Logistics Challenges in a New Distribution Paradigm: Drone Delivery

Connect Robotics Case Study

André Alves Ferreira Sousa Conceição

Department of Engineering and Management, Instituto Superior Técnico

Abstract

This paper 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 Connect Robotics 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, last-mile deliveries, vehicle routing problem, transportation trends, logistics trends.*

1. Introduction

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 paper'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, in this paper a Mixed Integer Linear Programming (MILP) model was developed to analyse the cost and time savings that could be obtained with drone deliveries in Farmácia da Lajeosa.

The paper is structured as follows: in Section 2, the relevant literature on drone technology, the role of drones and drone delivery problems is presented. In Section 3, the mathematical model of the PDSVRP is introduced, along with the required changes to obtain three different variants. In Section 4, the results obtained in the analysis of the daily delivery operations are presented and discussed. In Section 5, the results for the single delivery operation are shown. In Section 6, the conclusions of this paper are presented.

2. Literature Review

2.1. 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). 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).

2.2. The future of last-mile 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. 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.

2.3. 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. 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 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. The second problem 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, they presented a mixed integer linear programming (MILP) formulation, which minimises the time required to serve all the customers. Furthermore, they propose two heuristic approaches for solving problems with a practical size since MILP solvers required several hours to solve the formulation for problems with only ten customers. 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. 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. 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. 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. 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. 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. 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. 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. 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.
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 found 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 work's problem is the PDSTSP from Murray and Chu (2015). However, the models presented in this paper were 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. Mathematical model for the drone delivery problem

3.1. Problem statement and model variants

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). 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, generate new constraints that imply a routing problem to be modelled differently from the common logistics problems. 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 (1) and single delivery operation (2). 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 minimization (a) and time minimization (b). In fact, when the goal is to minimise time the recharge time of the drone is an important characteristic to take into consideration. These model variants will be identified by the perspective (1 or 2) from which the problem is approached and the model objective (a or b).

3.2. 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.

3.3. Model formulation (1a)

Indexes

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

Sets

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

Parameters

- $\tau^C_{i,j}$ – travel time of car in minutes to go from node i in N_0 to node j in N_+
- $d^C_{i,j}$ – distance travelled in kilometres by car from node i in N_0 to node j in N_+
- $\tau^D_{i,j}$ – travel time of drone in minutes to go from node i in N_0 to node j in N_+
- $d^D_{i,j}$ – 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

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 ($1 \leq u_i \leq c+2$)

Objective function

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

Constraints

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

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

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

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

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

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

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

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

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

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

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. Constraint (2) ensures that drones can only deliver to customers if the maximum flight time is not exceeded. Constraint (3) assigns each drone trip to a maximum of one customer. The following constraint (4) is 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. Constraint (5) requires each car route to either not leave from the depot or leave once from the depot. Equation (6) is linked with constraint (5) and each car route must return once to the depot if it has left the depot or not return if it has not. Equation (7) guarantees that every car route that visits a customer must leave that customer. Constraint (8) eliminates subtours in each car route. The remaining constraints establish the variables' domain. Constraint (9) is 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.

3.4. Formulation changes introduced to obtain the model variants

The mathematical formulation presented 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.

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

New objective function

$$minimise\ w \tag{12}$$

Additional constraints

$$w \geq \sum_{i\in C'} \sum_{t\in T} (\tau^D_{0,i} + \tau^D_{i,c+1}) \times y_{i,t} + recharge \times \left(\left(\sum_{i\in C'} \sum_{t\in T} y_{i,t}\right) - 1\right) \tag{13}$$

$$w \geq \sum_{i\in N_0} \sum_{\substack{j\in N_+ \\ j\neq i}} \sum_{r\in R} \tau^C_{i,j} \times x_{i,j,r} \tag{14}$$

Equation (12) minimises the latest time at which either the car routes or drone trips finish all the deliveries. For this purpose, constraints (13) and (14) provide a lower bound for the total time of drone trips (with the necessary recharges) and the car routes, respectively.

3.4.2. 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 constraint (4) by constraint (15).

$$\sum_{\substack{i\in N_0 \\ i\neq j}} \sum_{r\in R} x_{i,j,r} + \sum_{t\in T} y_{j,t} = 1 \qquad \forall j \in C \tag{15}$$

This new equation (15) considers that each customer must be visited only once by either vehicle, instead of having a demand to be met.

3.4.3. Single operation with time minimisation (2b)

To obtain the model variant for single operation with time minimisation, the objective function is changed to equation (12), as in model 1b. Thus, equations (13) and (14) must also be included. Finally, since this is also a single operations model like model 2a, the constraint (4) is also replaced with constraint (15).

4. 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 a sample of 15 days extracted from the demand data collected in Farmácia da Lajeosa.

4.1. Cost analysis

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.

Table 1 – 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 €

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 the following table, the transportation costs and the savings obtained with the model results are presented.

Table 2 - 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.

4.2. Time analysis

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.

Table 3 - 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

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 4 along with the transportation time of the current operations, as well as the transportation times obtained with the model.

Table 4 - 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.

5. 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 (A) was one without drone restrictions where every client could be served by drone. The second scenario (B) 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 (C) 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.

5.1. 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 results obtained are presented in the following tables.

Table 5 - 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%

Table 6 - 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%

Table 7 - 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%

5.2. 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. The results obtained are presented in the following tables.

Table 8 - 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%

Table 9 - 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%

Table 10 - 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%

6. Conclusions

The introduction of drone deliveries in Farmácia da Lajeosa by the company Connect Robotics is analysed in this work regarding possible cost and time savings.

A drone delivery model with vehicle routing was developed, the PDSVRP, based on the PDSTSP, to portray the situation. Four variants of this model were developed to explore different perspectives of the problem, concerning the analysis of the daily delivery operations, as well as single delivery operations.

The results obtained demonstrate that there is potential for reducing transportation costs and times significantly with drones. Although, the drones also have an investment cost, which was not the focus of this paper, but cannot been forgotten when analysing the adoption of drones in delivery. 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.

Furthermore, some ideas regarding future work are suggested. It would be interesting to apply this model to a scenario with more clients and more drones available, model emissions to study the environmental impact of utilising drones, study the possibility of installing drone-ports that could extend the range of drones and model time window constraints.

Finally, it is expected that by extending the PDSTSP and applying the PDSVRP model variants developed to a real case, this paper can stand as an interesting contribution to the literature regarding drone delivery problems.

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