drone delivery model for rural last-mile deliveries, which is precisely the case of Connect Robotics and Farmácia da Lajeosa. Furthermore, it was already possible to find a significant amount of recent works modelling problems with drones, which represents a trend that must not be ignored.

By analysing the problem and the logistics challenges faced by Connect Robotics and Farmácia da Lajeosa, it was considered that a drone delivery optimisation model would be capable of supporting their endeavour. However, the drones' unique characteristics, such as the battery conditions, the low maximum payload, and the susceptibility to adverse weather conditions, generate new constraints that imply a routing problem to be modelled differently from the common logistics problems. Therefore, one of the sections in the literature review of this dissertation focused on researching previous contributions to drone delivery problems, since it was essential to understand how these constraints were modelled and if there was any problem similar to the one approached in this work. Most of these problems are inspired by the model proposed by the partnership of Matternet with Mercedes and also by UPS, where drones are deployed from a delivery truck. Nevertheless, it was also possible to find a model formulation for a problem that considers drones delivering in parallel with another vehicle, the PDSTSP from Murray and Chu (2015), which is more closely related to the situation to be addressed in this work. Therefore, the formulation of the PDSTSP was adapted to the situation of Connect Robotics and Farmácia da Lajeosa generating a new drone delivery problem, the PDSVRP.

In its essence, the problem at hand concerns the delivery operations of Farmácia da Lajeosa. Nowadays, they receive several orders every day from different customers, which they serve with a small fleet of cars. However, given the delivery service contract signed with Connect Robotics, drones will be a part of their operation and these may bring benefits regarding cost and time savings. Nevertheless, given the volume of operations that occur daily in Farmácia da Lajeosa, these benefits are not easily quantified. Moreover, it will also be necessary to decide for every single delivery operation on which vehicles to employ and which routes to take when facing scenarios where multiple customers must be served in the same time window. Therefore, the PDSVRP will comprise some variants to approach the situation presented from two different perspectives: the daily delivery operations and single delivery operation. The daily operations will consider the fulfilment of customers' demand which usually requires multiple delivery operations throughout the day. This broader scenario must be considered given that the utilisation of drones is limited, and they will not be available for every delivery operation. Hence, this perspective will enable a more comprehensive study on the financial viability and the gains in employing drones, as well as quantify the possible time savings. On the other hand, the single operation model will provide decision support for the vehicles and routes given a set of customers that must be served once. By testing this variant of the model, it will be possible to obtain an insight on the benefits of having drones when dealing with specific and time sensitive situations. Furthermore, both perspectives will be studied for two different objectives: cost minimisation and time minimisation. In fact, when the goal is to minimise time the recharge time of the drone is an important characteristic to take into consideration. In Figure 17, all the variants of the model are presented.

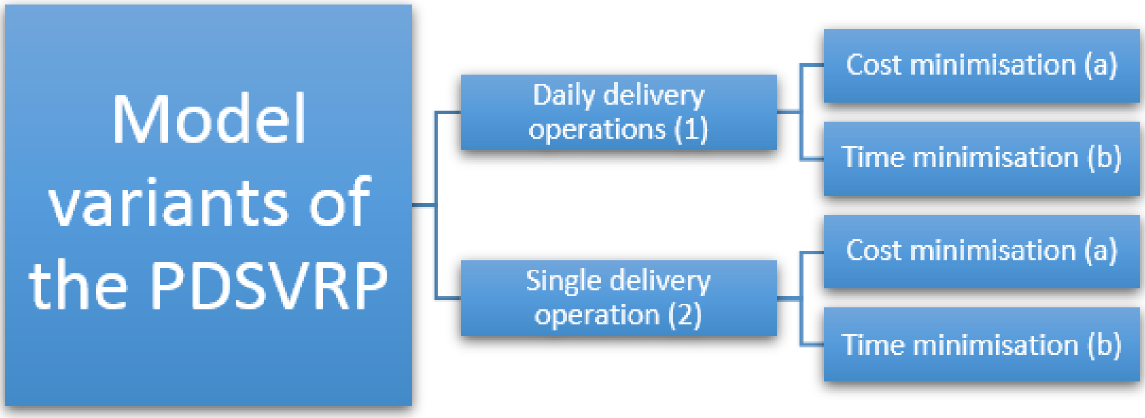


Figure 17 - Model variants.

As depicted in Figure 17, these model variants will be identified by the perspective from which the problem is approached and the model objective. For example, the variant of the model that considers single operations and minimises cost is the model 2b.

4.2. Model characterisation

Based on the PDSTSP from Murray and Chu (2015), the PDSVRP represents a scenario where a set of customers must be served from a single depot and the deliveries must be made by either a car or a drone. The PDSTSP featured a single delivery operation and all customers had to be served once in the minimum amount of time with only one car route and multiple drones. However, unlike the PDSTSP, this model considers the demand of each customer and consequently car's and drone's capacity, multiple car routes instead of a single vehicle route and the computation of delivery costs for each vehicle, which allows to establish cost minimisation as the objective function.

In the model variant for daily operations, the daily demand for each customer must be fulfilled, which means each customer may be served more than once per day in different operations. Contrarily, the model variant for single operations does not consider demand, hence customers are visited only once like in the original problem (PDSTSP). Regarding the demand of customers in the daily operations, the model considers a set of known product quantities demanded from each customer even though the orders are usually received throughout the day. Hence, the model considers that each car route that serves a customer delivers more than one unit of product per customer, and each drone that visits a customer also delivers more than one unit of product to that customer. Hence, the model attempts to replicate a scenario where a set amount of orders is aggregated and then delivered at the same time.

The distances between each customer and the depot are provided to the model for both the car and the drone. Similarly, the travel time of car is also provided to the model and the travel time of drone is computed as a function of distance travelled and drone speed. This data is utilised by the model to generate efficient solutions regarding cost and time. The overall cost of a given solution only considers transportation and these transportation costs are calculated through the energy costs and fuel costs associated with the total flight time of drones and the total distance travelled by cars, respectively.

Finally, the objective of the model is either to minimise the cost or the time of serving all customers by drone and car, depending on the variant of the model utilised.

4.3. Model formulations

The formulations of the model are thoroughly described in this section. First, the notation is presented. Then, the mathematical model of the daily operations model with cost minimisation (1a) and its description. In the end, the necessary changes required to obtain the other variants are detailed. It is important to mention that this formulation shares a common notation with the PDSTSP but adds some important features to allow for the proposed changes regarding demand and multiple car routes.

4.3.1. Notation

The model formulation requires a notation to represent all the characteristics of the scenario to be portrayed.

The following indexes will help define the physical location of every node in the network and identify the car routes and drone trips.

Indexes

- i, j, k – location indexes
- r – car routes
- t – drone trips

The following sets represent the customers that must be served, the different types of nodes in the network, the drone deliveries and the car routes. The customers and the depot are assigned to a node in the network which corresponds to a physical location. It is important to note that the depot is represented as node 0 when it is the departing node and node $c+1$ when it is the final node. Additionally, the sets of drone trips also serve the purpose of limiting the availability of drones.

Sets

- $C = \{1,2,\dots,c\}$ – set of customers
- $C' \subseteq C$ - subset of customers that may receive packages from the drone
- $N = \{0,1,\dots,c+1\}$ – set of all nodes in the network
- $N_0 = \{0,1,\dots,c\}$ – set of nodes from which the drones and the car can depart
- $N_+ = \{1,2,\dots,c+1\}$ – set of nodes that the drones and the car may visit
- T – set of drone trips t
- R – set of car routes r

Furthermore, the following parameters must be provided to the model and characterise the scenario presented.

Parameters

- $\tau_{i,j}^{C}$ – travel time of car in minutes to go from node i in N_0 to node j in N_+
- $d_{i,j}^{C}$ – distance travelled in kilometres by car from node i in N_0 to node j in N_+
- $\tau_{i,j}^{D}$ – travel time of drone in minutes to go from node i in N_0 to node j in N_+
- $d_{i,j}^{D}$ – distance travelled by drone in kilometres from node i in N_0 to node j in N_+
- $demand_i$ – products' quantity demanded by each customer i in C
- s^D – speed of drone in kilometres per hour
- $cost^D$ – energy cost of drone per minute in euros
- $cost^C$ – fuel cost of a car per kilometre in euros
- e – maximum flight time in minutes of a drone without recharging
- $recharge$ – time necessary for the drone to completely recharge between trips
- q^D – maximum quantity of products delivered by drone to each customer per trip
- q^C – maximum quantity of products delivered by car to each customer per route
- M – big enough number

Finally, two types of variables were considered: decision and auxiliary. The decision variables are binary variables and will characterise the solution obtained and serve as inputs for calculating the deliveries' cost and time.

Variables

- $y_{i,t} \in \{0,1\}$ – binary variable that is equal to one if customer i is served by drone trip t
- $x_{i,j,r} \in \{0,1\}$ – binary variable that is equal to one if car route r goes from i to j
- u_i – auxiliary variable ($1 \leq u_i \leq c+2$)

4.3.2. Mathematical model (1a)

Given the characteristics of the problem and the defined indexes, sets, parameters, scalars and variables, the mathematical model of daily operations with cost minimisation (1a) was developed with the objective of minimising the overall cost to serve all the customers' orders utilising both transportation modes (Car and drone).

Objective function

$$minimise\ z = cost^C \times \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} d^C_{i,j} \times x_{i,j,r} + cost^D \times \sum_{i \in C'} \sum_{t \in T} (\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} \tag{1}$$

Furthermore, the constraints below were established to shape the model according to the characteristics of the delivery problem.

Constraints

$$(\tau^D_{0,i} + \tau^D_{i,c+1}) \leq e + M\left(1 - y_{i,t}\right) \qquad \forall i \in C^{'}, t \in T \tag{2}$$

$$\sum_{i \in C^{'}} y_{i,t} \leq 1 \qquad \forall t \in T \tag{3}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} \sum_{r \in R} q^C \times x_{i,j,r} + \sum_{t \in T} q^D \times y_{j,t} \geq demand_j \qquad \forall j \in C \tag{4}$$

$$\sum_{j \in N_+} x_{0,j,r} \leq 1 \qquad \forall r \in R \tag{5}$$

$$\sum_{i \in N_0} x_{i,c+1,r} = \sum_{j \in N_+} x_{0,j,r} \qquad \forall r \in R \tag{6}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} x_{i,j,r} = \sum_{\substack{k \in N_+ \\ k \neq j}} x_{j,k,r} \qquad \forall j \in C, r \in R \tag{7}$$

$$u_i - u_j + 1 \leq (c+2)\left(1 - x_{i,j,r}\right) \qquad \forall i \in C, j \in \{N_+ : j \neq i\}, r \in R \tag{8}$$

$$1 \leq u_i \leq c + 2 \qquad \forall i \in N_+ \tag{9}$$

$$x_{i,j,r} \in \{0,1\} \qquad \forall i \in N_0, j \in \{N_+ : j \neq i\}, r \in R \tag{10}$$

$$y_{i,t} \in \{0,1\} \qquad \forall i \in C^{'}, t \in T \tag{11}$$

Finally, the model also includes some additional computations to extract further information regarding the solution.

Additional computations

$$total\ drone\ deliveries = \sum_{i \in C'} \sum_{t \in T} y_{i,t} \tag{12}$$

$$total\ flight\ time\ of\ drone = \sum_{i \in C'} \sum_{t \in T} (\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} \tag{13}$$

$$total\ car\ routes = \sum_{j \in N_+} \sum_{r \in R} x_{0,j,r} \tag{14}$$

$$total\ travel\ time\ of\ car = \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} \tau^C_{i,j} \times x_{i,j,r} \tag{15}$$

The objective function (1) of this model minimises the total cost of all the delivery operations and it is divided into two parts: the cost with car routes and the cost with drone trips. The cost with car routes is calculated as a function of the total distance travelled in the car routes and the fuel cost. The cost with drone trips is calculated as a function of the total flight time of drones and the energy cost.

The two first constraints are related to drone deliveries. Constraints (2) ensure that drones can only deliver to customers if the maximum flight time is not exceeded. Constraints (3) assign each drone trip to a maximum of one customer. The following constraints (4) are related to both drone and car and assures the demand of every customer is met by either transportation mode. The subsequent constraints are related to car routes. Constraints (5) require each car route to either not leave from the depot or leave once from the depot. Equations (6) are linked with constraints (5) and each car route must return once to the depot if it has left the depot or not return if it has not. Equations (7) guarantee that every car route that visits a customer must leave that customer. Constraints (8) eliminate subtours in each car route. The remaining constraints establish the variables' domain. Constraints (9) are related with the auxiliary variable utilised in the subtour elimination. Equation (10) specifies the domain of the binary variable related with car routes. Equation (11) limits the utilisation of drone trips to customers that are able and willing to receive packages by drone.

Finally, the additional computations provide useful information regarding the drone trips and the car routes of the solution. Equation (12) calculates the number of drone deliveries. Equation (13) computes the total flight time of drones. Equation (14) obtains the number of car routes. Equation (15) sums the total travel time of cars.

4.3.3. Formulation changes introduced to obtain the model variants

The mathematical formulation presented in 4.3.2 requires some changes in the objective function and its constraints to obtain the model variants (1b, 2a and 2b). Hence this section will present the changes introduced in the mathematical model of 1a to obtain the other model variants. Additionally, in the appendices 1, 2 and 3, a complete mathematical formulation of each of these variants is displayed.

4.3.3.1. Minimisation of time instead of cost (1b)

The main difference between model 1a and 1b is the change in the objective function. Instead of minimising the cost of the daily delivery operations this variant of the model minimises time. Therefore, the objective function is the equivalent of a $\min\{\max\{total\ flight\ time\ of\ drone + recharge,\ total\ travel\ time\ of\ car\}\}$ since it attempts to minimise the time it takes for both drones and cars to meet the demand of every customer. The goal is to make all the deliveries in the quickest time possible with both transportation modes working in parallel, hence the time minimised must be the longest between the car or the drone and not the sum of these times. Additionally, as the previous expression suggests, for calculating the necessary time for drones to make the deliveries the drone recharge time is also considered. Furthermore, considering that this expression is not linear it could not be solved with linear programming. Consequently, the expression was linearized with the objective and constraints that were introduced in the model and are represented below.

New objective function

$$minimise\ w \tag{16}$$

Additional constraints

$$\text{w} \geq \sum_{i\in C'}\sum_{t\in T}(\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} + recharge\ \times \left(\left(\sum_{i\in C'}\sum_{t\in T} y_{i,t}\right) - 1\right) \tag{17}$$

$$w \geq \sum_{i\in N_0}\sum_{\substack{j\in N_+ \\ j\neq i}}\sum_{r\in R}\tau^C_{i,j} \times x_{i,j,r} \tag{18}$$

Moreover, since the total cost of the operations is no longer considered in the objective function, it is included as an additional equation to enable cost comparisons between solutions.

Additional computations

$$total\ cost\ = cost^C \times \sum_{i\in N_0}\sum_{\substack{j\in N_+ \\ j\neq i}}\sum_{r\in R} d^C_{i,j} \times x_{i,j,r} + cost^D \times \sum_{i\in C'}\sum_{t\in T}(\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} \tag{19}$$

Equation (16) minimises the latest time at which either the car routes or drone trips finish all the deliveries. For this purpose, constraints (17) and (18) provide a lower bound for the total time of drone trips (with the necessary recharges) and the car routes, respectively. Finally, equation (19) computes the total cost of the solution similarly to the objective function of model 1a.

4.3.3.2. Single delivery operation instead of daily delivery operations (2a)

The single operation is a simplification of the daily operations. Therefore, the only change needed to obtain model 2a from model 1a is to replace constraints (4) by equations (20).

$$\sum_{\substack{i\in N_0 \\ i\neq j}}\sum_{r\in R} x_{i,j,r} + \sum_{t\in T} y_{j,t} = 1 \qquad \forall j \in C \tag{20}$$

These new equations (20) considers that each customer must be visited only once by either vehicle, instead of having a demand to be met.

4.3.3.3. Single operation with time minimisation (2b)

To obtain the model variant for single operation with time minimisation, the objective function is changed to equation (16), as in model 1b. Thus, equations (17) and (18) must also be included. Similarly, the equation (19) is added to the additional computations. Finally, since this is also a single operations model like model 2a, the constraints (4) are also replaced with equations (20).

5. Results

The resolution of the problem of Farmácia da Lajeosa will be presented in this chapter. The first step is to describe the data collected and the treatment required for the data to feed the models developed. Furthermore, the current operations will be analysed regarding cost and time. Afterwards, the results obtained will be divided into two sections: one for the daily operations models and another for the single operations models. For the implementation of the mathematical models the General Algebraic Modeling System (GAMS) software (GAMS, 2018) will be utilised.

5.1. Data collection and treatment

To implement the model, Connect Robotics and Farmácia da Lajeosa provided the necessary data. However, some calculations were also performed to complement this data. Therefore, this subchapter will include all the relevant data that was collected along with considerations, assumptions and calculations that were made to enable their implementation in the model. Due to the confidentiality of the data, the clients of Farmácia da Lajeosa (nursing homes) were identified by numbers to prevent recognition, only the total quantities of product ordered are presented and the real date these products were ordered is not displayed.

5.1.1. Customers' demand

To study the current operations in Farmácia da Lajeosa and the impact of drones it was necessary to analyse the customers' demand in a significant period. Therefore, the orders' data corresponding to the five clients demand for a period of 6 months was collected from Farmácia da Lajeosa. The total quantity of products ordered by these five clients was 14246 in the period analysed, which corresponds to several different order entries each day and a wide variety of products. This demand is distributed by the clients as illustrated in Figure 18.

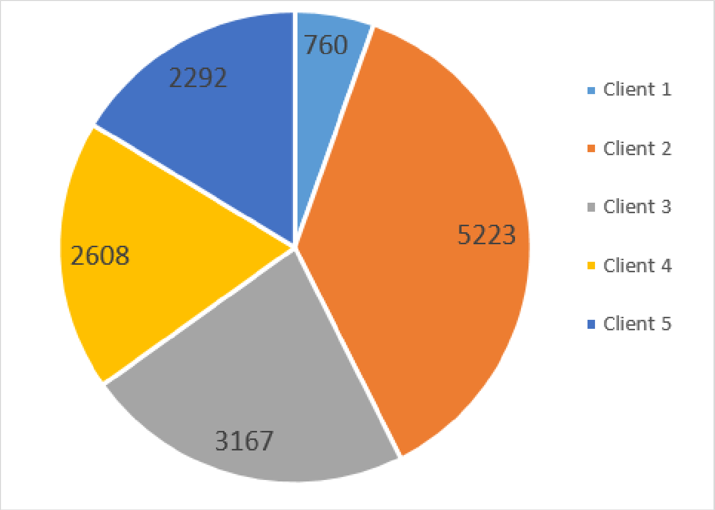


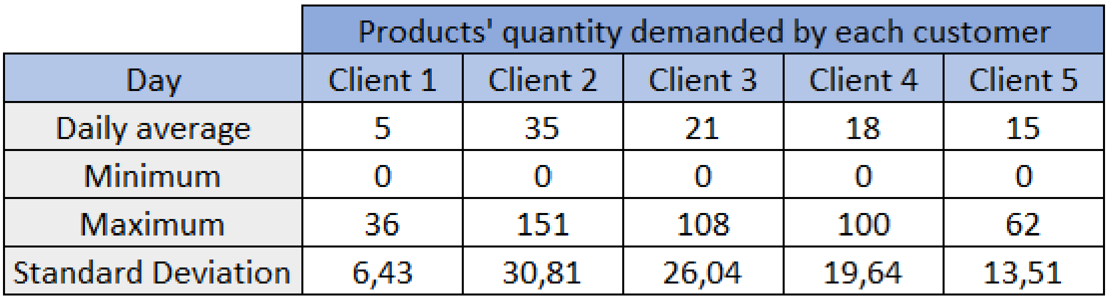
Figure 18 - Products' quantity ordered by each client

All clients put orders regularly and the quantity of products in these order entries range from 1 to 26 for the different clients and every client has at least one order entry for more than 15 products. The total quantities ordered in each day reach a maximum of 151 products for only one client.

However, by analysing these orders entries, it was possible to identify that in some cases different entries corresponded to the same order. The inexistence of data regarding the time of the entries do not allow to confirm this, but there are real examples that support it. In one day, there were seven order entries in a row featuring the same product and with the quantity ordered equal to one. In a different day, the total amount of orders entries corresponding to one client was 86. Hence, given this heterogeneity of the order entries and the impossibility to sort the information correctly by the real orders, the information was processed by products and for the implementation in the daily operations models it was only considered the total quantity of products demanded each day by each customer. For obtaining the results, the products demanded will be aggregated to represent the real orders based only in the quantity ordered, which is a better approximation of reality than the order entries analysed.

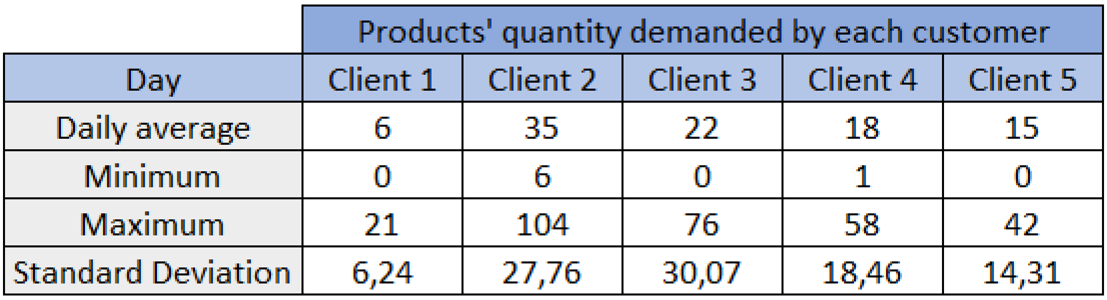
Nevertheless, processing the information by products ordered still resulted in a table with 151 days of products' quantity demanded by each customer. Given the size of this table it is not going to be presented in this section. Alternatively, it is displayed in appendix 4. Since it would not provide much added value to run the model that many times, a sample of 15 days was retrieved, which is close to 10% of the population analysed and it is assumed to be representative of the population. The criteria utilised to generate this sample was to run the random function of Excel until a sample without repeating days and similar statistical characteristics per client to the 151 days was obtained. In Table 4, the statistical information of the total population of 151 days is portrayed and in Table 5 are depicted those of the sample with 15 days. The sample is presented in Table 6.

Table 4 – Statistical characteristics of the 151 days analysed



	Products' quantity demanded by each customer				
Day	Client 1	Client 2	Client 3	Client 4	Client 5
Daily average	5	35	21	18	15
Minimum	0	0	0	0	0
Maximum	36	151	108	100	62
Standard Deviation	6,43	30,81	26,04	19,64	13,51

Table 5 - Statistical characteristics of the sample with 15 days



	Products' quantity demanded by each customer				
Day	Client 1	Client 2	Client 3	Client 4	Client 5
Daily average	6	35	22	18	15
Minimum	0	6	0	1	0
Maximum	21	104	76	58	42
Standard Deviation	6,24	27,76	30,07	18,46	14,31

Table 6 - Sample of 15 days of customers' demand

	Products' quantity demanded by each customer				
Day	Client 1	Client 2	Client 3	Client 4	Client 5
55	21	104	75	8	0
123	6	14	20	3	32
98	5	8	5	6	37
127	0	45	0	1	0
26	7	30	0	5	22
104	0	44	0	57	3
57	6	20	15	2	42
126	13	42	76	21	17
15	0	43	24	10	1
150	13	7	0	4	21
105	0	79	40	24	11
96	3	28	76	27	6
99	9	10	1	27	7
53	0	6	0	17	0
51	1	44	0	58	25

The reason behind utilising a sample of 15 days instead of implementing the model with the average quantity demanded is the high variability of this demand. This variability can be observed in the sample and also through the standard deviation of the products' quantity demanded by each client in the 151 days and the sample.

5.1.2. Delivery vehicles and transportation costs

One of the features contemplated in the model presented is the cost of transportation. Therefore, for each of the delivery vehicles considered it was necessary to estimate these costs. Given the heterogeneity in the fleet of cars utilised for deliveries, the average fuel consumption was validated with Farmácia da Lajeosa and the value considered was 6 litres per 100 kilometres. Regarding the fuel cost, it was assumed a value of 1,65€ per litre upon consulting the average cost of petrol (Maisgasolina, 2018). Finally, the fuel cost per kilometer was calculated with equation (21).

$$Fuel\ cost\ per\ kilometre\ (€/km) = \frac{Fuel\ consumption\ per\ 100\ km\ (l)}{100} \times fuel\ cost\ (€/l) \qquad (21)$$

The equation (21) provides an estimate of the fuel cost per kilometre of the delivery car. Moreover, all the data needed to implement the model regarding the delivery cars is summarised in Table 7.

Table 7 - Characteristics of the cars employed

Car	
Fuel consumption per 100 km (l)	6
Fuel cost (€/l)	1,65
Fuel cost per kilometre (€/km)	0,099

The other delivery vehicle, the drone, presented similar challenges in the calculation of delivery costs. However, most of the data was provided by Connect Robotics, such as the speed of the drone, its battery duration, the recharge time and the takeoff time. Still, it is important to mention that the battery duration, which impacts directly the maximum flight time of the drone, has been affected by the special container that is required to transport medicine. Therefore, the provided value will be considered for the cost estimation and the implementation of the models, but its potential variation will be tested in the single operations models. Therefore, to estimate the energy cost for delivering with drones, it was considered the battery duration and the cost of a full recharge, which was calculated through equation (22).

$$Energy\ cost\ per\ minute\ (€/min) = \frac{Cost\ of\ a\ full\ recharge(€)}{Battery\ duration\ (min)} \tag{22}$$

Equation (22) estimates an energy cost of the drone per minute of utilisation by considering the cost of recharging the drone and the total time the drone is utilised. Another important feature of the delivery drone is the attached box where the products are transported. By analysing the size of this box and the variety of products, the maximum quantity of products delivered by drone was defined as 5. Finally, the aforementioned data is presented in Table 8 and represents the drones' characteristics needed to implement the models.

Table 8 - Characteristics of the drones employed

Drone	
Speed (Km/h)	40
Battery duration (min)	35
Cost of a full recharge (€)	0,01150
Energy cost per minute (€/min)	0,0003286
Recharge time (min)	60
Takeoff time (min)	2
Maximum quantity of products delivered by drone	5

5.1.3. Distances and travel times

The subsequent step to enable the calculation of transportation costs and times is to provide the models with the distances and the travel times for both delivery vehicles. But first, to illustrate the positioning of each client regarding Farmácia da Lajeosa, a simple map was created with the location of each client and Farmácia da Lajeosa, which is the D (from depot) at the center. This map is displayed in Figure 19.

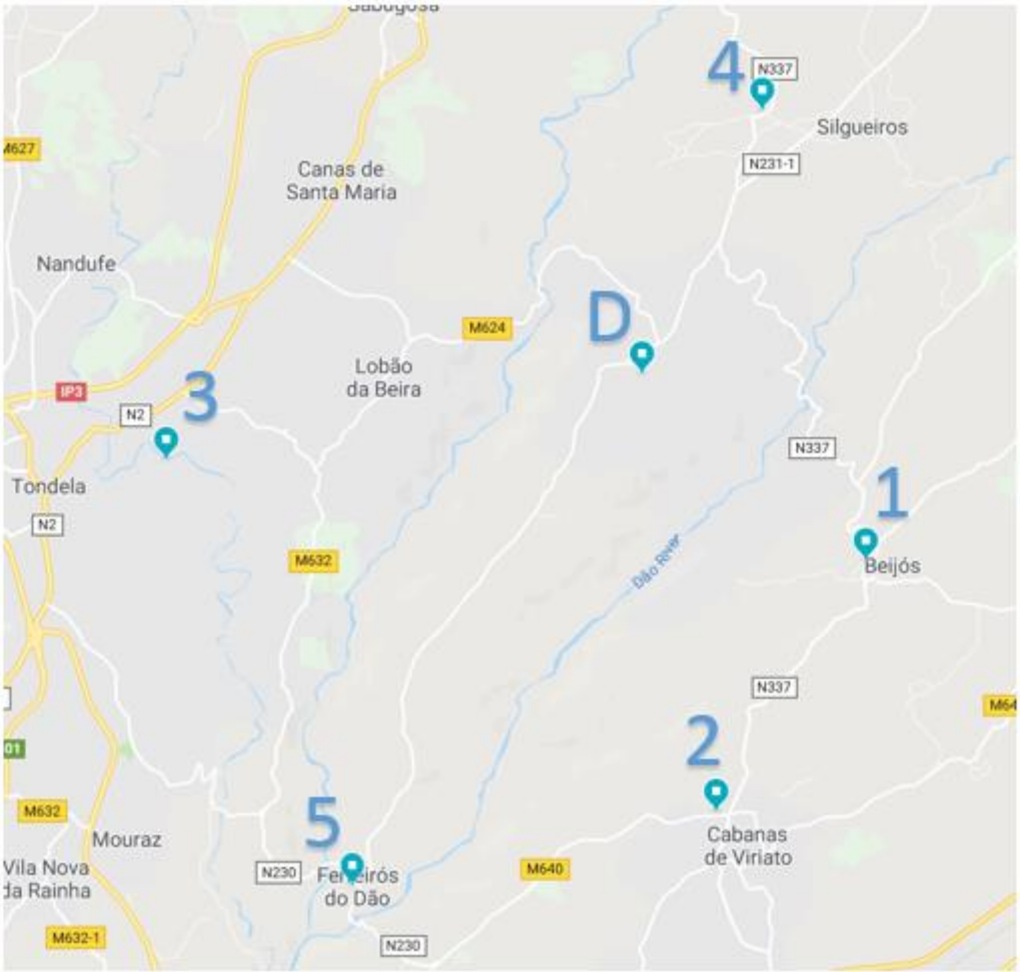


Figure 19 - Location of the clients and Farmácia da Lajeosa. Retrieved from Google Maps (2018).

For drones, the distances travelled represent the length of the routes authorized by ANAC to serve these clients. These distances are longer than the Euclidean distances since the drones need to deviate from houses, which results in longer flight times and higher battery consumption. Furthermore, ANAC also requires a flight altitude of 100 metres. The length of these routes was provided by Farmácia da Lajeosa and it is presented in Table 9.

Table 9 - Distance travelled by drone to reach the clients

	Distance travelled by drone (km)
Client 1	3,77
Client 2	5,98
Client 3	6,28
Client 4	4,22
Client 5	7,63

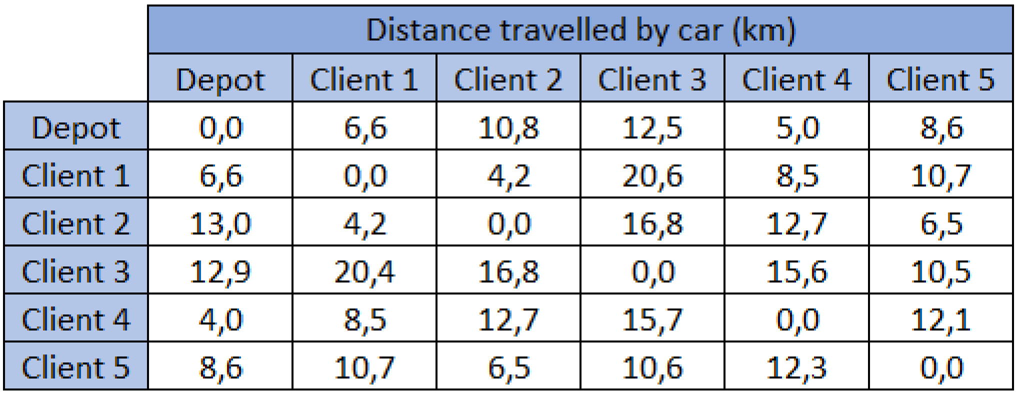
The travel time of the drone to reach these clients is calculated in the model through equation (23).

$$\begin{gathered} \mathit{Travel\ time\ of\ drone}\ (min) \\ = \mathit{Distance\ travelled\ by\ drone}\ (km) \times \frac{60}{\mathit{Speed}\ (km/h)} + \mathit{Takeoff\ time}\ (min) \end{gathered} \tag{23}$$

Equation (23) estimates the travel time of drone through the distance, the speed of the drone and the takeoff time, which is not only relevant for the time it takes but also because it consumes battery.

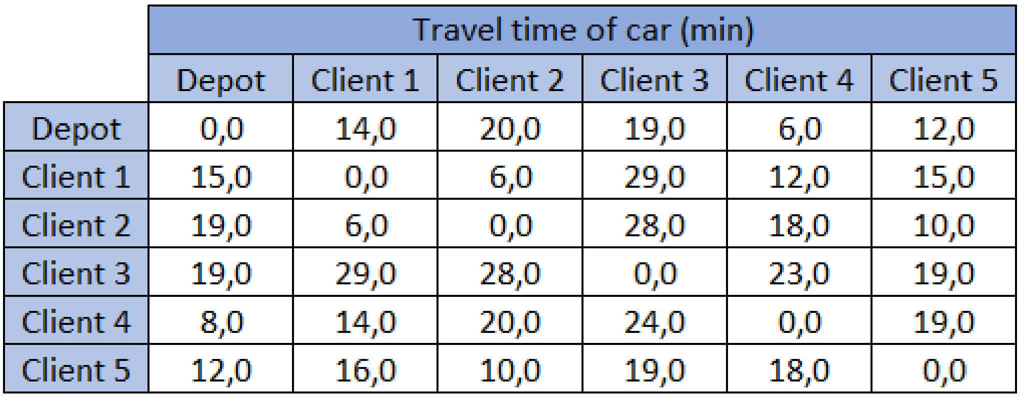
Regarding cars, the distances and travel times were estimated with Google Maps by simulating the routes between these locations (Google Maps, 2018). Moreover, the travel times are stable throughout the day since it is a rural area and it is not particularly affected by traffic. Therefore, the values implemented in the models are summarised in Table 10 and Table 11.

Table 10 - Distance travelled by car between every node in the network



	Distance travelled by car (km)					
	Depot	Client 1	Client 2	Client 3	Client 4	Client 5
Depot	0,0	6,6	10,8	12,5	5,0	8,6
Client 1	6,6	0,0	4,2	20,6	8,5	10,7
Client 2	13,0	4,2	0,0	16,8	12,7	6,5
Client 3	12,9	20,4	16,8	0,0	15,6	10,5
Client 4	4,0	8,5	12,7	15,7	0,0	12,1
Client 5	8,6	10,7	6,5	10,6	12,3	0,0

Table 11 - Travel time of car between every node in the network



	Travel time of car (min)					
	Depot	Client 1	Client 2	Client 3	Client 4	Client 5
Depot	0,0	14,0	20,0	19,0	6,0	12,0
Client 1	15,0	0,0	6,0	29,0	12,0	15,0
Client 2	19,0	6,0	0,0	28,0	18,0	10,0
Client 3	19,0	29,0	28,0	0,0	23,0	19,0
Client 4	8,0	14,0	20,0	24,0	0,0	19,0
Client 5	12,0	16,0	10,0	19,0	18,0	0,0

5.2. Current operations analysis

Before implementing the models with the collected data, it is necessary to analyse the current state of the operations, which will enable to compare it to the obtained results later. Therefore, this section will explain how the costs and time of the operations were estimated given that the demand is not known throughout the day. Lastly, it is described how the value for the maximum products' quantity delivered by car was defined.

5.2.1. Cost estimation

After processing the data collected from Farmácia da Lajeosa, the result was the demand information of the 151 days analysed, which is displayed in appendix 4.

Given that the data does not provide any information regarding the arrival time of the orders, to calculate the transportation it was assumed that the car had to visit every customer a number of times proportional to the demand of that customer. The parameter that defines that proportionality is the maximum product's quantity delivered by car. For example, according to this estimation, if the maximum product's quantity delivered by car is 5, a customer that demands 13 products is visited 3 times by the car. The utilisation of this parameter enables a more realistic approach since in the day-to-day planning the demand is not known in the beginning of the day and the car sometimes visits the same customer multiple times during the day. Furthermore, there is no indication of any type of route planning. Hence, the cost of transportation was calculated independently per client and day. The equation that was utilised to estimate the transportation costs is the following.

$$\begin{aligned}&\mathit{Daily\ transportation\ cost}\\&= \left\lceil \frac{\mathit{products'quantity\ demanded}}{\mathit{maximum\ products'quantity\ delivered\ by\ car}} \right\rceil \times \mathit{cost\ per\ trip}\end{aligned} \tag{24}$$

Equation (24) calculates the daily cost of transportation for one client by finding the number of car trips required to satisfy the demand, which is obtained through the ceiling function of the quotient between the products' quantity demanded and the maximum products' quantity delivered by car. The ceiling function finds the nearest following integer, which is necessary because there are no fractional trips. These number of trips is then multiplied by the cost per trip. This cost depends on the distance travelled by car to reach the client and it is calculated with the following equation.

$$\mathit{Cost\ per\ trip} = \mathit{fuel\ cost\ per\ kilometre} \times \mathit{distance\ travelled\ by\ car} \times 2 \tag{25}$$

Equation (25) estimates the cost of one trip to a given customer. Therefore, it is the product of the fuel cost per kilometre, presented in Table 7, and the total distance travelled. To obtain the distance travelled in the round trip, the distance travelled by car from the depot to each customer, presented in Table 10, must be multiplied by two since the car must return to the depot after the delivery.

5.2.2. Time estimation

Similarly to the cost estimation, the following equation was employed to estimate the daily transportation time of each client.

$$\begin{aligned} &Daily\ transportation\ time \\ &= \left\lceil \frac{products'\ quantity\ demanded}{maximum\ products'\ quantity\ delivered\ by\ car} \right\rceil \times time\ per\ trip \end{aligned} \tag{26}$$

Equation (26) employs the ceiling function again to obtain the number of car trips needed to satisfy the demand of the client and this value is multiplied by the time per trip. The following equation calculates this time.

$$Time\ per\ trip = time\ travelled\ by\ car \times 2 \tag{27}$$

Equation (27) multiplies by two the time travelled by car since in each trip the car must visit the customer and return to the depot. The time travelled by car is presented in Table 11.

5.2.3. Maximum products’ quantity delivered by car

To estimate the transportation costs and time it is necessary to define the maximum products’ quantity delivered by car. Furthermore, this parameter is also an input to the daily operations model and a value for this parameter must be defined which must be utilised in both the calculations for the current situation and the model implemented. Therefore, to analyse the variation of the cost with this parameter, the total cost of transportation was calculated for different values of the maximum products’ quantity delivered by car. The total cost sums the daily cost of transportation of every client calculated with the formulas mentioned in the previous section for the whole 151 days of data. The results are presented in Figure 20.

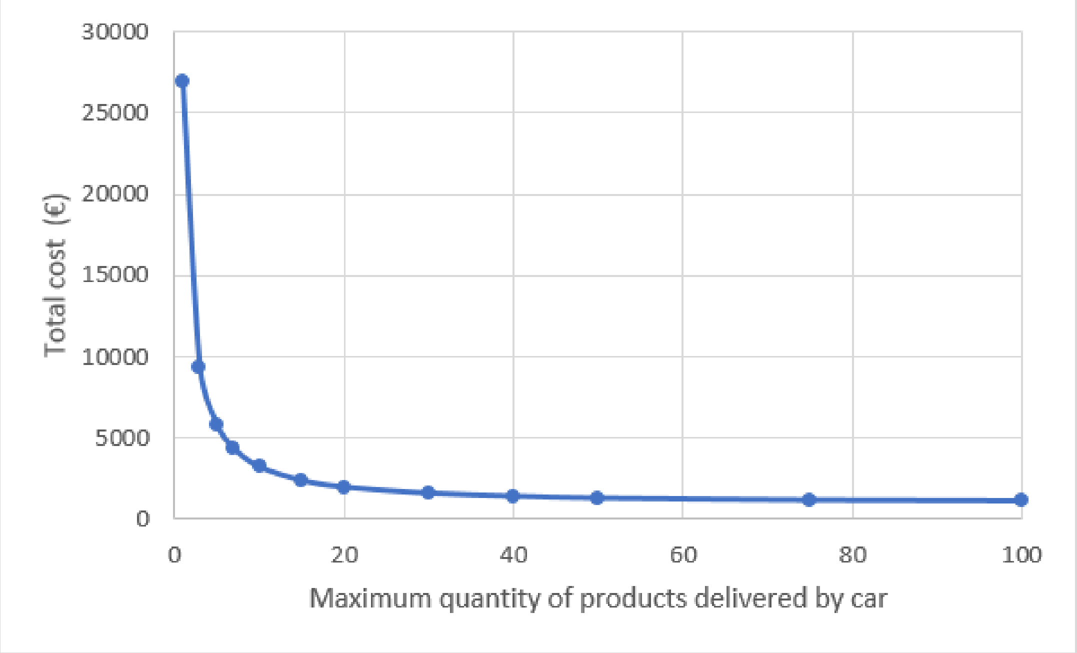


Figure 20 - Variation of total transportation cost with maximum quantity of products delivered by car

The same analysis was performed for the time. However, to ease the interpretation of the resuts the corresponding average time per day in hours was computed from the total time of transportation with the following formula.

$$Average\ time\ per\ day\ (h) = \frac{Total\ time\ (min)}{60 \times total\ days} \tag{28}$$

Equation (28) estimates an average time per day by dividing the total time in minutes by 60 to obtain the time in hours and by the total days analysed, which is 151. The resulting graphic is portrayed in Figure 21.

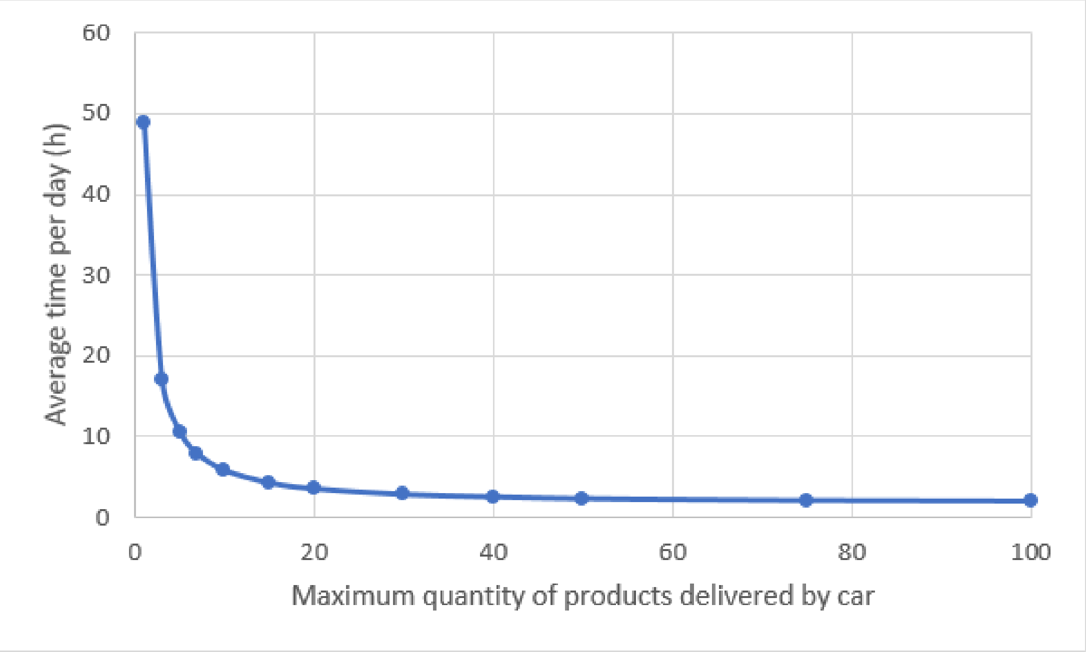


Figure 21 - Variation of average time per day with maximum quantity of products delivered by car

By observing the results in Figure 20 and Figure 21, the value of 30 was selected for the maximum products' quantity delivered by car. The reasoning for choosing this value can be explained through the balance between two aspects: first, it does not inflate the cost and time of the operations, and second, it still represents a flexible aggregation of the demand that considers the unknown demand. Furthermore, the utilisation of this value for the parameter results in an average number of deliveries per day of 5,8 for all clients. Even though sometimes the car must visit the same customer multiple times the daily average of deliveries is still 5,8, which fits the situation presented by Farmácia da Lajeosa where there were around 5 deliveries per day.

5.3. Results of the models for daily delivery operations

By utilising the data collected and the variants of the drone delivery model developed, the daily delivery operations were analysed by two perspectives: cost and time. Hence, this section will be divided in a cost analysis and a time analysis. These analyses will be performed on the sample of 15 days that was extracted from the demand data collected in Farmácia da Lajeosa.

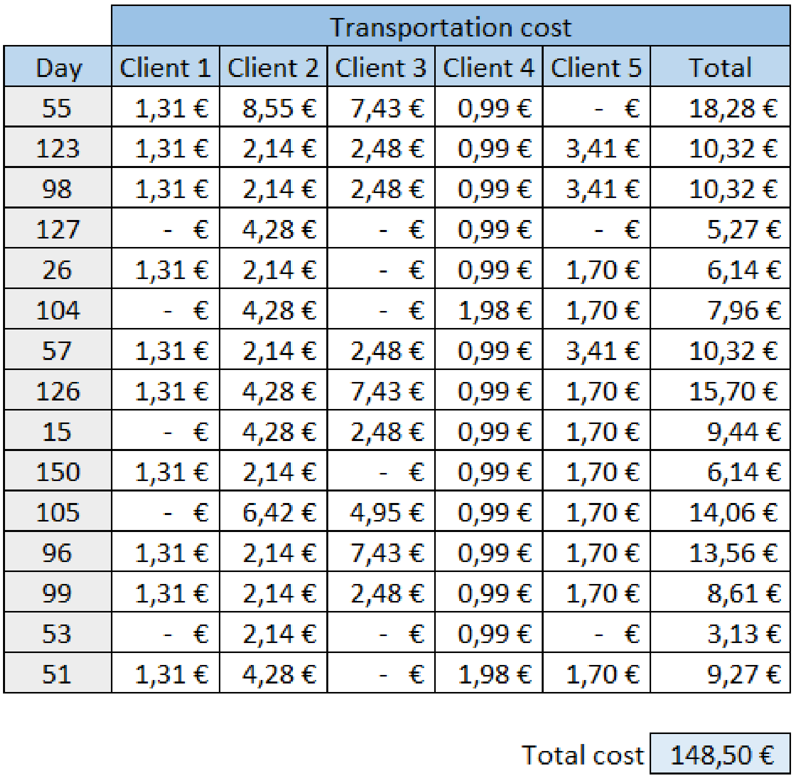
5.3.1. Cost analysis

This analysis will contemplate a study of the current situation and the model results. Afterwards, the current situation and the results of the model will be compared. Additionally, a sensitivity analysis will be performed on relevant parameters, such as the products quantity delivered by car and the number of drone trips.

5.3.1.1. Current situation

To analyse the costs of the current situation, the transportation costs were estimated utilising the methods explained in subchapter 5.2. These costs were estimated independently for each day and client, without considering routes between clients. Therefore, in Table 12, the transportation costs for the sample of 15 days are presented.

Table 12 - Estimate of the transportation costs of the current operations



	Transportation cost					
Day	Client 1	Client 2	Client 3	Client 4	Client 5	Total
55	1,31 €	8,55 €	7,43 €	0,99 €	- €	18,28 €
123	1,31 €	2,14 €	2,48 €	0,99 €	3,41 €	10,32 €
98	1,31 €	2,14 €	2,48 €	0,99 €	3,41 €	10,32 €
127	- €	4,28 €	- €	0,99 €	- €	5,27 €
26	1,31 €	2,14 €	- €	0,99 €	1,70 €	6,14 €
104	- €	4,28 €	- €	1,98 €	1,70 €	7,96 €
57	1,31 €	2,14 €	2,48 €	0,99 €	3,41 €	10,32 €
126	1,31 €	4,28 €	7,43 €	0,99 €	1,70 €	15,70 €
15	- €	4,28 €	2,48 €	0,99 €	1,70 €	9,44 €
150	1,31 €	2,14 €	- €	0,99 €	1,70 €	6,14 €
105	- €	6,42 €	4,95 €	0,99 €	1,70 €	14,06 €
96	1,31 €	2,14 €	7,43 €	0,99 €	1,70 €	13,56 €
99	1,31 €	2,14 €	2,48 €	0,99 €	1,70 €	8,61 €
53	- €	2,14 €	- €	0,99 €	- €	3,13 €
51	1,31 €	4,28 €	- €	1,98 €	1,70 €	9,27 €

Total cost 148,50 €

Given the method utilised to estimate the transportation costs, the costs for each client in each day is either proportional to the cost of one trip or zero if there is no demand in that day for that client. Furthermore, in the previous table, it is possible to observe the variability of the transportation costs. The main source of this variability is the demand, as shown in Figure 22.

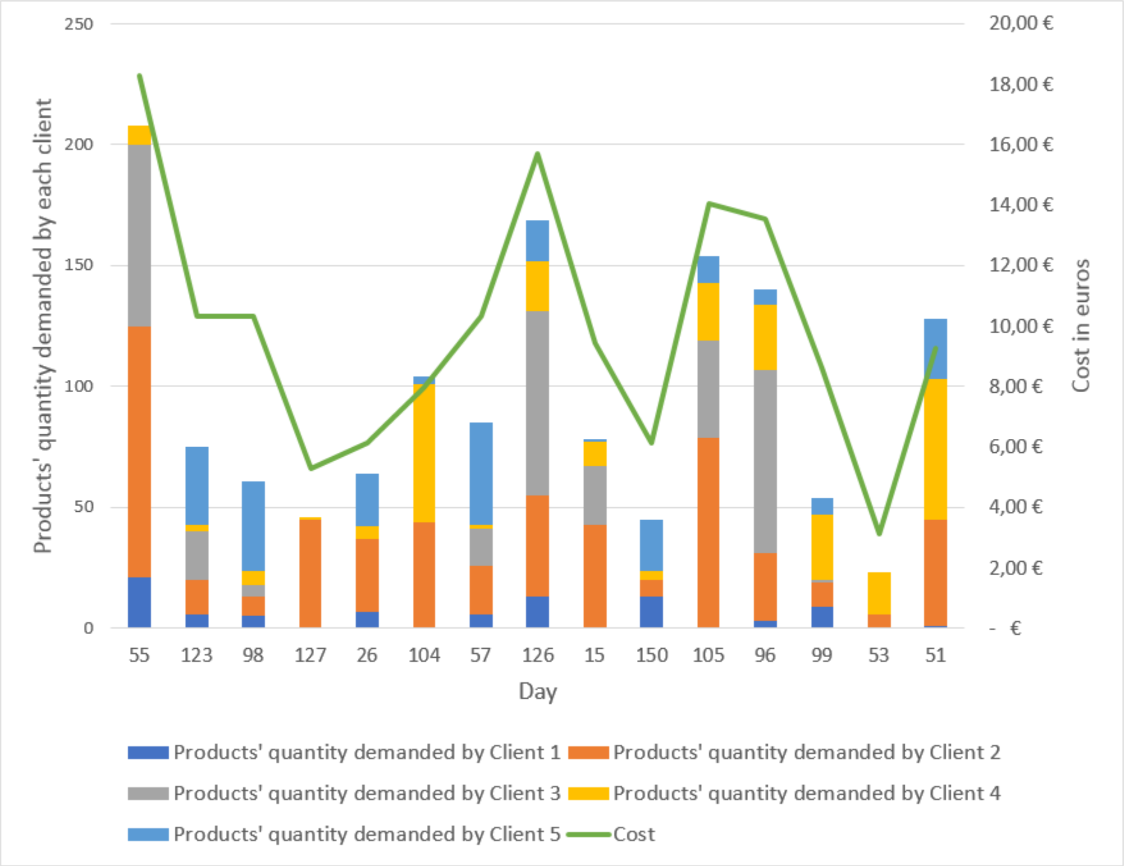


Figure 22 - Products' quantity demanded and transportation cost of each day in the current operations

However, by analysing this figure, it is possible to observe that the transportation costs are not equally proportional to the total demand in the different days. This situation can be explained by the distinct impacts that different clients have on the transportation costs due to the distance, as well as the different quantities demanded by these clients. Therefore, the average transportation cost of each client per product was calculated and it is presented in Figure 23.

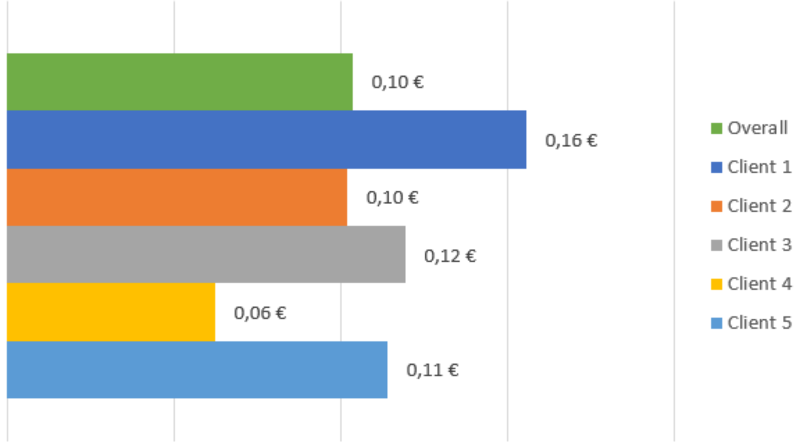


Figure 23 - Average transportation cost per product

The average transportation cost per product indicates that client 1 has the higher cost per product demanded and client 4 has the lower. These are the two clients that are closer to Farmácia da Lajeosa.

However, as displayed in Table 4, client 1 also has the lowest average demand. This situation results in less efficient deliveries than the deliveries made to client 4. Meanwhile, clients 2, 3 and 5 are closer to the overall average transportation cost. Furthermore, clients 2 and 3 also represent a larger share of the demand. To understand better the contribution of each client to the transportation costs, the distribution of the transportation costs per client was calculated and it is portrayed in Figure 24.

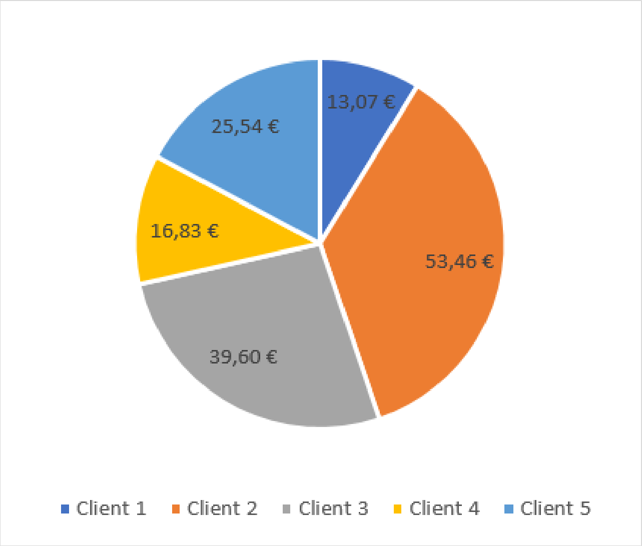


Figure 24 - Transportation costs per client

The contribution of each client to transportation costs is a result of the average demand and the distance of these clients to the depot. Thus, clients 2 and 3 have a greater weight than the other clients since they combine a longer distance to Farmácia da Lajeosa with the higher average demands of all the clients. Finally, client 4 has a higher average demand than clients 1 and 5 but the proximity of client 4 to the depot results in lower transportation costs.

5.3.1.2. Model results

The daily delivery operations model with cost minimisation (1a) was implemented and solved for the sample of 15 days to obtain the results presented subsequently. The utilisation of the same sample enables the comparison of these results with the costs estimated for the current operations. Moreover, the number of drone trips was limited to 6 each day to take into account the recharge times, since this model only minimises the transportation costs. However, the sensitivity of the model to this parameter variation will be tested afterwards. Moreover, this model has two operational differences regarding the current situation analysis. The existence of a new transportation vehicle, the drone, and also vehicle routing for the car. Hence, the transportation costs are displayed without the allocation of the transportation costs to each client. However, the total time of each vehicle spent in the delivery of products was displayed since it is an output of the model. Furthermore, given the amount of data gathered from 15 runs of the model, the results were organised and the information was summarised. The results of the model are displayed in Table 13. Additionally, the computational results are available in appendix 5.

Table 13 – Results obtained with the drone delivery model for the sample of 15 days (model 1a)

	Drone deliveries		Car routes		
Day	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation cost
55	6	134,34	3	182,00	10,71 €
123	6	134,91	1	42,00	2,61 €
98	6	135,81	1	37,00	2,49 €
127	4	82,48	1	41,00	2,17 €
26	6	151,11	1	41,00	2,19 €
104	4	92,71	2	61,00	3,55 €
57	6	149,19	1	48,00	3,20 €
126	4	91,36	2	142,00	8,57 €
15	6	126,03	1	68,00	4,01 €
150	6	106,47	1	24,00	1,74 €
105	6	133,44	2	115,00	6,76 €
96	6	145,14	2	111,00	7,12 €
99	4	120,50	1	34,00	1,93 €
53	6	110,52	0	0,00	0,04 €
51	3	65,82	2	62,00	3,96 €
				Total cost	61,02 €

Furthermore, it is possible to observe in Figure 25 the relation between the transportation costs and the total quantity of products demanded. These transportation costs are explained not only by the cost efficiency of drones in transporting smaller quantities but also by the car routes. Although, drones also enable efficient car routes, since drones can perform the more urgent deliveries and consequently allow for more efficient planning for the rest of the demand.

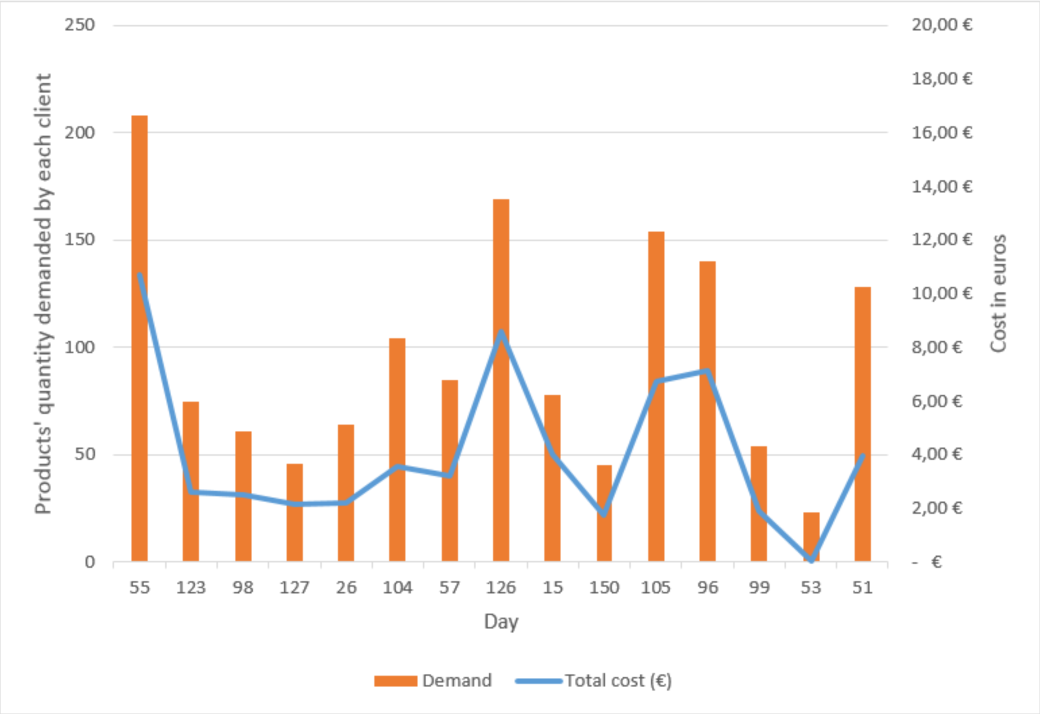


Figure 25 - Products' quantity demanded and transportation cost of each day with drones

5.3.1.3. Comparison and discussion

To compare the current situation with the results obtained with the model, the cost savings obtained through the utilisation of drones were computed. Consequently, in Table 14, the transportation costs and the savings obtained with the model results are presented.

Table 14 - Comparison between the current operations costs and the model results

Day	Current transportation costs (€)	Transportation costs with drones (€)	Savings with drones (€)	Savings with drones (%)
55	18,28 €	10,71 €	7,57 €	41%
123	10,32 €	2,61 €	7,71 €	75%
98	10,32 €	2,49 €	7,83 €	76%
127	5,27 €	2,17 €	3,10 €	59%
26	6,14 €	2,19 €	3,95 €	64%
104	7,96 €	3,55 €	4,41 €	55%
57	10,32 €	3,20 €	7,12 €	69%
126	15,70 €	8,57 €	7,13 €	45%
15	9,44 €	4,01 €	5,43 €	58%
150	6,14 €	1,74 €	4,40 €	72%
105	14,06 €	6,76 €	7,30 €	52%
96	13,56 €	7,12 €	6,45 €	48%
99	8,61 €	1,93 €	6,68 €	78%
53	3,13 €	0,04 €	3,09 €	99%
51	9,27 €	3,96 €	5,30 €	57%

Total	148,50 €	61,02 €	87,48 €	59%
Average	9,90 €	4,07 €	5,83 €	
Average savings with drones per month (€)			145,80 €	

It is possible to observe that the transportation cost savings are significant for every day of the sample tested with an average of 5,83 € saved per day. However, this sample represents only 10% of 6 months, since the 151 days corresponded to that period. Hence, in the previous table, these results are extrapolated to estimate the potential cost savings for one month. Furthermore, as portrayed in Figure 26, the higher savings in percentage correspond to the days with lower demand.

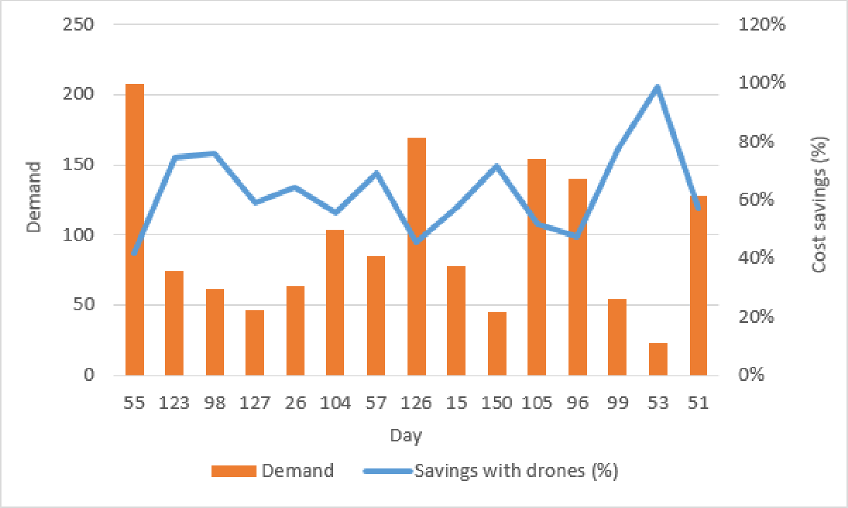


Figure 26 - Cost savings and demand of each day

Considering the drone is limited to 6 trips per day and has a lower capacity than the car, it is more efficient in days where the demand is lower. However, the cost savings in the days with higher demand still represent a significant value in euros.

5.3.1.4. Sensitivity analysis

Considering some of the assumptions and approximations made regarding certain model parameters, it is necessary to analyse the sensitivity of the model regarding the variation of these parameters. However, due to the volume of results required to test the whole sample of 15 days, the analysis was performed on either one or three days. From the cost perspective, there are two important parameters that might influence the results: the number of drone trips and the quantity of products delivered by car.

Number of drone trips

To analyse the sensitivity of the model regarding the variation of drone trips, the model was run for day 55 while considering a different number of drone trips available. The results obtained are presented in Table 15 and the computation results are displayed in appendix 5.

Table 15 - Sensitivity analysis for the variation of the number of drone trips (model 1a)

		Drone deliveries		Car routes			
Day	Number of drone trips	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation cost	Cost difference
55	0	0	0,000	4	250,000	14,63 €	-
	2	2	33,320	4	245,000	14,06 €	0,57 €
	4	4	65,820	3	209,000	12,52 €	1,54 €
	6	6	134,340	3	182,000	10,71 €	1,81 €
	8	8	167,660	2	177,000	10,13 €	0,57 €

By varying the number of drone trips available in one day, it was possible to register the impact of this variation in the outputs of the model. The results demonstrate that drone deliveries are preferred if available with the corresponding cost savings. However, from the column with the cost differences, which computes the differences between the transportation costs at each increment in the number of drone trips available, the difference decreased from 6 drone trips to 8 trips. Therefore, in the day analysed, the cost impact of utilising more drones decreases with each drone trip after 6 drone trips.

Products delivered by car

Since this parameter was selected by utilising estimations and assumptions, it is relevant to test the sensitivity of the model to its variation. Hence, days 55, 123 and 98 were analysed considering different values for this parameter: 20, 30 and 40. The results obtained are presented in Table 16. The computational results are available in appendix 5. For all the days analysed, increasing the maximum number of products delivered by car decreases the transportation costs. However, in two of these days, the cost difference is lower from 30 products to 40 products in relation to the cost difference from 20 products to 30 products. On another note, for each day, the value of products delivered by car that produces the highest total flight time of drones is 30.

Table 16 - Sensitivity analysis for the variation of the quantity of products delivered by car (model 1a)

		Drone deliveries		Car routes			
Day	Products delivered by car	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation cost	Cost difference
55	20	6	123,780	5	286,000	16,23 €	-
	30	6	134,340	3	182,000	10,71 €	5,52 €
	40	5	109,700	2	141,000	8,56 €	2,15 €
123	20	4	97,330	1	69,000	4,02 €	-
	30	6	134,910	1	42,000	2,61 €	1,41 €
	40	5	108,020	1	42,000	2,60 €	0,01 €
98	20	5	130,400	1	48,000	3,19 €	-
	30	6	135,810	1	37,000	2,49 €	0,70 €
	40	6	115,350	1	24,000	1,74 €	0,75 €

5.3.2. Time analysis

As in the previous cost analysis, this subsection will contemplate a study of the current situation, the model results and a comparison between the current situation and the results of the model. Finally, the model sensitivity to the existence of extra drone batteries as well as a different demand aggregation by the car will be analysed.

5.3.2.1. Current situation

For every day of the sample of 15 days, an estimate of the transportation time was calculated with the methods in subchapter 5.2. Similarly to the previous cost analysis, the transportation times were calculated independently for each day and client with no car routes serving multiple clients. These transportation times are depicted in Table 17.

Table 17 - Estimate of the transportation time of the current operations

	Transportation time (min)					
Day	Client 1	Client 2	Client 3	Client 4	Client 5	Total
55	28	160	114	12	0	314
123	28	40	38	12	48	166
98	28	40	38	12	48	166
127	0	80	0	12	0	92
26	28	40	0	12	24	104
104	0	80	0	24	24	128
57	28	40	38	12	48	166
126	28	80	114	12	24	258
15	0	80	38	12	24	154
150	28	40	0	12	24	104
105	0	120	76	12	24	232
96	28	40	114	12	24	218
99	28	40	38	12	24	142
53	0	40	0	12	0	52
51	28	80	0	24	24	156

Total time (min)	2.452
Average time per day (h)	2,72

Since every client is served independently the number of times needed to fulfil the demand, the transportation times are proportional to the number of trips or zero. Therefore, the variability of these times from day to day is caused by the demand. This variability can be observed in Figure 27.

Figure 27 - Products' quantity demanded and transportation time of each day in the current operations

Given that these results are for the same sample in the cost analysis, a similar outcome is produced due to the correlation that exists between the transportation time and the distance travelled. However, since these two parameters are not exactly proportional, there are still small differences. Regardless, the quantity demanded by each client still explains the differences in the transportation time for each day analysed. By calculating for each client the average transportation time per product, it is possible to analyse the impact of each client in the transportation time. These calculations are portrayed in Figure 28.

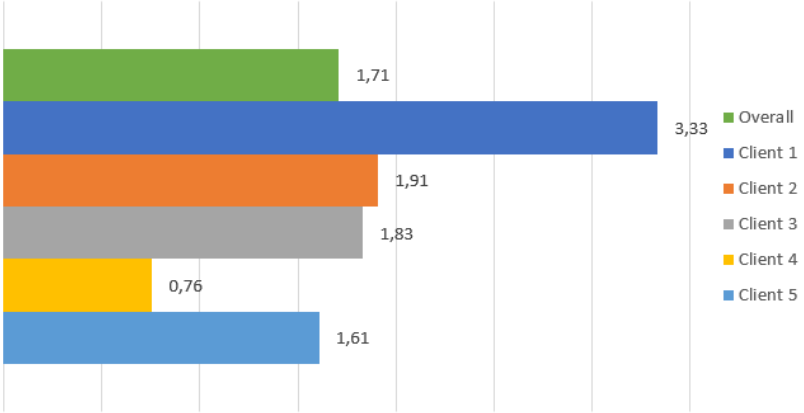


Figure 28 - Average transportation time in minutes per product

The highest average transportation time per product is from client 1, even though this client is one of the closest clients to Farmácia da Lajeosa in kilometres. However, there are two factors that cause an increase in this value: the low demand of this client which causes less efficient deliveries and the routes between the depot and this client that include several curvy roads. Conversely, client 4 has the lower transportation time per product delivered. Client 5 has a similar demand to client 4 but the round trip to client 5 takes almost two times as much as the round trip to client 4. Finally, clients 2 and 3 are closer to the overall average, but they also represent most of the demand. Consequently, the distribution of the transportation time per client was calculated and it is displayed in Figure 29

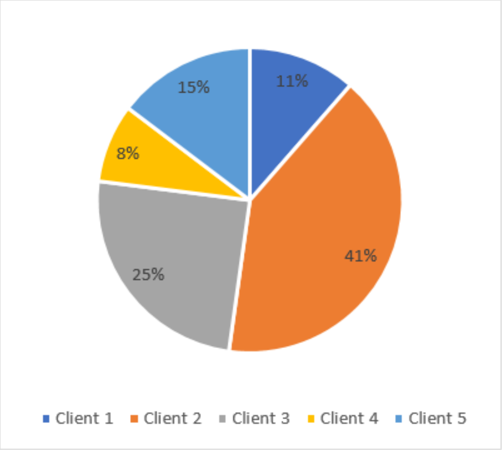


Figure 29 - Transportation time per client as a percentage of total time

From the clients' percentage of the total transportation time, it is possible to conclude that serving clients 2 and 3 represents the largest contribution to the time needed for the deliveries. Furthermore, the transportation times needed to serve client 4 are lower than those needed for clients 1 and 5 even though client 4 has a higher demand. The factor that mostly contributes to this outcome is the short distance between the depot and client 4.

5.3.2.2. Model results

The results for the daily delivery operations model with time minimisation (1b) were obtained by implementing and solving this model for each day of the sample of 15 days extracted from the demand data provided by Farmácia da Lajeosa. By utilising this sample, it is possible to compare the results obtained with the estimations made for the current delivery operations. Furthermore, the number of drone trips was not limited in the model considering that the introduction of the drone recharge time already constrains this number. The results obtained from the model consider not only the drone but also car routes. Therefore, the transportation times were not allocated to clients. Conversely, the transportation cost for all 15 days is displayed. In that regard, since the objective of this model is to minimise time, the results produced are different than those obtained for cost minimisation and the solutions found are costlier. Moreover, the time spent waiting for the drone to recharge in each day was computed since the time the drone needs to recharge influences the solutions found. Given the volume of results obtained from the 15 runs of the model, the data was summarised and it is presented in Table 18. The computational results are available in appendix 6.

Table 18 - Results obtained with the drone delivery model for the sample of 15 days (model 1b)

	Drone deliveries			Car routes		Transportation time (min)	Transportation cost
Day	Total	Total flight time of drones (min)	Total time waiting for recharge (min)	Total	Total travel time of cars (min)		
55	3	65,82	120,00	3	205,00	205,00	12,95 €
123	1	26,89	0,00	1	74,00	74,00	4,63 €
98	1	22,84	0,00	2	72,00	72,00	4,86 €
127	1	16,66	0,00	2	78,00	78,00	4,72 €
26	1	16,66	0,00	1	42,00	42,00	2,57 €
104	1	26,89	0,00	2	90,00	90,00	5,89 €
57	1	16,66	0,00	2	92,00	92,00	5,70 €
126	1	21,94	0,00	3	178,00	178,00	11,28 €
15	2	33,32	60,00	2	106,00	106,00	6,58 €
150	1	16,66	0,00	1	42,00	42,00	2,57 €
105	2	45,68	60,00	3	151,00	151,00	9,52 €
96	2	53,78	60,00	3	149,00	149,00	9,64 €
99	1	22,84	0,00	1	48,00	48,00	3,16 €
53	1	16,66	0,00	1	45,00	45,00	2,95 €
51	1	26,89	0,00	2	93,00	93,00	6,10 €

Total cost	93,10 €
Total time (min)	1.465
Average time per day (h)	1,63

Finally, the relation between the transportation time and the products' quantity demanded by each client is demonstrated in Figure 30.

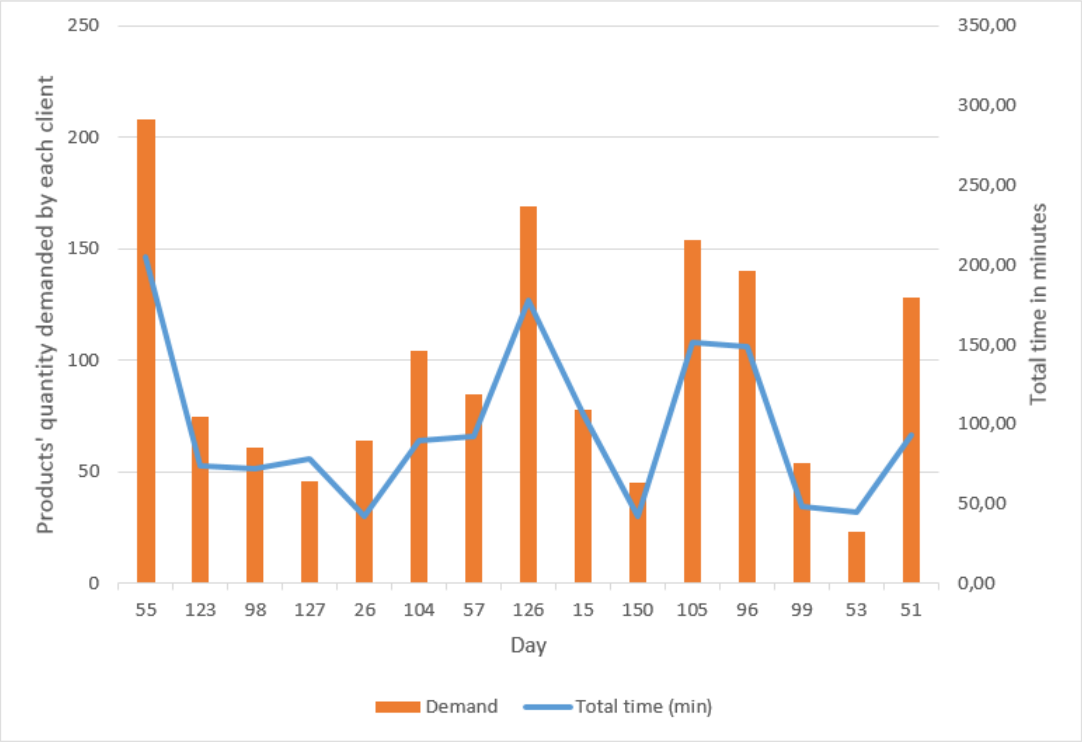


Figure 30 - Products' quantity demanded and transportation time of each day with drones

It is possible to observe in Figure 30 that the demand influences the transportation time. Nevertheless, a higher demand does not necessarily mean a longer transportation time since in some days the drone might help produce more efficient car routes.

5.3.2.3. Comparison and discussion

The current situation will be compared with the results obtained from the model by calculating the time savings obtained with the employment of drones in delivery. Therefore, these savings will be displayed in Table 19 along with the transportation time of the current operations, as well as the transportation times obtained with the model.

Table 19 - Comparison between the current operations transportation time and the model results

Day	Current transportation time (min)	Transportation time with drones (min)	Savings with drones (min)	Savings with drones (%)
55	314,00	205,00	109,00	35%
123	166,00	74,00	92,00	55%
98	166,00	72,00	94,00	57%
127	92,00	78,00	14,00	15%
26	104,00	42,00	62,00	60%
104	128,00	90,00	38,00	30%
57	166,00	92,00	74,00	45%
126	258,00	178,00	80,00	31%
15	154,00	106,00	48,00	31%
150	104,00	42,00	62,00	60%
105	232,00	151,00	81,00	35%
96	218,00	149,00	69,00	32%
99	142,00	48,00	94,00	66%
53	52,00	45,00	7,00	13%
51	156,00	93,00	63,00	40%

Total	2452,00	1465,00	987,00	40%
Average	163,47	97,67	65,80	

The minimisation of the transportation times utilising car routes and drones results in daily time savings of 65,8 minutes on average, which is more than one hour per day of time saved on the transportation of products. Furthermore, these time savings represent not only faster deliveries, but also less time spent by an employee delivering these products. The savings obtained in each day, along with the respective demand of the clients, are displayed in Figure 31. The lower savings obtained in the days with higher demand can be explained by the necessity to recharge the drone after each flight. This limitation reduces the advantages of drones when the objective is to deliver large quantities fast to many customers. The time savings are higher in the days that have customers with a small quantity of products demanded. In these situations, the drone can serve this customer faster than the car. However, if the quantities ordered are higher than the capacity of the drone it is not time efficient for the drone to deliver multiple times to the same customer, instead of sending a car. Even two deliveries to the same customer might not be time efficient as a consequence of the drone need to recharge between flights.

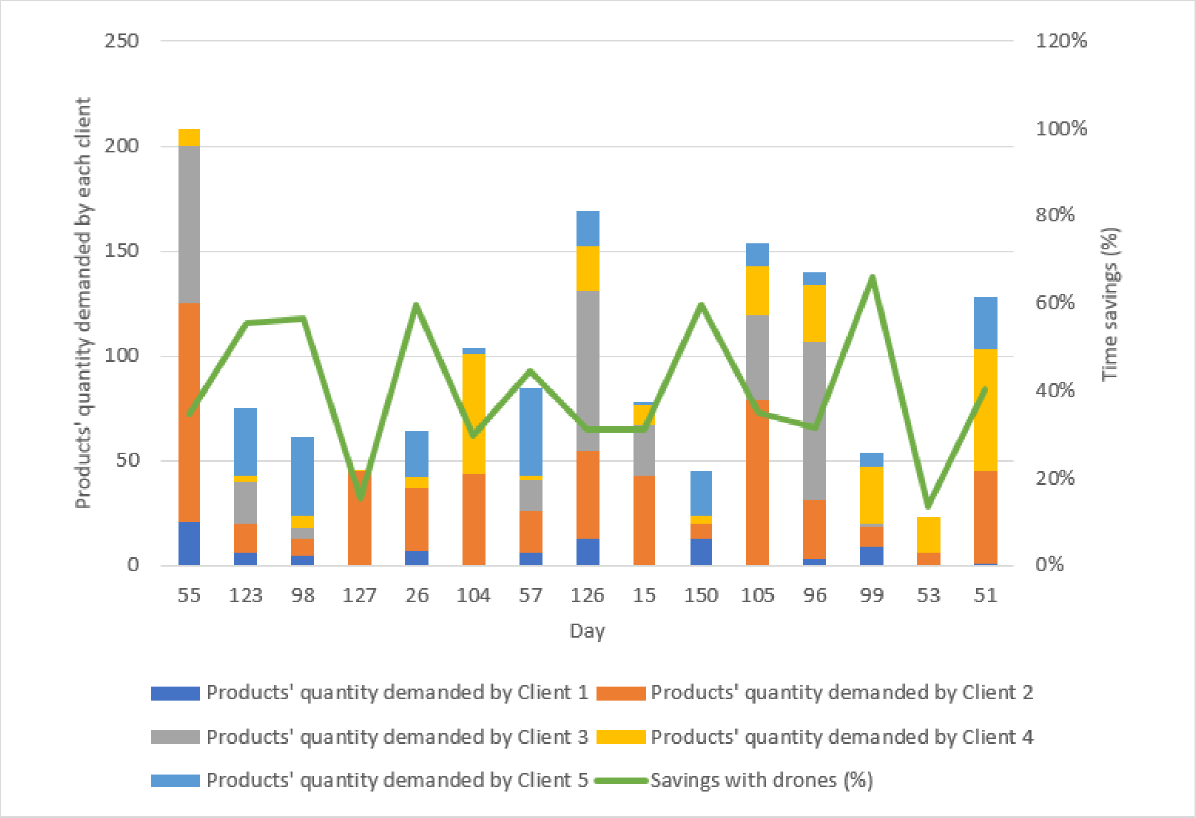


Figure 31 - Time savings and demand of each day

5.3.2.4. Sensitivity analysis

Given the assumptions on some model parameters a sensitivity analysis was performed to assess how the outputs of the model change with the variation of these parameters. In the analyses only three days of the sample were tested due to the volume of results required to test the whole sample of 15 days. There are two relevant parameters from the time perspective, the recharge time of drones and the quantity of products delivered by car.

Recharge time

Since it is possible to have some replacement batteries, the absence of recharge time has been tested to understand the impact in the model outputs. Hence, the model was run for three days while considering the recharge time to either 60 minutes or inexistent. The results from these runs are displayed in Table 20. The computational results are available in appendix 6. Given the results obtained, there were a lot more drone deliveries when drones did not have to wait until the drone recharged completely. However, the impact on time was relatively low since it did not reduce the number of car routes in any of the days, only reduced its length. Nevertheless, from a tactical standpoint it will always be advantageous to have the drone ready after a flight since the demand is not known beforehand. Only one replacement battery could be very useful.

Table 20 - Sensitivity analysis for the variation of the recharge time (model 1b)

		Drone deliveries			Car routes		
Day	Drone recharge time (min)	Total	Total flight time of drones (min)	Total time waiting for recharge (min)	Total	Total travel time of cars (min)	Transportation time (min)
55	60	3	65,820	120,000	3	205,000	205,000
55	0	6	134,340	0,000	3	177,000	177,000
123	60	1	26,890	0,000	1	74,000	74,000
123	0	3	58,860	0,000	1	68,000	68,000
98	60	1	22,840	0,000	2	72,000	72,000
98	0	3	56,160	0,000	2	66,000	66,000

Products delivered by car

Considering the demand is not known beforehand, this parameter was defined by analysing the data from the current operations of Farmácia da Lajeosa. However, it is important to test the sensitivity of the model when the value of this parameter is changed. Therefore, the days 55, 123 and 98 were tested for three different values of the parameter. In Table 21, the results provided by the model are displayed. The computational results are available in appendix 6.

Table 21 - Sensitivity analysis for the variation of the quantity of products delivered by car (model 1b)

		Drone deliveries			Car routes			
Day	Products delivered by car	Total	Total flight time of drones (min)	Total time waiting for recharge (min)	Total	Total travel time of cars (min)	Transportation time (min)	Time difference (min)
55	20	4	90,460	180,000	5	282,000	282,000	-
	30	3	65,820	120,000	3	205,000	205,000	77,00
	40	3	49,980	120,000	3	171,000	171,000	34,00
123	20	1	16,660	0,000	2	92,000	92,000	-
	30	1	26,890	0,000	1	74,000	74,000	18,00
	40	1	16,660	0,000	1	68,000	68,000	6,00
98	20	1	22,840	0,000	2	72,000	72,000	-
	30	1	22,840	0,000	2	72,000	72,000	0,00
	40	1	22,840	0,000	1	48,000	48,000	24,00

In each day analysed the time needed to transport all the products decreases with the increase of the quantity of products delivered by car. However, the number of drone deliveries is not reduced when increasing this parameter from 30 to 40. The role of the drone is to deliver small quantities of products to single clients and even with the increased capacity of the car the drone is still the most time efficient mode for these small deliveries.

5.4. Results of the models for single delivery operations

The single delivery operation models provide the optimal solution concerning the drone deliveries and the car routes required to serve a set of clients either by minimising cost or time. In these models the demand as a quantity of products required is not considered. Instead the clients need to be served once and it may or may not be possible to serve them by drones. Therefore, to contribute with valuable information to the problem of Connect Robotics and Farmácia da Lajeosa, three scenarios were analysed to understand the benefits of drones in the delivery of products. The first scenario tested was one without drone restrictions where every client could be served by drone. The second scenario considers a situation where the clients further away from the depot cannot be served by drone, since there are concerns regarding the effect of the extra weight of the container in the maximum flight time of the drone and consequently its capacity to reach these clients. Finally, the third scenario considers that the customers with higher average demand cannot be served by drone. The reasoning for testing this scenario is the drone lack of capacity to deliver large orders. Hence, it would be a common situation that the drone is unable to serve these customers. Furthermore, each scenario will be tested with no drones available, one drone trip available and two drone trips available, considering in this last case that there is one extra battery and the drone can make a second delivery immediately after the first. In Figure 32, the scenarios analysed are displayed and characterised.

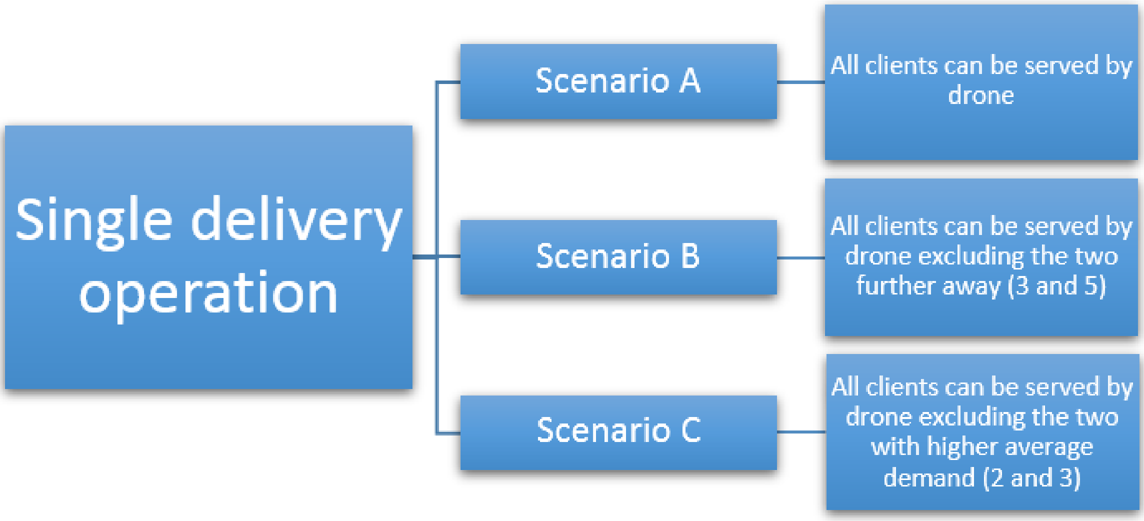


Figure 32 - Scenarios analysed with the single delivery operation models

5.4.1. Cost analysis

The single delivery operation model with cost minimisation (2a) was implemented and solved with the data collected from Farmácia da Lajeosa regarding the locations of the clients and considering the three scenarios proposed. The solutions obtained will be described and discussed regarding the benefits of drones from a cost perspective. Furthermore, the computational results are available in appendix 7.

5.4.1.1. Scenario A

This scenario does not consider any restrictions for the drone utilisation. Hence, it will provide an insight on the drone deliveries that represent a higher cost saving from all clients by considering the distances between them for the two transportation modes: car and drone. For instance, the road network in the region of Farmácia da Lajeosa has several curvy roads, which do not affect the drone. However, it is not easy to pinpoint where the higher cost savings can be obtained and this scenario will provide some answers in that direction.

When the car was the only delivery vehicle, the model solution was a single car route that started in client 3, which is the client further away from the depot. From this client, the car route went to the closest client until returning to the depot. According to the outputs of the model, the total transportation time for this car route is 74 minutes and it costs 4,57 € in fuel. It is important to note that it was a possibility that the solution contained two car routes, however that was not the optimal solution. The solution obtained is portrayed in Figure 33.

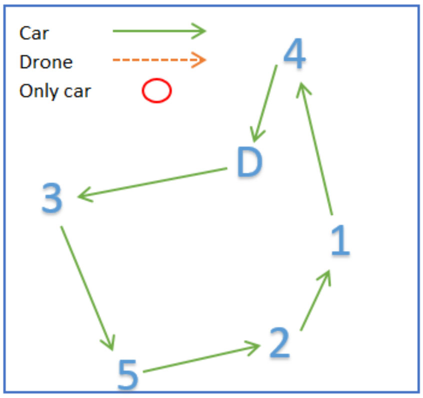


Figure 33 - Vehicle routing for scenario A without drones (model 2a)

As explained before, the same scenario was tested while considering one drone delivery. In the solution obtained, the drone is employed in the delivery to client 3 and there is still one car route, although a more cost-efficient one since the drone delivered to the client further away. In this solution, the drone took 22,84 minutes to make the delivery and return. Meanwhile, the car route with one less customer had its travel time reduced in 26 minutes. The cost of this solution is 3,16 € which represents 31% cost savings when compared to the solution without drones. This solution is depicted in Figure 34.

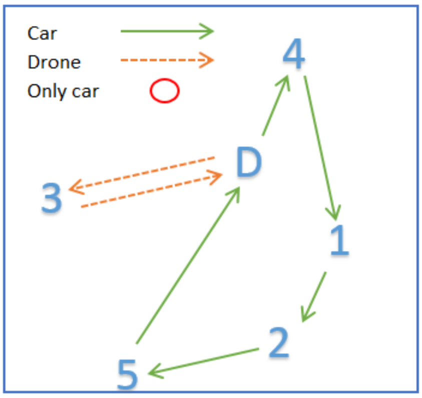


Figure 34 - Vehicle routing for scenario A with one drone trip available (model 2a)

The final test considered two drone deliveries instead of only one. The optimal solution in this scenario was to make both drone deliveries since it still represented savings in the cost of transportation. One drone delivery was to client 3 and the other was to client 4. By delivering to these clients with drones it was possible to reduce the car route time in 5 minutes when compared to the solution with one drone and 31 minutes when compared to the solution with no drones. However, the drone flight time will still require an operator monitoring it. Regarding cost, whose minimisation is the objective of the model, it was reduced significantly with a cost savings of 44% regarding the solution without drones. This is explained not only by the great cost efficiency of drone versus the car, but also to the route optimisation that is possible when the drone serves some of the customers. In Figure 35, the routes of this solution are presented.

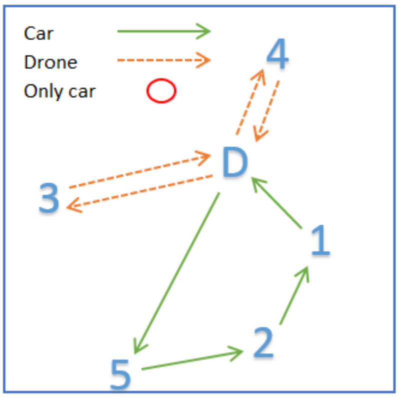


Figure 35 - Vehicle routing for scenario A with two drone trips available (model 2a)

In the two situations tested with drones, the utilisation of the available drone deliveries by the model is a relevant fact. If there were no benefits to utilising the drones the model solution could be two or three car routes. However, the solutions obtained did change the car routes to include the drone deliveries and the cost savings are significant. Finally, a summary of these results is displayed in Table 22

Table 22 - Results obtained with the drone delivery model for scenario A (model 2a)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Cost savings (%)
A	0	0	0,00	1	74,00	74,00	4,57 €	-
	1	1	22,84	1	48,00	48,00	3,16 €	31%
	2	2	39,50	1	43,00	43,00	2,58 €	44%

5.4.1.2. Scenario B

It is possible that the drone might not be able to reach every client due to the maximum flight time of the drone being affected by the weight of the container and also its effect on aerodynamics. Therefore, in this scenario, the model is implemented and solved considering that the drone cannot serve clients 3 and 5. These clients are the further away from the depot, hence those that might be out of reach for the drone to make the deliveries.

When this scenario is implemented and solved by the model without considering drone deliveries, the solution of the model is the same as the one presented in Figure 33 since the constraint added in this scenario only affects drones. Nevertheless, that solution is the basis for comparison with the solutions that consider drone deliveries.

If there is one drone delivery in this scenario, the optimal solution obtained by the model utilises the drone to serve client 4 and then a car route visits the remaining clients. Considering the constraints on serving clients 3 and 5, the drone serves the closest customer, which enables a more cost-efficient car route. As expected, the cost savings are less impactful than in scenario A, but the drone is still included in the model solution. Comparing it with the solution without drones, the drone delivery reduces the cost in 13%, from 4,57€ to 4,00€. Meanwhile, the car travel time is reduced in only 5 minutes. In Figure 36, the routing soluion is portrayed.

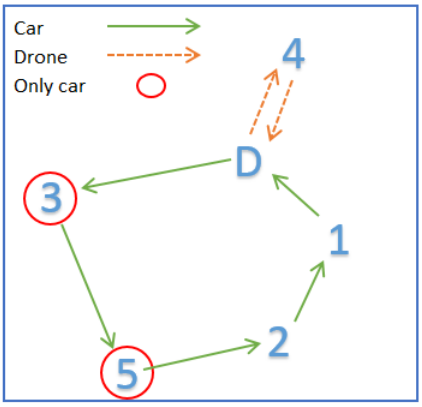


Figure 36 - Vehicle routing for scenario B with one drone trip available (model 2a)

When considering two drone deliveries instead of one, the optimal solution changes significantly. In this solution neither drone trip serve client 4, instead the drone serves clients 1 and 2, while the car follows a different route that starts in client 5 and ends in client 4. This car route takes 7 minutes less to complete than the route generated in the solution with one drone trip available, but the drone flies for a total of 37,25 minutes, which requires an employee to monitor. Moreover, the total cost of transportation is reduced in 16% to total of 3,85€. However, when compared to the previous solution with only one drone delivery the difference is small. The vehicle routing of this solution is presented in Figure 37.

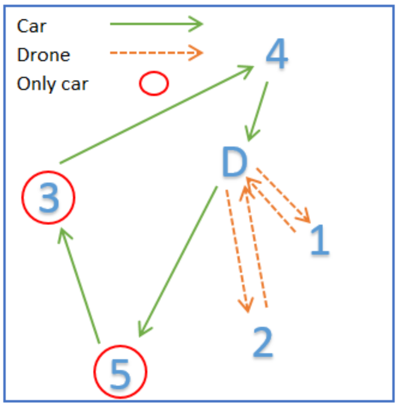


Figure 37 - Vehicle routing for scenario B with two drone trips available (model 2a)

Although in this scenario drone deliveries do not generate as much savings as in scenario A, it is relevant to notice that drone deliveries were always a part of the optimal solution again and every drone trip available was utilised. The transportation time was also reduced with the utilisation of drones even without time minimisation as the objective function, due to the increased efficiency of the car routes that did not have to cover as many kilometres. These results are summarised in Table 23.

Table 23 - Results obtained with the drone delivery model for scenario B (model 2a)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Cost savings (%)
B	0	0	0,00	1	74,00	74,00	4,57 €	-
	1	1	16,66	1	69,00	69,00	4,00 €	13%
	2	2	37,25	1	62,00	62,00	3,85 €	16%

5.4.1.3. Scenario C

Sometimes the order of a client cannot be delivered by a drone due to their size, since the drone does not have the same capacity as the car. Hence, it is relevant to test how the model solution changes given a scenario where the drone cannot deliver to some of the clients. The clients considered in this scenario are the clients 2 and 3, since their higher average demand makes the scenario tested plausible.

Similarly to scenario A and B, the implementation of the model without drones provides the results portrayed in Figure 33, since the constraints added only pertain to drone deliveries. It still is the basis for comparison.

The optimal solution with one drone trip available is delivering by drone to client 4 and delivering by car to the other customers in a single car route. This is the same solution as in scenario B, since serving client 4 by drone is still the most cost-efficient solution when it is not possible to utilise the drone to deliver the orders of client 2 and 3. The cost savings are 13% and the transportation takes 5 minutes less. The vehicle routing is displayed in Figure 38.

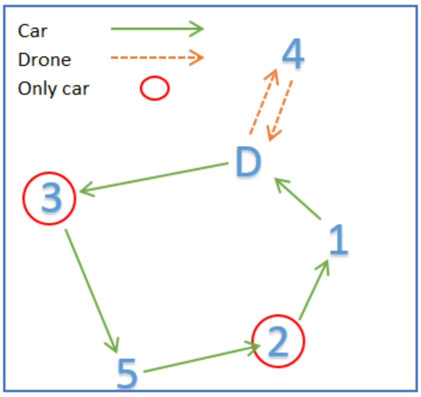


Figure 38 - Vehicle routing for scenario C with one drone trip available (model 2a)

For two drone deliveries the optimal solution obtained with the model for scenario C is necessarily different than the optimal solution for scenario B, since in that scenario one of the drone deliveries was made to client 2 and in this scenario that client cannot be served by drone. Regardless, the solution found still utilised both drone deliveries. The delivery to client 4 remained and the other drone delivery was made to client 5. However, the cost savings were only 0,02€ when comparing to the solution with one drone delivery. The vehicle routing obtained is presented in Figure 39.

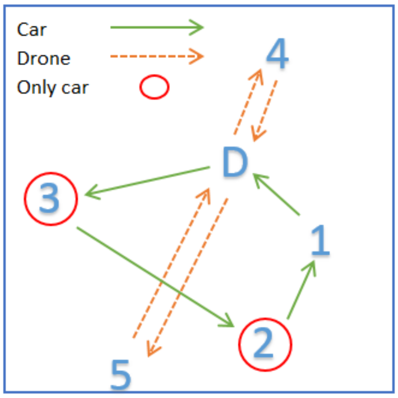


Figure 39 - Vehicle routing for scenario C with two drone trips available (model 2a)

If the drone is not able to deliver the orders to these two clients, the benefit of having the drone available for a second delivery is very slim. However, this does not affect the usefulness of the ability to fly the drone a second time immediately after one flight if two different delivery operations happen within a short period. In fact, from the results of the analysis of the daily delivery operations, more than one delivery operation is required to meet the clients' demand in some days. The results for scenario C are summarised in the Table 24.

Table 24 - Results obtained with the drone delivery model for scenario C (model 2a)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Cost savings (%)
C	0	0	0,00	1	74,00	74,00	4,57 €	-
	1	1	16,66	1	69,00	69,00	4,00 €	13%
	2	2	43,55	1	68,00	68,00	3,98 €	13%

5.4.2. Time analysis

For the analysis from a time perspective, the single delivery operation model with time minimisation (2b) was implemented and solved for the same three scenarios. Similarly to the cost analysis, the distances and times between clients and the depot for both the car and the drone fed to this model were calculated from the data provided by Farmácia da Lajeosa. The time benefits of each scenario will be analysed and discussed through the outputs of the model. Moreover, the computational results for solving this model are available in appendix 7.

5.4.2.1. Scenario A

Since there are no constraints on which clients to serve in this scenario, it will be possible to analyse if drone deliveries reduce the time needed to make the deliveries and how much time can potentially be saved with drone deliveries. Additionally, the solutions generated by the drone delivery model will indicate which deliveries the drone should make, if any, to minimise the total transportation time to deliver the all the clients.

The first model implementation in this scenario does not consider drones, hence all the deliveries have to be made by the car. The solution obtained comprised a car route starting in client 4 and visiting the other clients until returning to the depot. The solutions' total transportation time required is 74 minutes and costs 4,62€. This solution is depicted in Figure 40 and it will serve as the basis for comparison with all the solutions with drones.

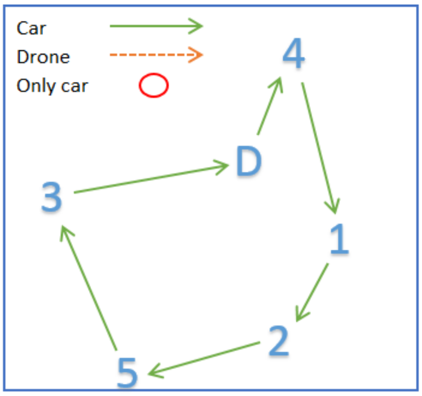


Figure 40 - Vehicle routing for scenario A without drones (model 2b)

When testing this scenario with one drone trip available, the solution provided by the model included a drone delivery to client 3 and a car route through all the remaining clients. This drone delivery to client 3 takes approximately 11,42 minutes, while a similar trip by car from the depot to this client takes 19 minutes. If the returning trip is taken under consideration the difference is even more significant. Regardless, since the car is not serving any clients directly in the model solution, the benefits of the drone delivery are measured on how more time-efficient the car route is. Hence, with a transportation time of 48 minutes instead of 74 minutes, the time savings obtained are 35%. Since the solution is the same as the one obtained in scenario A with model 2a, it has already been portrayed in Figure 34.

If there are two drone trips available instead of one, the solution of the model utilises both these drone deliveries to serve clients 3 and 4 since it is still possible to save time with the extra drone trip. The transportation time of the solution obtained reduces the car route in 32 minutes when compared with the solution without drones, which represents a total time savings of 43% for the transportation time required to serve all customers. However, the drone has a flight time of 39,5 minutes to make the two round trips in the solution. The routes of this solution are displayed in Figure 41.

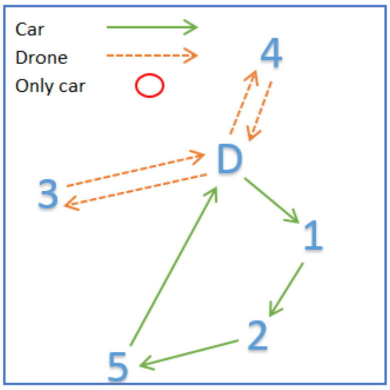


Figure 41 - Vehicle routing for scenario A with two drone trips available (model 2b)

Utilising drones for deliveries in this scenario generates significant time savings since the drone is able to serve clients individually faster than the car. The advantage of the car is to make routes through several clients and the employment of drones to deliver to some of the clients significantly improves the time efficiency of these routes. The summary of the results obtained for this scenario are presented in Table 25.

Table 25 - Results obtained with the drone delivery model for scenario A (model 2b)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Time savings (%)
A	0	0	0,00	1	74,00	74,00	4,62 €	-
	1	1	22,84	1	48,00	48,00	3,16 €	35%
	2	2	39,50	1	42,00	42,00	2,58 €	43%

5.4.2.2. Scenario B

In this scenario it is tested what are the potential benefits in the transportation time of utilising the drone for deliveries if the drone maximum flight time is reduced and it is no longer able to serve clients 3 and 5. Hence, the single delivery operation model with time minimisation was implemented with that additional constraint.

The results obtained with the model when there are no drone deliveries available are the same as those portrayed in Figure 40, since the constraint only affects the deliveries by drone. However, that solution is still the basis of comparison.

If a drone delivery is available, the solution of the model assigns the drone to client 4 which reduces the total transportation time in 6 minutes, which represents a time saving of 8%. Client 4 is the closest client to Farmácia da Lajeosa and consequently removing this client from the car route does not generate savings similar to those obtained in scenario A. However, utilising the drone still reduces the transportation time and the drone only takes 16,66 minutes to deliver and return. In Figure 42, the vehicle routing of this solution is portrayed.

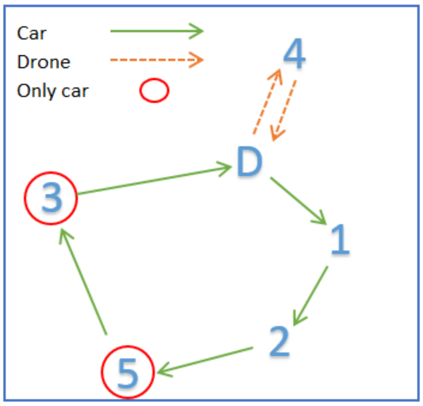


Figure 42 - Vehicle routing for scenario B with one drone trip available (model 2b)

In the optimal solution of this scenario for two drone trips available, the client 4 is no longer served by the drone. Instead, the drone deliveries are utilised in the delivery of products to clients 1 and 2. The extra drone delivery increases the drone flight time in 37,25 minutes but reduces the transportation time in 18% when compared to the solution without drones. The solution obtained is portrayed in Figure 43.

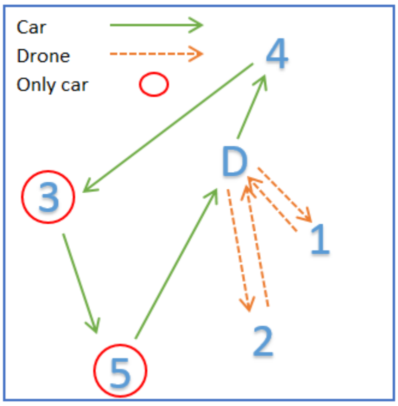


Figure 43 - Vehicle routing for scenario B with two drone trips available (model 2b)

The time savings in scenario B are lower that those in scenario A. The inability to serve the clients that are further away from Farmácia da Lajeosa has a significant impact. However, every drone delivery still represented savings in time. The results obtained for this scenario are summarised in Table 26.

Table 26 - Results obtained with the drone delivery model for scenario B (model 2b)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Time savings (%)
B	0	0	0,00	1	74,00	74,00	4,62 €	-
	1	1	16,66	1	68,00	68,00	4,05 €	8%
	2	2	37,25	1	61,00	61,00	3,85 €	18%

5.4.2.3. Scenario C

Considering the limited transportation capacity of the drone, it was important to test the model for this scenario where the drone is not able to serve clients 2 and 3.

If it is not possible to deliver by drone, the model solution is equal to the one portrayed in Figure 40, since the added constraint only affects the deliveries by drone.

When the model is solved with one delivery by drone, client 4 is served by drone and the car route visits the remaining clients. This solution reduces the transportation time in 8%. Meanwhile, the drone flight time is only 16,66 minutes since client 4 is the client closer to the depot. The routing of the solution is portrayed in Figure 44.

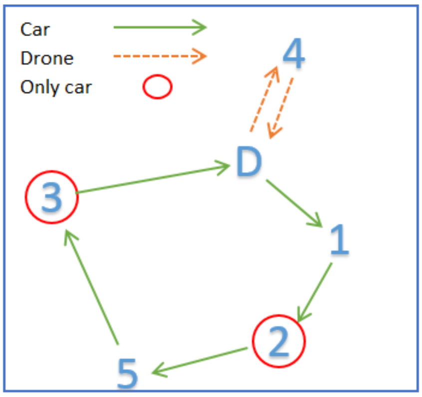


Figure 44 - Vehicle routing for scenario C with one drone trip available (model 2b)

If two drones are available to deliver, the solution that minimises the transportation time features a drone deliver to client 4 and another to client 2. This solution reduces the transportation time in 1 minute when comparing to the solution with one drone trip available despite increasing the cost in 0,17€. This solution routes are depicted in Figure 45.

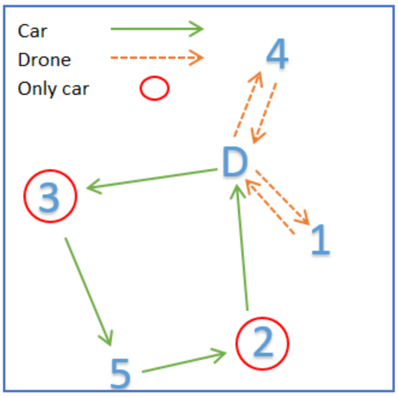


Figure 45 - Vehicle routing for scenario C with two drone trips available (model 2b)

If clients 2 and 3 cannot be served by drone, the transportation time is still reduced in 7 minutes but the difference between utilising one or two drones is only 1 minute. The summary of the solutions obtained in this scenario is presented in Table 27.

Table 27 - Results obtained with the drone delivery model for scenario C (model 2b)

		Drone deliveries		Car routes				
Scenario	Drones trips available	Total	Total flight time of drones (min)	Total	Total travel time of cars (min)	Transportation time (min)	Total cost (€)	Time savings (%)
C	0	0	0,00	1	74,00	74,00	4,62 €	-
	1	1	16,66	1	68,00	68,00	4,05 €	8%
	2	2	31,97	1	67,00	67,00	4,22 €	9%

5.4.3. Discussion of the results obtained with the single delivery operation models

It is possible to obtain significant cost savings in delivery operations where the drone can deliver to every client. In scenario A, drones represented cost savings of 31% with one drone employed and 44% with two drones employed. Similarly, if the goal is to minimise time, drones can reduce the transportation time in 43% with two drone deliveries, which is a difference of 32 minutes. However, when some clients cannot be served by drone, the cost and time savings are significantly reduced. In scenario B, the cost savings are only 13% and 16% for one and two drone deliveries, respectively. Hence, the utilisation of drones can still provide a great flexibility to serve clients, but it does not have the same impact on costs. As for the time savings, they are also lower in scenario B. One drone can reduce the transportation time in 6 minutes and another reduces it in 7 more minutes. Nevertheless, this is a scenario that can be entirely avoided if the drone can serve the clients further away, which is not certain at this point. As for scenario C, it is certainly a plausible delivery operation given the usual demand in Farmácia da Lajeosa. Similar situations will occur, where the orders are simply too large for the drone to carry them. The results obtained in the scenario tested demonstrate that the both the cost and time savings are reduced significantly. The cost savings were only 13% for both one and two drone deliveries, with a difference of 0,02% between them, and the time savings were only 8% and 9%. Nevertheless, all drone trips available were still a part of the optimal solution.

However, it is important to observe that in all the scenarios the impact of adding the possibility of one drone trip is higher than the impact of adding a second drone trip. This is a consequence of the lack of alternatives for the drone since there are only 5 clients and in two of the scenarios only 3 can receive deliveries by drone. Therefore, the utilisation of a second drone trip in the same delivery operation does not create the same impact. However, the usefulness of having a substitute battery can be justified by the readiness of the drone to be utilised in a second delivery operation that occurs in a short amount of time after a first delivery operation.

Finally, the results obtained with the two different objective functions are not very different, which is caused by the existent correlation between the costs and the time in the model and in reality as well. These differences can be observed in Table 28, and in several of the situations tested there is no difference between the solutions for cost and time minimisation. And the differences that exist are always small. Considering there are only 5 clients and some of the scenarios constrain the delivery by drones to some of the clients, the pool of alternatives is also not very large which contributes to this situation.

Table 28 - Comparison of the results obtained with models 2a and 2b

		Transportation time (min)			Total cost (€)		
Scenario	Drones trips available	Cost minimisation	Time minimisation	Difference	Cost minimisation	Time minimisation	Difference
A	0	74,00	74,00	0,00	4,57 €	4,62 €	0,05 €
A	1	48,00	48,00	0,00	3,16 €	3,16 €	- €
A	2	43,00	42,00	1,00	2,58 €	2,58 €	- €
B	0	74,00	74,00	0,00	4,57 €	4,62 €	0,05 €
B	1	69,00	68,00	1,00	4,00 €	4,05 €	0,05 €
B	2	62,00	61,00	1,00	3,85 €	3,85 €	- €
C	0	74,00	74,00	0,00	4,57 €	4,62 €	0,05 €
C	1	69,00	68,00	1,00	4,00 €	4,05 €	0,05 €
C	2	68,00	67,00	1,00	3,98 €	4,22 €	0,23 €

6. Conclusions and future work

The growth of the drone industry has been fast due to the disruptive potential of the technology which enable its utilisation in several applications. One of these applications is the delivery of packages by drone, that has already justified an investment by numerous companies. The possibility to reach remote areas and perform last-mile deliveries fast and efficiently may be the answer to the omnichannel fulfilment and on-demand deliveries trend. Hence, the integration of drones in logistics is a transforming, challenging and valuable procedure. However, there are logistics challenges to overcome in order to employ drones in delivery, which are caused by its battery conditions, the low maximum payload, and the susceptibility to adverse weather conditions.

From the literature review it was possible to conclude that most of the drone research has been focusing in the model proposed by the partnership of Matternet and Mercedes, where drones are deployed from a delivery truck. However, the delivery service proposed by Connect Robotics to Farmácia da Lajeosa does not contemplate drones being launched from trucks. Instead, drones perform deliveries independently of other vehicles. Therefore, it was necessary to explore this different configuration. Hence, the features of the problem presented by Connect Robotics led to the development of a mathematical model for this new drone delivery problem, the PDSVRP, which is based on the PDSTSP of Murray and Chu (2015), where a drone delivers packages concurrently with a truck. The PDSVRP utilises the same notation as the PDSTSP but extends the formulation by including multiple vehicle routes and the utilisation of a maximum flight time of drones to calculate if clients can be served by drone. Furthermore, it also considers the demand of customers and the vehicles capacity. Therefore, instead of having the clients served once, their demand must be met, which may comprise multiple visits by the delivery vehicles. Furthermore, the transportation costs were also introduced, enabling the possibility to establish a new objective function, which is cost minimisation. Moreover, four variants of the model were created to approach the problem from different perspectives. The first perspective is the daily delivery operations with client's demand to be met with multiple deliveries to each client to enable the study of the impact of drones in a significant period. The other perspective is the single delivery operation which comprises a single delivery to each client and can provide support to the day-to-day planning of Farmácia da Lajeosa by analysing the benefits of drones in specific scenarios. Finally, both perspectives were studied for cost and time minimisation, hence the four variants.

After developing the PDSVRP, which incorporated the features of the situation portrayed in Farmácia da Lajeosa, the daily operations of Farmácia da Lajesoa were analysed to quantity the potential savings that could be obtained with the introduction of drones in their daily delivery operations, since it is not easy to quantify these benefits. By comparing the current operations with the results obtained with the daily delivery operations model, it was possible to determine that it is possible to obtain significant savings in transportation costs and times with a delivery drone, as well as an efficient car routing, since the transportation costs were reduced in 59% and the transportation times in 40%. Additionally, the utilisation of drones also reduces the time employees spend making the deliveries by car. However, this savings in transportation cost do not consider other costs such as the investment required, and this investment must also be considered in a decision to implement drones. Conversely, the model does not consider the costs of maintaining the car fleet and utilising drones might also lead to a reduction of the car fleet. Furthermore, the results obtained with the single delivery operation model provided additional information regarding the utilising drones for delivery in Farmácia da Lajeosa. If every client can be served by drone it is possible to reduce the cost of a delivery operation throughout all clients in 31% with one drone delivery and 44% with two drone deliveries. The savings in time are similar with less 35% of transportation time with one drone delivery and 43% with two. However, if some clients cannot be served by drone due to the limited capacity of the drone these benefits are reduced and the advantages of a second drone in the same delivery operation may not be justifiable. The same is true if the drone cannot reach the clients further away. Nevertheless, a substitute battery is still very useful since the drone can be utilised again immediately to participate in a second delivery operation that occurs in a short period. Nevertheless, given the assumptions and approximations, Farmácia da Lajeosa and Connect Robotics still need to verify the results obtained to check if they accurately depict the current situation and the scenario envisioned with the changes brought by drone deliveries.

Hereinafter, some ideas regarding future work are suggested since the limited scope of this dissertation that was necessary to focus on the situation at hand did not allow to explore all other possibilities surrounding the deliveries by drone.

First, it would be interesting to apply this model to a scenario with more clients and more drones available, since in the scenario studied the possibilities were narrowed with only five clients and the daily operations are still heavily dependent on another vehicle due to the size of the orders which reduces the advantages the drone can provide. Moreover, a possible extension to the model could be including vehicles' emissions to study the environmental impact of utilising drones, given the on-going trend to search for more environmentally friendly technologies and the belief that drones can be an answer in that regard. Furthermore, the possibility of installing drone-ports could be studied, since it would extend the range of drones by enabling their recharge without returning to the depot. This approach tackles the logistics challenges brought by the limited battery differently than the current approach of Connect Robotics. Moreover, given the two objective functions utilised, multicriteria optimisation could also be applied to this model to obtain more balanced solutions and evaluate trade-offs. Additionally, time window constraints could be added to the PDSVRP to analyse the benefits of drones in the delivery of time sensitive orders, considering that the drone is able to deliver packages faster than car in several situations and requires less effort. In the dissertation, the time windows constraints were not considered due to a lack of information regarding the urgency of the orders. However, it is also a common issue in the pharmaceutical industry. In what concerns the pharmaceutical industry and urgent deliveries, the utilisation of drones in another echelon of transportation could also be studied. Since it is possible that local distribution centres might be able to benefit from utilising drones when delivering to drugstores.

Finally, by extending the PDSTSP and apply the PDSVRP model variants developed to a real case, this dissertation stands as an interesting contribution to the literature regarding drone delivery problems.

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Appendices

Appendix 1 – Mathematical formulation of model 1b

Objective function

$$minimise\ w \tag{16}$$

Constraints

$$\mathrm{w} \geq \sum_{i \in C'} \sum_{t \in T} (\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} + recharge\ \times \left(\left(\sum_{i \in C'} \sum_{t \in T} y_{i,t} \right) - 1 \right) \tag{17}$$

$$w \geq \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} \tau^C_{i,j} \times x_{i,j,r} \tag{18}$$

$$(\tau^D_{0,i} + \tau^D_{i,c+1}) \leq e + M\big(1 - y_{i,t}\big) \qquad \forall i \in C', t \in T \tag{2}$$

$$\sum_{i \in C'} y_{i,t} \leq 1 \qquad \forall t \in T \tag{3}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} \sum_{r \in R} q^C \times x_{i,j,r} + \sum_{t \in T} q^D \times y_{j,t} \geq demand_j \qquad \forall j \in C \tag{4}$$

$$\sum_{j \in N_+} x_{0,j,r} \leq 1 \qquad \forall r \in R \tag{5}$$

$$\sum_{i \in N_0} x_{i,c+1,r} = \sum_{j \in N_+} x_{0,j,r} \qquad \forall r \in R \tag{6}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} x_{i,j,r} = \sum_{\substack{k \in N_+ \\ k \neq j}} x_{j,k,r} \qquad \forall j \in C, r \in R \tag{7}$$

$$u_i - u_j + 1 \leq (c + 2)\big(1 - x_{i,j,r}\big) \qquad \forall i \in C, j \in \{N_+ : j \neq i\}, r \in R \tag{8}$$

$$1 \leq u_i \leq c + 2 \qquad \forall i \in N_+ \tag{9}$$

$$x_{i,j,r} \in \{0,1\} \qquad \forall i \in N_0, j \in \{N_+ : j \neq i\}, r \in R \tag{10}$$

$$y_{i,t} \in \{0,1\} \qquad \forall i \in C', t \in T \tag{11}$$

Additional computations

$$total\ drone\ deliveries = \sum_{i \in C'} \sum_{t \in T} y_{i,t} \tag{12}$$

$$total\ flight\ time\ of\ drone = \sum_{i\in C'}\sum_{t\in T}(\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} \tag{13}$$

$$total\ car\ routes = \sum_{j\in N_+}\sum_{r\in R} x_{0,j,r} \tag{14}$$

$$total\ travel\ time\ of\ car = \sum_{i\in N_0}\sum_{\substack{j\in N_+\\ j\neq i}}\sum_{r\in R}\tau^C_{i,j} \times x_{i,j,r} \tag{15}$$

$$total\ cost\ = cost^C \times \sum_{i\in N_0}\sum_{\substack{j\in N_+\\ j\neq i}}\sum_{r\in R} d^C_{i,j} \times x_{i,j,r} + cost^D \times \sum_{i\in C'}\sum_{t\in T}(\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} \tag{19}$$

Appendix 2 – Mathematical formulation of model 2a

Objective function

$$minimise\ z = cost^{C} \times \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} d^{C}_{i,j} \times x_{i,j,r} + cost^{D} \times \sum_{i \in C'} \sum_{t \in T} (\tau^{D}_{0,i} + \tau^{D}_{i,c+1}) \times y_{i,t} \qquad (1)$$

Constraints

$$(\tau^{D}_{0,i} + \tau^{D}_{i,c+1}) \leq e + M\big(1 - y_{i,t}\big) \qquad \forall i \in C^{'}, t \in T \qquad (2)$$

$$\sum_{i \in C^{'}} y_{i,t} \leq 1 \qquad \forall t \in T \qquad (3)$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} \sum_{r \in R} x_{i,j,r} + \sum_{t \in T} y_{j,t} = 1 \qquad \forall j \in C \qquad (20)$$

$$\sum_{j \in N_+} x_{0,j,r} \leq 1 \qquad \forall r \in R \qquad (5)$$

$$\sum_{i \in N_0} x_{i,c+1,r} = \sum_{j \in N_+} x_{0,j,r} \qquad \forall r \in R \qquad (6)$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} x_{i,j,r} = \sum_{\substack{k \in N_+ \\ k \neq j}} x_{j,k,r} \qquad \forall j \in C, r \in R \qquad (7)$$

$$u_i - u_j + 1 \leq (c + 2)\big(1 - x_{i,j,r}\big) \qquad \forall i \in C, j \in \{N_+ : j \neq i\}, r \in R \qquad (8)$$

$$1 \leq u_i \leq c + 2 \qquad \forall i \in N_+ \qquad (9)$$

$$x_{i,j,r} \in \{0,1\} \qquad \forall i \in N_0, j \in \{N_+ : j \neq i\}, r \in R \qquad (10)$$

$$y_{i,t} \in \{0,1\} \qquad \forall i \in C^{'}, t \in T \qquad (11)$$

Additional computations

$$total\ drone\ deliveries = \sum_{i \in C'} \sum_{t \in T} y_{i,t} \qquad (12)$$

$$total\ flight\ time\ of\ drone = \sum_{i \in C'} \sum_{t \in T} (\tau^{D}_{0,i} + \tau^{D}_{i,c+1}) \times y_{i,t} \qquad (13)$$

$$total\ car\ routes = \sum_{j \in N_+} \sum_{r \in R} x_{0,j,r} \qquad (14)$$

$$total\ travel\ time\ of\ car = \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} \tau^{C}_{i,j} \times x_{i,j,r} \qquad (15)$$

Appendix 3 – Mathematical formulation of model 2b

Objective function

$$minimise\ w \tag{16}$$

Constraints

$$\mathrm{w} \geq \sum_{i \in C'} \sum_{t \in T} (\tau_{0,i}^{D} + \tau_{i,c+1}^{D}) \times y_{i,t} + recharge\ \times \left(\left(\sum_{i \in C'} \sum_{t \in T} y_{i,t} \right) - 1 \right) \tag{17}$$

$$w \geq \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} \tau_{i,j}^{C} \times x_{i,j,r} \tag{18}$$

$$(\tau_{0,i}^{D} + \tau_{i,c+1}^{D}) \leq e + M\left(1 - y_{i,t}\right) \qquad \forall i \in C^{'}, t \in T \tag{2}$$

$$\sum_{i \in C^{'}} y_{i,t} \leq 1 \qquad \forall t \in T \tag{3}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} \sum_{r \in R} x_{i,j,r} + \sum_{t \in T} y_{j,t} = 1 \qquad \forall j \in C \tag{20}$$

$$\sum_{j \in N_+} x_{0,j,r} \leq 1 \qquad \forall r \in R \tag{5}$$

$$\sum_{i \in N_0} x_{i,c+1,r} = \sum_{j \in N_+} x_{0,j,r} \qquad \forall r \in R \tag{6}$$

$$\sum_{\substack{i \in N_0 \\ i \neq j}} x_{i,j,r} = \sum_{\substack{k \in N_+ \\ k \neq j}} x_{j,k,r} \qquad \forall j \in C, r \in R \tag{7}$$

$$u_i - u_j + 1 \leq (c+2)\left(1 - x_{i,j,r}\right) \qquad \forall i \in C, j \in \{N_+ : j \neq i\}, r \in R \tag{8}$$

$$1 \leq u_i \leq c + 2 \qquad \forall i \in N_+ \tag{9}$$

$$x_{i,j,r} \in \{0,1\} \qquad \forall i \in N_0, j \in \{N_+ : j \neq i\}, r \in R \tag{10}$$

$$y_{i,t} \in \{0,1\} \qquad \forall i \in C^{'}, t \in T \tag{11}$$

Additional computations

$$total\ drone\ deliveries = \sum_{i \in C'} \sum_{t \in T} y_{i,t} \tag{12}$$

$$total\ flight\ time\ of\ drone = \sum_{i \in C'} \sum_{t \in T} (\tau_{0,i}^{D} + \tau_{i,c+1}^{D}) \times y_{i,t} \tag{13}$$

$$total\ car\ routes = \sum_{j \in N_+} \sum_{r \in R} x_{0,j,r} \tag{14}$$

$$total\ travel\ time\ of\ car = \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} \tau_{i,j}^{C} \times x_{i,j,r} \tag{15}$$

$$total\ cost\ = cost^{C} \times \sum_{i \in N_0} \sum_{\substack{j \in N_+ \\ j \neq i}} \sum_{r \in R} d_{i,j}^{C} \times x_{i,j,r} + cost^{D} \times \sum_{i \in C'} \sum_{t \in T} (\tau_{0,i}^{D} + \tau_{i,c+1}^{D}) \times y_{i,t} \tag{19}$$

Appendix 4 – Products' quantity demanded by each customer

	Client				
Day	1	2	3	4	5
1	21	56	65	35	19
2	15	124	1	50	32
3	9	40	0	21	34
4	6	14	22	8	8
5	0	11	0	0	0
6	12	90	74	0	25
7	8	16	67	3	10
8	5	52	1	53	7
9	0	37	11	7	17
10	5	54	5	25	11
11	0	56	0	0	0
12	0	13	67	11	11
13	13	18	19	12	33
14	7	22	0	57	17
15	0	43	24	10	1
16	0	66	3	35	21
17	0	7	0	2	2
18	0	60	41	12	17
19	12	5	60	4	15
20	2	6	13	5	4
21	6	38	0	100	10
22	11	13	6	9	23
23	0	1	9	0	0
24	0	0	1	0	0
25	11	76	35	15	15
26	7	30	0	5	22
27	7	3	6	1	8
28	6	75	9	68	44
29	1	43	90	1	25
30	0	17	0	0	4
31	30	58	20	23	12
32	14	10	82	1	2
33	1	59	2	34	16
34	0	35	16	5	27
35	12	5	10	18	7
36	0	6	0	1	0
37	1	50	44	9	16
38	13	77	61	47	20
39	3	48	19	1	36
40	2	12	15	48	20
41	7	61	0	1	0
42	0	62	31	11	10
43	12	14	65	4	4
44	7	17	10	50	37
45	2	41	12	24	17
46	1	5	7	7	40
47	0	3	0	2	0
48	0	108	27	20	11
49	10	18	64	3	18
50	2	12	2	7	6
51	1	44	0	58	25
52	4	0	7	7	18
53	0	6	0	17	0
54	0	68	24	8	43
55	21	104	75	8	0
56	6	3	0	49	14
57	6	20	15	2	42
58	1	26	9	26	5
59	0	36	0	1	4
60	0	69	45	22	20
61	6	6	50	2	1
62	2	14	8	43	18
63	8	77	12	7	47
64	3	106	1	35	10
65	0	10	0	0	0
66	0	24	25	8	16
67	18	3	83	6	5
68	0	12	5	57	33
69	3	57	23	3	3
70	0	109	19	23	27
71	0	8	0	0	4
72	0	49	108	7	14
73	20	16	9	3	14
74	1	11	4	51	18
75	11	56	15	2	25
76	0	9	15	3	3
77	8	31	13	26	1
78	5	21	32	4	32
79	2	104	48	4	16
80	7	45	8	50	1
81	1	97	8	18	24
82	0	12	0	1	3

	Client				
Day	1	2	3	4	5
83	10	15	70	21	28
84	3	27	37	1	21
85	0	8	0	45	0
86	13	60	9	36	5
87	0	85	2	5	43
88	3	7	0	0	0
89	0	13	31	43	62
90	12	9	82	38	6
91	1	2	17	3	10
92	0	46	4	6	9
93	3	44	2	20	40
94	0	4	13	3	2
95	0	64	16	13	15
96	3	28	76	27	6
97	3	52	7	49	33
98	5	8	5	6	37
99	9	10	1	27	7
100	7	14	31	2	5
101	17	151	25	9	5
102	7	66	69	7	8
103	1	7	14	3	38
104	0	44	0	57	3
105	0	79	40	24	11
106	8	8	39	7	2
107	20	17	0	54	27
108	2	59	16	4	37
109	0	87	14	21	17
110	0	36	0	4	0
111	0	10	51	4	5
112	18	17	50	8	10
113	6	39	5	45	7
114	0	52	2	45	7
115	0	5	9	1	26
116	0	6	0	0	0
117	7	12	18	1	7

	Client				
Day	1	2	3	4	5
118	7	43	69	15	18
119	12	48	15	36	7
120	2	65	7	25	41
121	1	23	10	6	12
122	0	20	0	0	0
123	6	14	20	3	32
124	1	23	8	12	30
125	1	9	0	56	6
126	13	42	76	21	17
127	0	45	0	1	0
128	7	62	52	5	39
129	5	29	65	0	10
130	24	88	8	50	11
131	4	9	9	4	4
132	4	43	0	39	41
133	2	6	7	4	0
134	12	9	13	8	23
135	15	31	93	12	25
136	0	6	5	58	2
137	36	97	10	1	22
138	1	41	1	43	7
139	0	3	0	1	1
140	3	21	41	0	16
141	7	46	54	1	15
142	4	9	0	44	6
143	8	21	10	37	50
144	0	39	14	0	12
145	0	2	0	2	0
146	3	95	84	12	34
147	7	13	17	15	13
148	7	8	3	53	9
149	3	29	9	20	28
150	13	7	0	4	21
151	0	2	0	0	0

Appendix 5 – Computational results of model 1a

Main results of model 1a

	Computational results						
Day	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
55	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
123	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
98	784	785	981	0,008	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
127	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
26	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
104	784	785	981	0,008	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
57	784	785	981	0,008	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
126	784	785	981	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
15	784	785	981	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
150	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
105	784	785	981	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
96	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
99	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
53	784	785	981	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
51	784	785	981	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

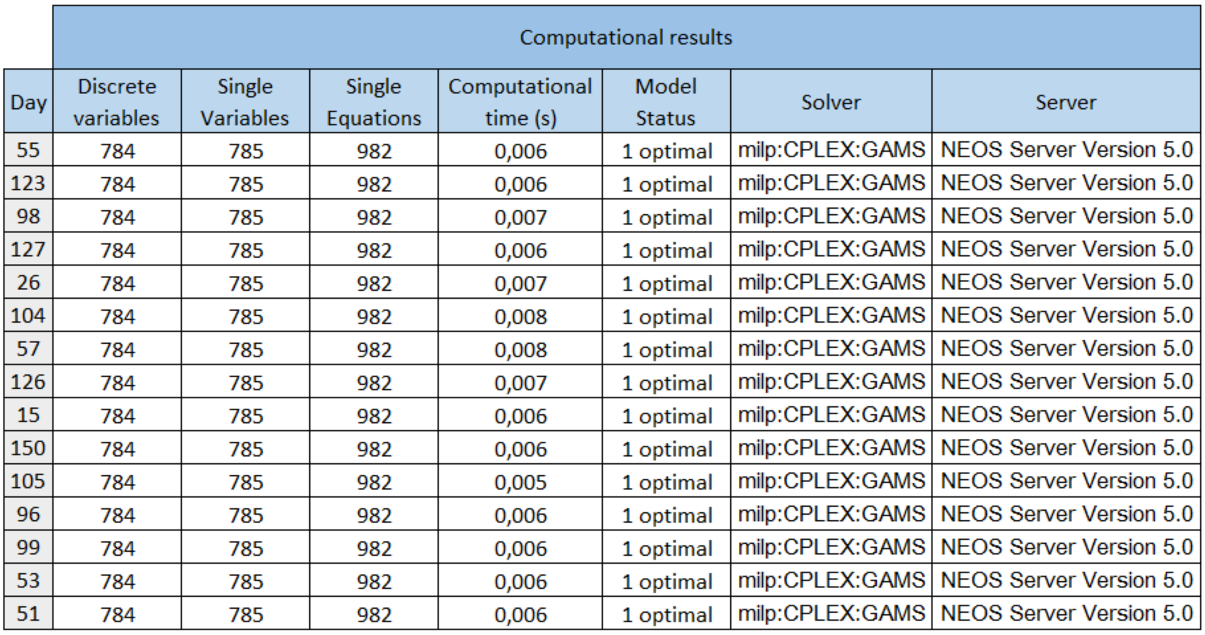
Sensitivity analysis of model 1a

	Computational results						
Drone trips	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
0	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
2	756	757	949	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
4	770	771	965	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
8	798	799	997	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
10	812	813	1013	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

		Computational results						
Day	Products delivered by car	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
55	20	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
123	20	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	981	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
98	20	784	785	981	0,006	2 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	981	0,006	3 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

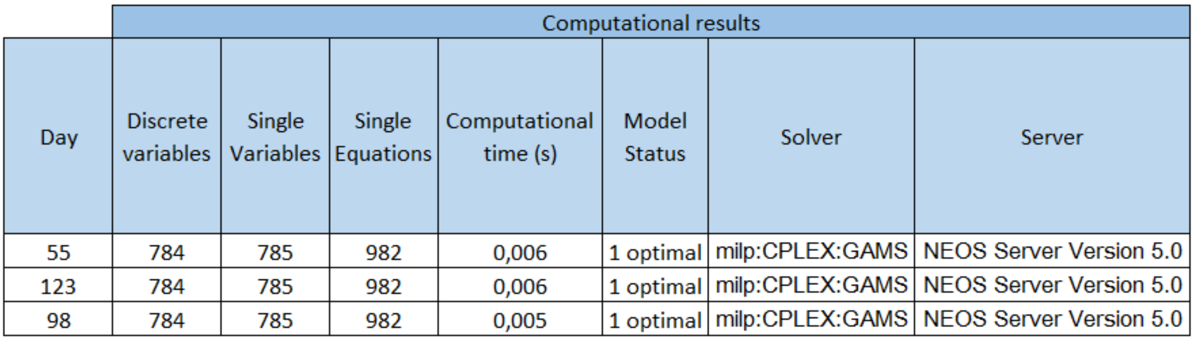
Appendix 6 – Computational results of model 1b

Main results of model 1b

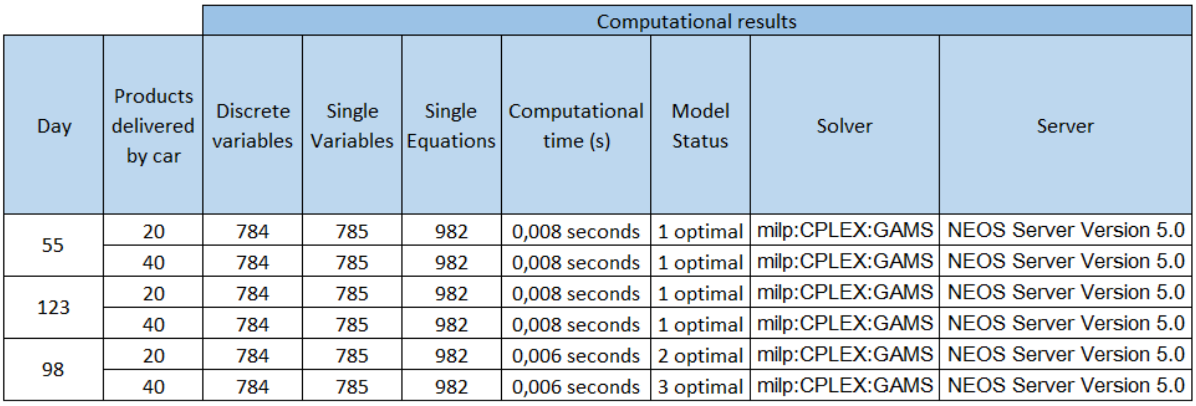


	Computational results						
Day	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
55	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
123	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
98	784	785	982	0,007	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
127	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
26	784	785	982	0,007	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
104	784	785	982	0,008	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
57	784	785	982	0,008	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
126	784	785	982	0,007	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
15	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
150	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
105	784	785	982	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
96	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
99	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
53	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
51	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

Sensitivity analysis of model 1b



	Computational results						
Day	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
55	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
123	784	785	982	0,006	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
98	784	785	982	0,005	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0



		Computational results						
Day	Products delivered by car	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
55	20	784	785	982	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	982	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
123	20	784	785	982	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	982	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
98	20	784	785	982	0,006 seconds	2 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
	40	784	785	982	0,006 seconds	3 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

Appendix 7 – Computational results of models 2a and 2b

Results for the 3 scenarios with model 2a

		Computational results						
Scenario	Drones available	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
A	0	784	785	981	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
A	1	749	750	941	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
A	2	756	757	949	0,007 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	0	784	785	981	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	1	749	750	943	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	2	756	757	951	0,005 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	0	784	785	981	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	1	749	750	943	0,005 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	2	756	757	951	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0

Results for the 3 scenarios with model 2b

		Computational results						
Scenario	Drones available	Discrete variables	Single Variables	Single Equations	Computational time (s)	Model Status	Solver	Server
A	0	784	785	982	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
A	1	749	750	942	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
A	2	756	757	950	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	0	784	785	982	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	1	749	750	944	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
B	2	756	757	952	0,005 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	0	784	785	982	0,006 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	1	749	750	944	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0
C	2	756	757	952	0,008 seconds	1 optimal	milp:CPLEX:GAMS	NEOS Server Version 5.0