Designing unmanned aerial vehicle networks for biological material transportation

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Abstract

Unmanned Aerial Vehicles (UAVs) may solve, or at least reduce, the negative impacts of road transport such as accidents, pollution and congestion. The objective of this paper is to design UAV networks for biomedical material transportation in line with the Drone4Care project. Political, Economic, Social, Technological, Environmental, Legal (PESTEL) analysis provides an overview of the macro-environmental factors that should be considered. To identify the internal and external factors that are favourable and unfavourable to achieve this objective, Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is also performed. The raised issues are translated into a number of quantifiable scenario elements containing the most plausible up-coming events that may impact the future of UAV networks. Four location models are developed and applied to the city of Brussels and its periphery with respect to the associated market in terms of biomedical product flows (blood units or medical samples that are transported between hospitals, laboratories, and blood transfusion centres). In the context of separate case studies of scenario-based analysis, the experiments show that the use of charging stations is useful to extend the mission ranges and to gain market share. The results also show the possibility of gradually implementing the bases without requiring any major changes such as closing a base.

Keywords: Unmanned aerial vehicle, Drone, Location-allocation problems, Network design, Biologistics.

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1. Introduction

According to Dalamagkidis (2015), an Unmanned Aerial Vehicle (UAV), which is also known as a drone, is a pilotless aircraft or a flying machine without an on-board human pilot or passengers. Its control functions may be either on-board or off-board (remote control). UAVs are the main component of an Unmanned Aircraft System (UAS), which also includes the control station and any other system elements that are necessary to enable flight, i.e., the command and control link and the launch and recovery elements. The absence of pilots on board allows for greater availability, reduced costs, and expanded missions on a large scale. UAVs are versatile enough to be assigned to particular missions that are dangerous, tedious, or repetitive.

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Gartner's forecast (Forni and van der Meulen, 2017) shows growing revenues that are estimated to reach $ 11.2 billion in 2020 (they were $ 6 billion in 2017) and 100,000 potential jobs (European Council, 2019), including the market for personal and commercial drones. The latter covers a variety of applications and accounted for 174,100 drones that were sold in 2017. The projections for 2020 indicate that UAVs for transport will represent only 1% of the commercial UAV market and will be mainly for business-to-business (B2B) applications.

Rapid growth in UAVs over the last decade has led to their innovative applications in several industries (Beloev, 2016; Hassanalian and Abdelkefi, 2017; Sadgrove et al., 2018; PwC, 2019; Miranda et al., 2019). Examples of the applications of UAVs are presented in Rao et al. (2016). The transportation sector is highly concerned with this new vehicle since it potentially may be able to solve or at least reduce the negative impacts such as those from pollution or road congestion. For small shifting or instead of using human labor, UAV can be used to transport small products (Sarkar et al., 2019). Furthermore, the abilities of UAVs to be autonomous, modular, and fast with high reactivity are significant incentives for their use to supply emergency commodities in a disaster-affected region (Chowdhury et al., 2017) and in the specific field of biomedical transportation. Medicines, vaccines, and units of blood require prompt deliveries when the need arises. Blood samples are collected all over the country in different blood collection centres; then they have to be transported in a blood transfusion establishment and imperatively processed within a within a timeframe after collection. According to the degree of urgency, the timeframe can be very short. Indeed, it depends on factors such as the kind of components to measure, of the patient's condition and of the situation. (e.g. epidemic or pandemic). An example of practical tests conducted in the city of Antwerp is the MEDRONA project that consists of transportation by drones of medical parcels between hospitals and laboratories (Neuray, 2020). Beyond the development of UAV technology, deep changes are beginning to occur in logistic activities, as the improvements over traditional transportation systems are substantial.

Otto et al. (2018) provide a review of optimization problems considering the use of UAVs for operations planning to civil applications. The paper underlines the advantage to combine and assist the operations with available vehicles and robots. The collaborative truck and drone delivery team has received much attention recently; Coutinho et al. (2018) provide a taxonomy and review recent contributions in UAV trajectory optimization and UAV routing. Since their review, several research papers broaden our understanding of vehicle routing problem with drones. The latter is an extension of the classic capacitated vehicle routing problem, where trucks and drones are used for delivery. For instance, Ha et al. (2018) minimize operational cost including transportation cost and the cost incurred by the waiting time of a vehicle for another. Chang and Lee (2018) examine the routing problem with a truck and drones, in which the truck carries drones to some centres where drones can fly for delivering customers. Ham (2018) investigate multiple depots, multiple trucks, and multiple drones and developed a constraint programming approach. However, he disregards the meeting of two types of vehicles, making the problem different from Wang and Sheu (2019). Jeong et al. (2019) propose a new model to enable the realistic implementation of the hybrid delivery team for real world last mile delivery service.

This study deals with the UAV network design problem for biomedical material transportation in line with the Drone4Care project. The logistical issues are investigated to understand the prerequisites for the deployment of UAVs, develop new solutions, determine optimal locations for UAV launch bases, and assess the impacts of the main variables on UAV network design and performance. The design decisions include facility location, i.e. where to open the facilities, and allocation of the demand points to the open facilities (Ortiz-Astorquiza et al., 2018). For a classification of different types of non-emergency and emergency health care facility location, refer to Ahmadi-Javid et al. (2017).

Regarding the scientific literature on UAV network design, Yakıcı (2016) determines the location of bases and the routing of small UAVs at tactical level. The author proposes an integer linear program to maximise the total score collected from visited interest points and develops a colony optimization metaheuristic. Hong et al. (2017) are interested in the distribution of charging stations for UAVs in order to ensure the deliveries in an urban area. They formulate a coverage location model, referred to as distance-restricted maximal coverage location model, and solve it by the way of a heuristic based on a simulated annealing with a greedy algorithm. Liu et al. (2019) investigate the location-routing problem of UAVs in border patrol for intelligence, surveillance, and reconnaissance; two heuristic algorithms combined with local search strategies are designed for solving the problem.

In the care sector, Pulver et al. (2016) address the maximum coverage problem for defibrillators in the Salt Lake City area. In their approach, the authors discrete the geographical space using the Finite Dominating Set method that was developed by Murray and Tong (2007) in order to improve the effectiveness of the resolution. Boutilier et al. (2017) study the implementation of UAVs for the distribution of external automated defibrillators in Toronto in order to reduce the response time by three minutes. First, the resolution of a linear programming problem makes it possible to determine the locations of the bases, and, in a second step, a queue-type model allows one to determine the number of UAVs that should be assigned to each base. This type of problem has also been studied by Kim et al. (2017) with respect to the care of patients with chronic diseases in rural areas. Their first model aim to find the optimal number of drone center locations using the set covering approach, and their second model is related to a multi-depot vehicle routing problem with pickup and delivery requests. As solution approaches, a partition and a Lagrangian Relaxation methods are developed. In the paper by Dorling et al. (2017), the Drone Delivery Problem focuses on the drone's energy consumption and payload effect, which are not covered by the traditional Vehicle Routing Problem. They mathematically derive and experimentally validate an energy consumption model for multirotor drones. Sanfridsson et al. (2019) study used a mixed methodology describing bystanders' experiences of retrieving an automated external defibrillator delivered by a drone in simulated out-of-hospital cardiac arrest situations. They show, by analyses of qualitative data from observations, interviews of participants and video recordings, that it makes sense for bystanders to interact with a drone in this simulated suspected out-of-hospital cardiac arrest situations.

In the field of UAV network design, the paper by Shavarani et al. (2018) is the closest to our work. They develop the Amazon case study to examine the implementation of UAV bases for deliveries using a hierarchical facility location model to find the distribution of facilities in two levels of launch and recharge stations. The facilities can be either launching facility, which is the distribution centre or recharge station. UAVs perform a round trip from the nearest launch station to the demand point, making the paper different from this one. Our goal is to form the general guidelines and policies of a UAV network for biological materials such as units of blood or medical samples that are transported between hospitals, laboratories, and blood transfusion centres. Methodologically, our contribution is to propose network design models, where the demand is assigned to a path instead of a facility. This allows to reduce the number of variables and the number of constraints compared to the facility location problems based on the well-known covering and median problems.

The remainder of the chapter is structured as follows. Section 2 begins with PESTEL analysis that will provide an overview of the various macro-environmental factors that should be taken into consideration. To specify the objectives of the project and identify the internal and external factors that are favourable and unfavourable to achieve those objectives, SWOT analysis is also performed. After a detailed definition of the problem in Section 3, the formulations for various scenarios are provided in Section 4. In section 5, the data are estimated to apply the developed location models to the city of Brussels and its periphery, in Section 6 scenario-based analyses are performed. We present our conclusions in Section 7.

2. Market analysis

Commercial UAVs entered in 2017 in a phase called Ştrough of disillusionmentŤ on Gartner Hype Cycle for Emerging Technologies (Forni and van der Meulen, 2017), suggesting that some expectations of the technology would have been overrated. Therefore, a strategic analysis related to the use of UAV for biomedical transportation is relevant. Strategic analysis is described by Johnson et al. (2017)) and divided into three sections: diagnosis, choices, and implementation. As the model developed in this paper is intended to be a support for strategic choices (e.g., drone network architecture, location of the bases), a prior diagnosis is, therefore, necessary; this is developed in this section. First, a PESTEL analysis describes the environment where the objective is to identify the main factors capable to influence the market. Then a SWOT analysis addresses the strategic capacity of the organization, in order to be competitive on the considered market: this aims to guide the choices for the drone network developed in this study.

Based on the literature review, support from industrial and academic experts, and by the problem owners (Drone4Care project managers), the key factors to perform a PESTEL analysis (Johnson et al., 2017) related to UAVs were identified. Subsequently, our analysis, summarised in Table 1, was validate by the experts and problem owners. The analysis identifies two main factors that may have significant impacts on the UAV market: the evolution of regulations relating to the operation of UAVs, and their technological development and related systems. Thus, many factors, such as the occurrence of accidents involving drones, sociological aspects related to public concerns (invasion of privacy and the perception of drone safety), and political and economic pressures can influence the way in which regulations are built. Nevertheless, certain airspace bans, limitations on speeds and mass, etc. can be anticipated. Concerning medical transport, assessing societal aspects (the notion of the public utility of the drone in this case) can be beneficial to obtain derogations.

Factors	Favourable elements	Unfavourable elements
Political	• European Union allocates funding to projects related to UAV (Sesar: Joint Undertaking, 2017). • Awareness by the DGTA (Direction Générale du Transport Aérien) and Belgocontrol (2018) of the need to deploy tools.	• Autonomous flight not currently authorized (Moniteur belge, 2019). • *Several years needed to establish a regulatory framework in Europe* (European RPAS Steering Group (ERSG), 2013).
Economic	• *UAVs are becoming a potential alternative for logistics activities* (Raj and Sah, 2019). • Stakeholder pressure: many companies are involved in the development of UAVs in logistics (Amazon, DHL, and Google). • *The sector's potential is estimated to create 100,000 jobs by 2035 and generate €11 billion* (Forni and van der Meulen, 2017).	• Potential impact on traditional activities (such as road transport) replaced by drone powered solutions, estimated at M€ 43.6 annually for the Transport & Logistics sector (PwC, 2018). • Difficulty to evaluate and predict maintenance costs of UAVs (Chapman, 2017). • Cost redundancy if a backup transport solution (such as road transport) is needed, for example, to ensure service in all weather conditions.
Sociocultural	• Engagement of the population in new technologies. • *Useful aspect of drones for the population (saving lives).*	• *Concerns about invasion of privacy* (Turner, 2015). • *Concerns about the risk of accidents in urban use* Clothier et al. (2015); Watkins et al. (2020). • Negative image of military drones.

Technological	• *Presence of many leading companies in the sector in Europe.* • Many research projects receive European support, which provide a favourable breeding ground for the development of the sector. • *Wide range of technological solutions.*	• Detect and avoid principle not yet fully mature. • *Complex communications (frequency bands).* • *Dependency on many technologies: aviation, autonomy, surveillance, communication, manufacturing.*
Environmental	• *Few nuisances (e.g. noise)* (Watkins et al., 2020). • *Low environmental impact* (Goodchild and Toy, 2018).	• Dependent on weather conditions (Watkins et al., 2020).
Legal	• Ongoing legislative work at the European level (EASA European Union Aviation Safety Agency, 2019). • Legislation being put in place at the DGTA level.	• *Designation of responsibilities (drone manufacturer, operator, and pilot).*

Table 1: PESTEL analysis related to transportation by UAVs. Factors in italics correspond to those expected to remain effective in the long term.

Using the same methodology, we complete this section with the SWOT analysis related to biological material transportation by UAVs provided in Table 2.

The ability to react quickly to demand is one of the most important pillars of a Digital Supply Chain (Büyüközkan and Göçer, 2018). Rapidity is an essential criterion due to the nature of the products that are transported and the urgency that is inherent in the sector. UAVs have an advantage in this respect due to their more direct routes and their insensitivity to road traffic jams. The quality of service is crucial to ensuring the optimal distribution of products, and the use of UAVs opens up new possibilities for establishing traceability. The costs to transport biomedical products by roads are significant, particularly when transport requires special conditions (temperature, urgency, etc.). The use of UAVs provides the advantage of greater flexibility, particularly due to the absence of a pilot, and therefore enables easier human resources management. Due to the multitude of actors, the simplicity of the service is

Strengths	Weaknesses
• Increased speed to transport urgent medical products. • Reduced delivery costs. • Increased delivery efficiency. • Improving the responsiveness of transport services. • Flexibility of transport planning. • Easy access to remote areas. • Technological contributions: geolocation and applications. • Reduction of the carbon footprint.	• Limited operating ranges. • Limited payload (size and mass). • Difficulties regarding the reliability (many models are prototypes). • Sensitivity to weather conditions. • Initial investment costs. • Need for better regulation in the aviation sector. • High R&D costs of systems equipping and supporting the UAVs.
Opportunities	Threats
• Reduction of public sector care costs. • Improvement of the quality of medical transport. • New applications. • Innovation for new services/options. • Transport service to remote areas. • New emerging market. • Increased operating range (charging stations and solar panels).	• Safety issues (occurrence of accidents and the safety of the transported equipment). • Restrictive regulatory framework. • Risk of rejection by the public (privacy, security...). • Failure rate. • Influence of NGOs. • Reorganization/adaptation of the traditional road sector.

Table 2: SWOT analysis related to biological material transportation by UAVs.

also an asset. The use of UAV systems necessarily requires computerized procedures for which adequate training must be provided. The competition analysis underlines the important role of public authorities in establishing regulations. The power of customers and the threat of new entrants or substitutes (such as returning to the use of the traditional road network) encourage a strategy of differentiation and innovation by providing the following: functionalities that improve the service and the exploitation of the strengths that are provided by technology (speed, lower operating costs, flexibility...).

Several choices for the study come out of this analysis.

- To comply with a will of rapidity and flexibility of the service, a Vertical Take-Off and Landing (VTOL) drone is selected: this will make possible both proximity with customer sites and the ability to access as close as possible to customers in urban areas for loading and unloading the drones.
- In addition, a maximum take-off weight is limited to 25 kg to comply with regulation aspects. These choices lead to a constraint for the model due to the limited range of such UAVs.
- Regulation of the airspace leads to take into account in the model some prohibited zones in the Brussels area, where implantation of drone bases is not allowed.

3. Problem description

To ship materials, a shipper orders a transportation service from a centralized system. This order is placed using a dedicated tool that could take the form of a mobile application to ensure that customers can be monitored at all times. The centralized system receives the orders, and, according to their specificities (date, weight of the transported material, transport temperature...), determines the optimal assignment of a UAV considering all the network parameters (number of drones available at each base, their flying range, meteorological data, etc.). Despite the fact that off-sight flight is currently unauthorised, it is assumed that the centralized system autonomously calculates the UAV's trip and communicates the GPS coordinates to be followed. Depending on the required transport temperature, the receptacle (which is thermally insulated) is equipped with eutectic gel blocks that are preconditioned to the appropriate temperature before its departure.

A UAV takes off from the selected departure base, subject to validation of the mission by both customers (the shipper and receiver, ensuring their availability to load and unload), and goes to the pickup site. The customer, thanks to the dedicated application, can follow the progress of the UAV and is informed of its approach so that he/she can go to the landing site to load the equipment into the UAV's receptacle. Then, the drone takes off to reach the delivery location. Depending on the distance, a recharging step in the itinerary could be done at one of the stations. The receiving customer is notified of the approach of the UAV so that he/she can go to the landing site to proceed with the unloading. After the validation of the unloading by the receiving customer, the UAV returns to a base.

The manager of a UAV base ensures that the drones in his/her base are in working order (batteries recharged, summary maintenance is performed...), and monitors the smooth running of ongoing flights. He/she has an overview of the customer orders, the UAV flight parameters such as the position, the flight video, and the parameter status such as the flying range. He/she can take over the piloting of a UAV using the manual mode. Figure 1 illustrates a drone mission.

The objective is to determine the optimal location of the bases that are dedicated to the launch and receipt of UAVs, i.e., the places where the UAVs are on standby to carry out a transport mission, where they can be recharged and where their maintenance is performed. A variant of this problem, taking into account the location of recharging stations, is also considered.

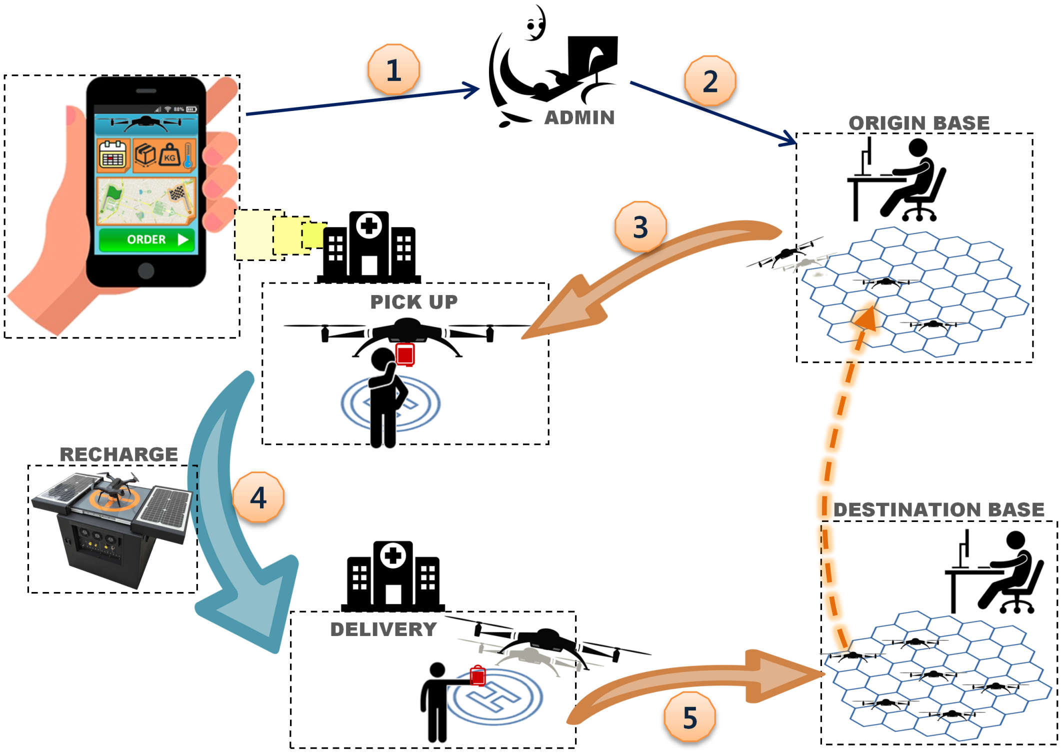

Figure 1: Illustration of a typical drone mission.

4. Mathematical programming formulation

We assume an unlimited number of UAVs located at a set, M of potential bases that are indexed by $j \in \{0, ..., m\}$, a set of pickup and delivery points. The transport demand is considered deterministic and known and is given in terms of the number of shipments f_i to carry during the considered period of time on path i, $\forall i \in N = \{0, ..., n\}$. The objective is to locate bases (and recharging stations) and to assign flows to those sites in order to minimize the total transportation costs.

Several scenarios are studied. In the first one, as the flying range is assumed to be infinite, all the demands have to be satisfied, resulting in a satisfaction rate of 100%. Moreover, UAVs are constrained to return to their origin base after the delivery. This constraint is relaxed in other scenarios. However, the associated costs of repositioning UAVs due to imbalances are not considered. That is, in the second scenario, UAVs are allowed to end their trip at any base. In the third and fourth scenario a 23 km flying range is considered. Finally, in the last scenario, the possibility to recharge the UAVs during a mission is taken into consideration. The recharging operations can be performed at a base station, where it is assumed that an operator of the base station manages the recharging operation with existing equipment, or at a recharging station equipped with automatic and wireless recharging systems, implanted away from base stations. The four scenarios are summarised in Table 3.

Assumptions	Scenarios			
	1	2	3	4
Origin base=destination base	✓	✗	✗	✗
Flying range	∞	∞	23 km	23 km
One recharging station is allowed	✗	✗	✗	✓
Satisfaction rate= 100%	✓	✓	✗	✗

Table 3: Scenarios' definition.

4.1. Scenario 1

Let α, $\beta \in \mathbb{R}_0^*$ be the costs per km of empty and loaded UAVs, and respectively; $b_j \in \mathbb{R}_0^*$ be the fixed operating costs of base j. The distance between the pickup site of path i and base j is denoted by d_{ij}^p, where d_i represents the distance between the pickup and the delivery sites of path i and d_{ij}^d is the distance between the delivery site of path i and base j, where $i \in N$ and $j \in M$. The formulation of the problem uses the following as decision variables:

$$w_j = \begin{cases} 1 & \text{if base } j \text{ is opened,} \\ 0 & \text{otherwise,} \end{cases} \qquad \forall j \in M,$$

$$x_{ij} = \begin{cases} 1 & \text{if path } i \text{ starts at base } j, \\ 0 & \text{otherwise,} \end{cases} \qquad \forall i \in N, j \in M.$$

The objective function is as follows:

$$\min \left(\sum_{i=1}^{n} \sum_{j=1}^{m} f_i \left(\alpha \left(d_{ij}^p + d_{ij}^d \right) + \beta d_i \right) x_{ij} + \sum_{j=1}^{m} b_j w_j \right) \tag{1a}$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad \forall i \in N \tag{1b}$$

$$\sum_{i=1}^{n} x_{ij} \leq w_j \sum_{i=1}^{n} f_i \qquad \forall j \in M \tag{1c}$$

$$w_j, x_{ij} \in \{0, 1\} \qquad \forall i \in N, j \in M \tag{1d}$$

The first term of the objective function (1a) represents the transport costs of an empty UAV from the origin base to the pickup site, from its delivery site to the destination base, and the transport costs of a loaded UAV on used paths; the second term is the fixed operating costs of the bases. Constraints (1b) assign each path to one departure base. Constraints (1c) ensure that a base j can be used by path i iff base j is opened. Constraints (1d) define the binary conditions of the variables.

4.2. Scenario 2

In this scenario, UAVs are allowed to end their trip at any base, new binary variables

$$y_{ij} = \begin{cases} 1 & \text{if path } i \text{ ends at base } j, \\ 0 & \text{otherwise,} \end{cases} \qquad \forall i \in N, j \in M.$$

are introduced and the objective function is written as:

$$\min \left(\alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d_{ij}^{p} x_{ij} + \beta \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d_i x_{ij} + \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d_{ij}^{d} y_{ij} + \sum_{j=1}^{m} b_j w_j \right) \tag{2a}$$

Subject to:

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad \forall i \in N \tag{2b}$$

$$\sum_{i=1}^{n} x_{ij} \leq w_j \sum_{i=1}^{n} f_i \qquad \forall j \in M \tag{2c}$$

$$\sum_{i=1}^{n} y_{ij} \leq w_j \sum_{i=1}^{n} f_i \qquad \forall j \in M \tag{2d}$$

$$\sum_{j=1}^{m} x_{ij} = \sum_{j=1}^{m} y_{ij} \qquad \forall i \in N \tag{2e}$$

$$w_j, x_{ij}, y_{ij} \in \{0, 1\} \qquad \forall i \in N, j \in M \tag{2f}$$

The first term of the objective function (2a) represents the transport costs of an empty UAV from the origin base to the pickup site, the second term is the transport costs of a loaded UAV on used paths, the third term is the transport costs of an empty UAV from the delivery site to the destination base, and the fourth term is the fixed operating costs of the bases. Constraint (2b) states that the demand has to be satisfied. Constraints (2c) and (2d) ensure that a base j can be used by path i iff base j is opened. Constraints (2e) ensure that the UAV returns to a base and constraints (2f) define the binary conditions of the variables.

4.3. Scenario 3

In this scenario, the UAVs are also allowed to end their trip at any base. Moreover, since the flying range of a UAV, which is denoted as $\tau \in \mathbb{R}_0^*$, is limited in terms of the distance, some demands may not be satisfied. That is the reason why a parameter $\tau \in [0, 1]$, denoting the satisfaction rate, is introduced. Constraint (2b) is therefore replaced by constraints (2 *bis*) and (2 *ter*).

$$\sum_{i=1}^{n} \sum_{j=1}^{m} f_i x_{ij} \geq \tau \sum_{i=1}^{n} f_i \tag{2 \textit{bis}}$$

which states that a rate, τ, of the total demand has to be satisfied.
Besides, constraints (2 *ter*) guarantee the uniqueness of the assignment of a departure base to a path.

$$\sum_{j=1}^{m} x_{ij} \leq 1 \quad \forall i \in N \tag{2 ter}$$

In addition, flying range constraints (3) have to be added to the model:

$$\sum_{j=1}^{m} x_{ij} d_{ij}^{p} + d_i \sum_{j=1}^{m} x_{ij} + \sum_{j=1}^{m} y_{ij} d_{ij}^{d} \leq A \quad \forall i \in N \tag{3}$$

4.4. Scenario 4

In scenario 4, the possibility of recharging the battery during a mission, at any open base (generating no extra implantation costs, because equipment is already present) or at some recharging stations (where an automatic charging system is implanted) is considered. A dummy base, which is indexed as $m+1$, is added to M to take into account a path without recharging stations. In this case, it is considered that $\tilde{d}_{im+1}^{p} = 0$ and $\tilde{d}_{im+1}^{d} = d_i$, where $i \in N$. Let $\tilde{d}_{ik}^{p}$ be the distance between the pickup node of path i and recharging station and $\tilde{d}_{ik}^{d}$ be the distance between the delivery node of path i and recharging station k, where $i \in N$ and $k \in M$. If the recharging station is not a base, let $s_k \in \mathbb{R}_0^*$ be its fix operating costs, and z_k be the binary variables such that the following holds:

$$z_k = \begin{cases} 1 & \text{if recharging station } k \text{ is opened,} \\ 0 & \text{otherwise,} \end{cases} \qquad \forall k \in M,$$

$$r_{ik} = \begin{cases} 1 & \text{if route } i \text{ used the recharging station } k, \\ 0 & \text{otherwise,} \end{cases} \qquad \forall i \in N, k \in M \cup \{m+1\}.$$

In this scenario, the objective function becomes the following:

$$\begin{aligned} \min \ \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d_{ij}^{p} x_{ij} + \beta \sum_{i=1}^{n} \sum_{k=1}^{m+1} f_i (\tilde{d}_{ik}^{p} + \tilde{d}_{ik}^{d}) r_{ik} + \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d_{ij}^{d} y_{ij} \\ + \sum_{j=1}^{m} b_j w_j + \sum_{j=1}^{m} s_j z_j (1 - w_j) \end{aligned}$$

where the first term represents the transport costs of an empty UAV from the origin base to the pickup site. If the transport between bases is performed by passing through a recharging station, the second term corresponds to the transport costs of loaded UAVs from the pickup site to the recharging station and from the recharging station to the delivery sites; otherwise, it is the transport costs of loaded UAVs from the pickup to the delivery sites of path i. The third term is the transport costs of an empty UAV from the delivery site to the destination base. The fourth term is the fixed operating costs of the bases and the last term is the fixed operating costs of the recharging stations not located at a base. The latter is not linear since

it includes the product of two binary variables. To linearize the objective function and to consequently make the model more tractable, the binary variables $\tilde{z}_j = z_j w_j \ \forall j \in M$ are introduced.
The objective function can thus be written as follows:

$$\begin{aligned} \min \quad & \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d^p_{ij} x_{ij} + \beta \sum_{i=1}^{n} \sum_{k=1}^{m+1} f_i (\tilde{d}^p_{ik} + \tilde{d}^d_{ik}) r_{ik} + \alpha \sum_{i=1}^{n} \sum_{j=1}^{m} f_i d^d_{ij} y_{ij} \\ & + \sum_{j=1}^{m} b_j w_j + \sum_{j=1}^{m} s_j z_j - \sum_{j=1}^{m} s_j \tilde{z}_j \end{aligned} \tag{4}$$

This objective function is subject to binary conditions on the variables, constraints (2 *bis*), (2 *ter*) and (2c) to (2e), and the following constraints:

Subject to:

$$\sum_{k=1}^{m+1} r_{ik} = \sum_{j=1}^{m} x_{ij} \qquad \forall i \in N \tag{5}$$

$$\sum_{i=1}^{n} r_{ij} \leq z_j \sum_{i=1}^{n} f_i \qquad \forall j \in M \tag{6}$$

$$\sum_{j=1}^{m} x_{ij} d^p_{ij} + \sum_{k=1}^{m} \tilde{d}^p_{ik} r_{ik} \leq A \qquad \forall i \in N \tag{7}$$

$$\sum_{j=1}^{m} y_{ij} d^d_{ij} + \sum_{k=1}^{m} \tilde{d}^d_{ik} r_{ik} \leq A \qquad \forall i \in N \tag{8}$$

$$\sum_{j=1}^{m} x_{ij} d^p_{ij} + d_i r_{im+1} + \sum_{j=1}^{m} y_{ij} d^d_{ij} \leq A(2 - r_{im+1}) \qquad \forall i \in N \tag{9}$$

$$\tilde{z}_j \leq w_j \qquad \forall j \in M \tag{10}$$

$$\tilde{z}_j \leq s_j \qquad \forall j \in M \tag{11}$$

$$\tilde{z}_j \geq w_j + s_j - 1 \qquad \forall j \in M \tag{12}$$

Constraints (5) allow one to use no more than one recharging station in path i, and no recharging stations are allowed if path i is not served. Constraints (6) state that a recharging station can be used iff a recharging station or a base is opened. Constraints (7) and (8) ensure that the path to and from the recharging station does not exceed the flying range limit while constraints (9) are the flying range limit for a path without an intermediary recharging station. Constraints (10) and (11) force $\tilde{z}_j$ to be zero if either w_j or z_j are zero, and constraints (19) make sure that $\tilde{z}_j = 1$ if both binary variables w_j and z_j are set to 1.

5. Data

In this section, the assumptions that are made to assess the data are explained.

5.1. Sites

The facilities located in Figure (2) and outside Figure (3) Brussels from which biomedical products leave or are shipped are hospitals, Red Cross blood transfusion facilities, LBS laboratories and Curepath (Centre Universitaire inter Régional d'Expertise en Anatomie Pathologique Hospitalière). Facilities with lower volume, such as Red Cross sampling sites, are not taken into account in this study.

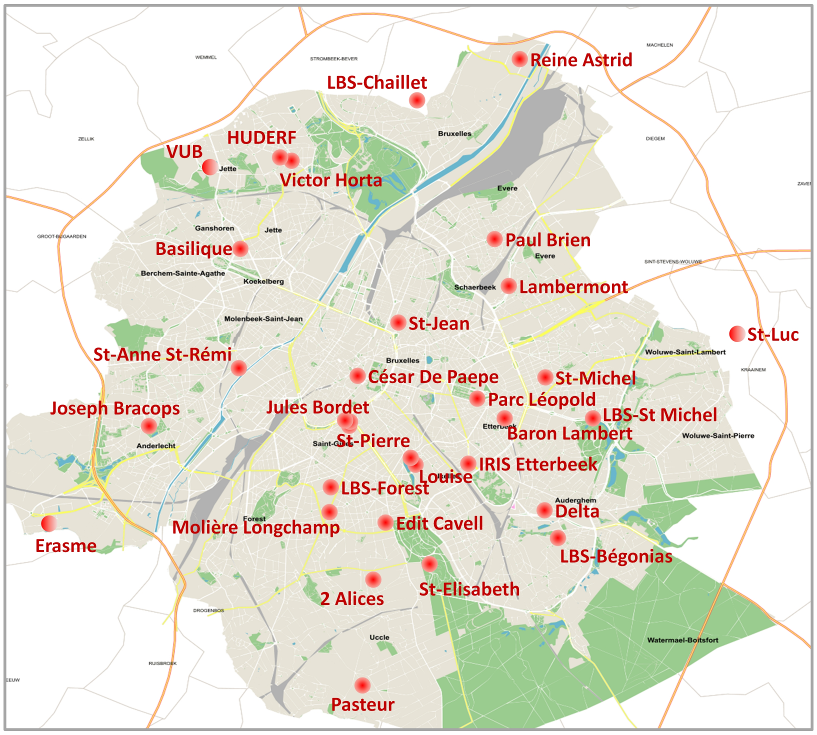

Figure 2: Mapping of customer sites in Brussels.

5.2. Potential locations

The city of Brussels and its periphery is square-patterned with a grid of potential bases every 2 km. The no-fly zones, i.e. areas that are prohibited to UAVs (such as airports and heliports), which are shown in Figure 4, define the exclusion parameters for potential bases or potential recharging stations.

5.3. Flows

Biomedical products intended for transportation are blood products and derivatives (e.g., whole blood, red blood cell concentrates, platelets, and fresh frozen plasma), human samples for analysis (such as urine, amniotic fluid, serum, tissues, smears), and medical products (vaccines, medicines, pharmacy preparations). Blood is initially collected from donors by Blood Transfusion Establishments (in French: Etablissements de Transfusion Sanguine, ETS), which provide the link between the donor and the blood product (BeQuinT, 2015). These ETSs ensure the supply and qualification of donations, the preparation of the blood components (red blood cells, platelets, and plasma), the storage and the distribution to hospital blood banks. Therefore, these ETSs provide the link between the blood product and the patient.

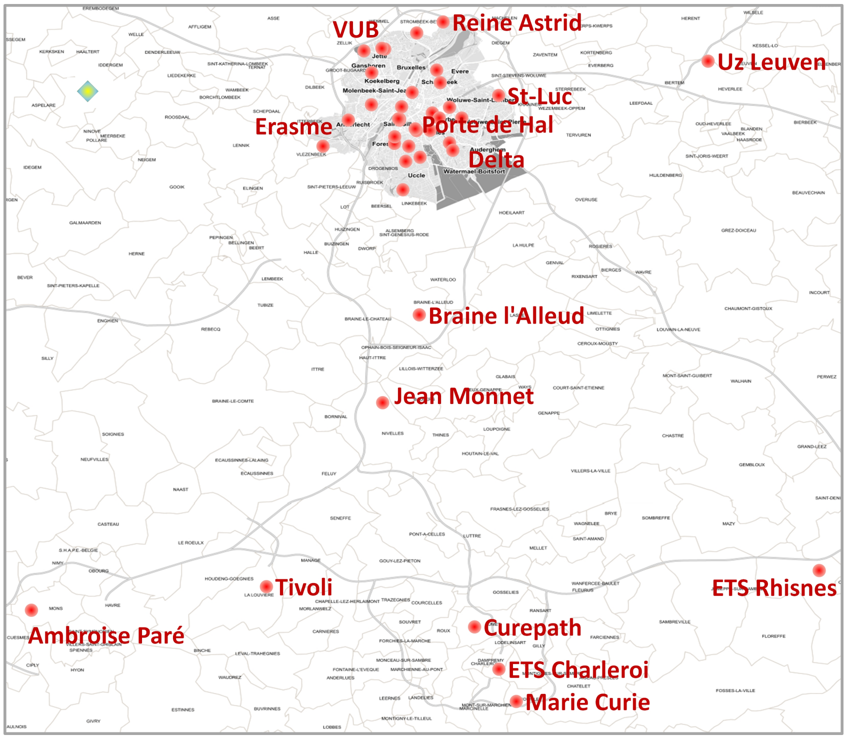

Figure 3: Mapping of customer sites outside of Brussels.

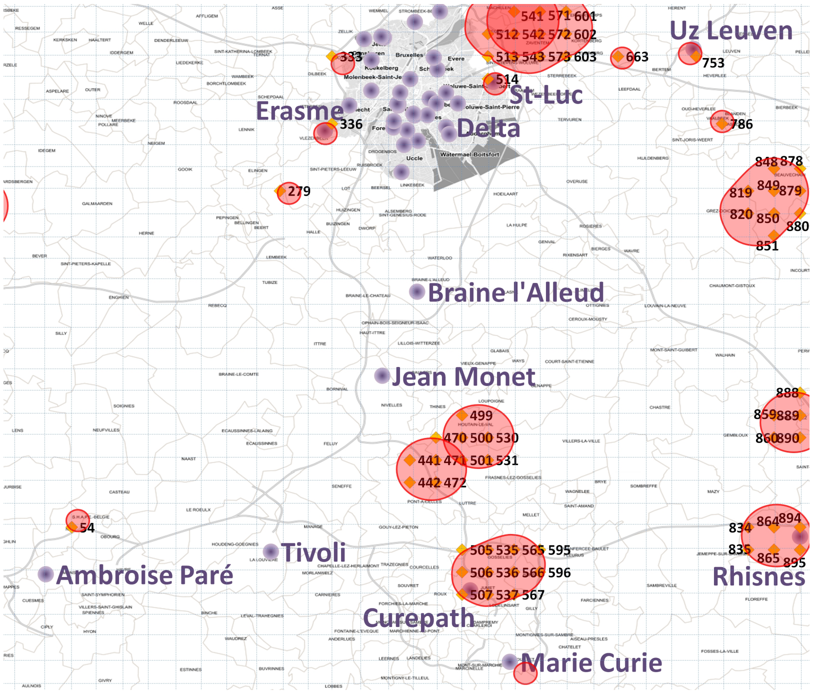

Figure 4: Mapping of the no-fly areas in red (Belgocontrol, 2018) and the excluded sites in orange colour. The other nodes of the blue dotted grid correspond to potential base locations.

In Belgium, there are five ETS accredited establishments. In Brussels, the Blood Service, which is a Red Cross entity in Uccle, is accredited as an ETS. In 2016, the Red Cross accepted 182,554 blood, plasma and platelet samples. It meets the blood needs of 43 hospital blood banks in the Wallonia-Brussels region (Croix-Rouge de Belgique,, 2016). For Belgium as a whole, the total number of blood requests that was distributed was 565,708 (BeQuinT, 2015). Samples are taken in hospitals, doctors' offices or laboratories. They are then analysed on site if the establishment is equipped to perform the required analyses, or they are sent to other specialized establishments. For Brussels, the LBS Medical Laboratory provides a list of 722 analyses, 287 of which are outsourced to other laboratories or university hospitals LBS Medical Laboratory (2018). The flow estimates are based on the data that are provided by Drone4Care, the data on the shuttle trips between CHIREC hospitals and the Curepath laboratory, the data that are collected from the Charleroi Red Cross centre and then generalized to Brussels hospitals, and the data from the LBS and the LHUB networks (Croix-Rouge de Belgique,, 2016; LBS Medical Laboratory, 2018).
The flows are expressed in terms of the quantity of cargo that can be transported by UAVs per week. The distribution of the 2683 products that are transported per week between 101 pickup-delivery pairs is shown in Figure 5.

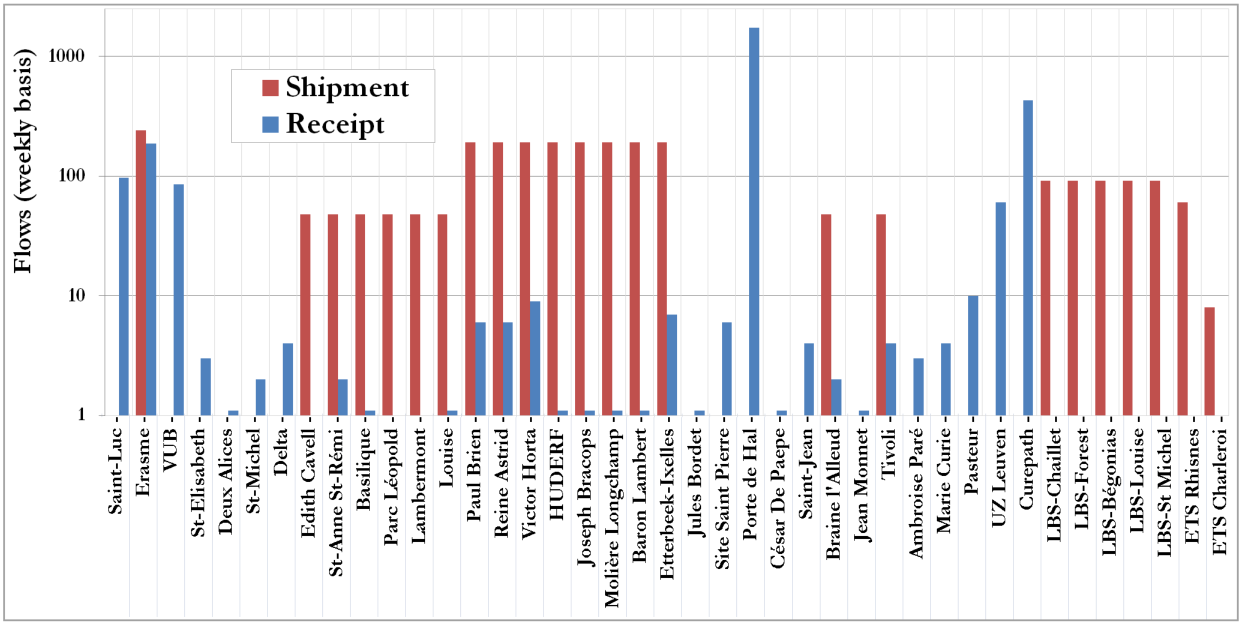

Figure 5: Weekly volumes that are exchanged between customer sites.

5.4. Distance

To calculate the orthodromic distance between sites, we use the formula:

$$60 \arccos[\sin\varphi_A \sin\varphi_B + \cos\varphi_A \cos\varphi_B \cos(\lambda_A - \lambda_B)].1,852\ km$$

where φ_A, λ_A and φ_B, λ_B are the geographical latitudes and longitudes in radians of the two points of A and B, respectively. The altitude differences between sites are neglected. Figure 6 displays the distribution of the distances between the pickup and delivery sites. Since a UAV with a limited range of 23 km can only be chartered for lines with shorter distances (unless recharging stations are provided), 65% of the lines can be covered, representing 83% of the market.

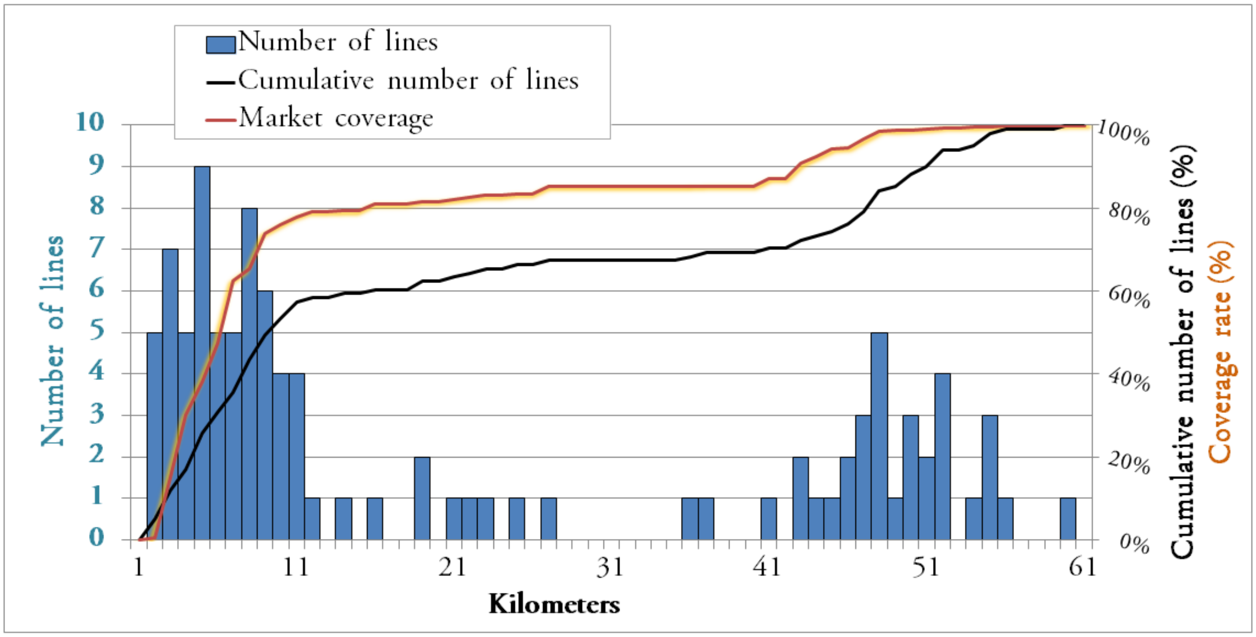

Figure 6: Lines to be served based on the distance.

5.5. UAVs characteristics

In scenarios 3 and 4, the flight time is assumed to be 55 minutes, which is consistent with the limitations of the octocopter UAV Hercules 20 that is currently on the VTOL market (DroneVolt, 2018). The hypothesis relating to the activity of drones is 1500 trips of 20 *km* on average, per year and per drone, and an estimated speed of 25 *km/h* (which is lower than maximum speed of the UAV, in order to optimise battery efficiency and thus increase the flight time). This results in a range for the UAV of 23 *km*. The assumptions made for the UAV are as follows.

- Mass of the empty UAV (with batteries): 13 *kg* (DroneVolt, 2018).
- Weight of the transport box with thermal equipment: 4 *kg* Cool Sarl (2020).
- Payload: 3 *kg*.
- Optimal speed based on battery optimization: 25 *km/h*.
- Cost of the drone: 20000 €.
- Maintenance every 200 flight hours.
- Regular change of propellers and engines.
- The cost of the consumed energy is based on D'Andrea (2014):

$$Cost\ per\ km = \frac{c}{e}\ (\frac{m_p + m_v}{370\ \eta\ r} + \frac{p}{v})$$

where:	$m_v = 17\ kg$	mass of a Hercule 20 UAV (with battery)
	$m_p = 3\ kg$	loading
	$\eta = 0.5$	engine and propeller efficiency (D'Andrea, 2014)
	$r = 3$	lift-to-drag ratio (D'Andrea, 2014)
	$p = 0.1\ kW$	power consumed by electronics (D'Andrea, 2014)
	$v = 25\ km/h$	average speed
	$c = 0.27\ \text{€}/kWh$	cost of electricity Luminus (2018)
	$e = 0.8$	charging efficiency (D'Andrea, 2014)

The data, on which the cost calculations for the UAV are based, are summarised in Table 4.

Component	Data
UAV depreciation (cost of the UAV including administrative procedures + capital cost)	22000€ for a 5000 h lifespan
Insurance premium	1500€/year
Engine	8x200€ for 2200 h trips
Propellers	100€ for 100 h trips
Maintenance	250€ every 200 h
Hourly wage (one operator for monitoring and light maintenance of 20 drones, one 20 km mission every 2 hours)	40€/h
Energy cost per km at load	0.13€
Energy cost per km at empty	0.11€

Table 4: Cost components.

The resulting operating costs per km are 0.699€ empty and 0.702€ loaded.

5.6. *Costs of setting up a base*

To take into account the price variations between municipalities, an adjustment factor κ (Figure 7) is used. The costs of setting up a base are composed of the following.

- Rent: κ 1600€$/month$
- Rental costs insurance: 100€$/month$, electricity (excluding recharging drones): 300€$/month$, staff not dedicated to the activity (maintenance, security, and training): 800€$/month$, and miscellaneous costs: 200€$/month$.
- Depreciation of equipment (5 years): Equipment costs and capital costs: 60000€ (Shavarani et al., 2018). The estimated costs of setting up a base are 552€ + κ368€ per week.

5.7. *Costs of setting up a recharging station*

Regarding the costs of setting up a recharging station, it is assumed that each of them is equipped with automatic and wireless recharging systems, such as the Dronebox or the Skysense Charging Pad (Shavarani et al., 2018). Two recharging systems are required to ensure adequate coverage when experiencing breakdowns. The time that is needed to recharge a UAV is one hour. It is also assumed that the rent and the rental costs are 300€/month, the depreciation of equipment (5 years) results in capital costs of 1000€ and the maintenance costs are 200€/month. This represents a total of 157€ /week.

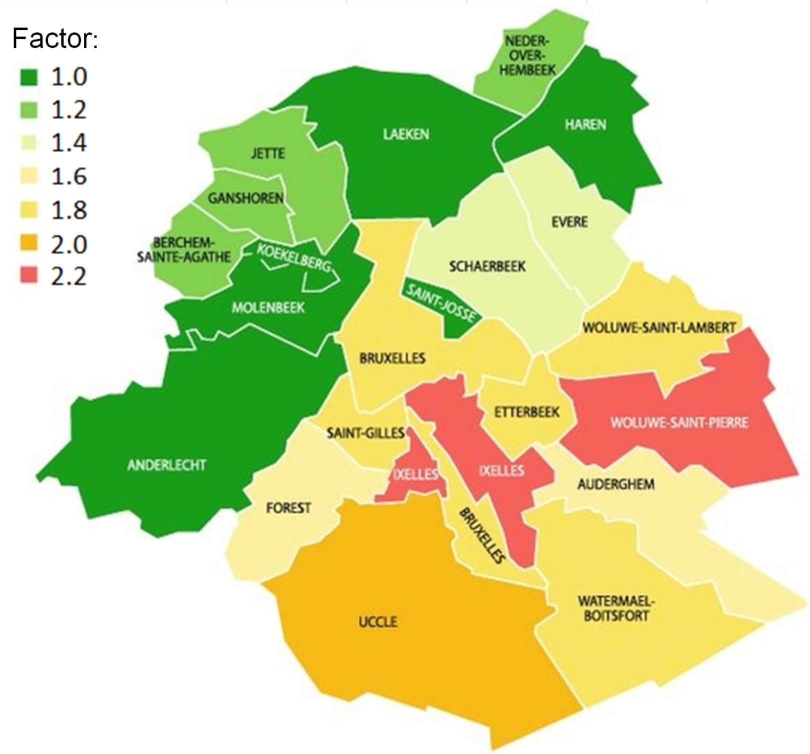

Figure 7: Adjustment factor for real estate prices in Brussels. Source: (Fédération Royale du Notariat belge, 2016), cited by Farr (2017).

6. Computational experiments

We have tested our mathematical model to check the validity of the model and to get some insights that could help us to develop heuristics for bigger cases. All of the optimization steps have been performed on a personal computer (2.80 GHz Intel Core i7 processor and 16 GB of RAM) with CPLEX 12.8 as solver and Windows 10 as the operating system. Because we must solve binary programming models, the Optimization Programming Language (OPL) has been used to solve the model thanks to the classical branch-and-cut CPLEX solver with the default parameters.

6.1. The case of Brussels

The mapping tools that are employed come from the BruGIS online geographic information system.

6.1.1. Scenario 1

The optimal solution obtained in 131 s. results in a total cost of 50344€ including 48062€ for the trips and 2282€ for the bases. Since the UAV must return to its departure base, the distance that is covered by an empty UAV (36040 km) is greater than the loaded distance (32579 km). Figure 8 represents the number of trips by travelled distances and the demand satisfaction rate.

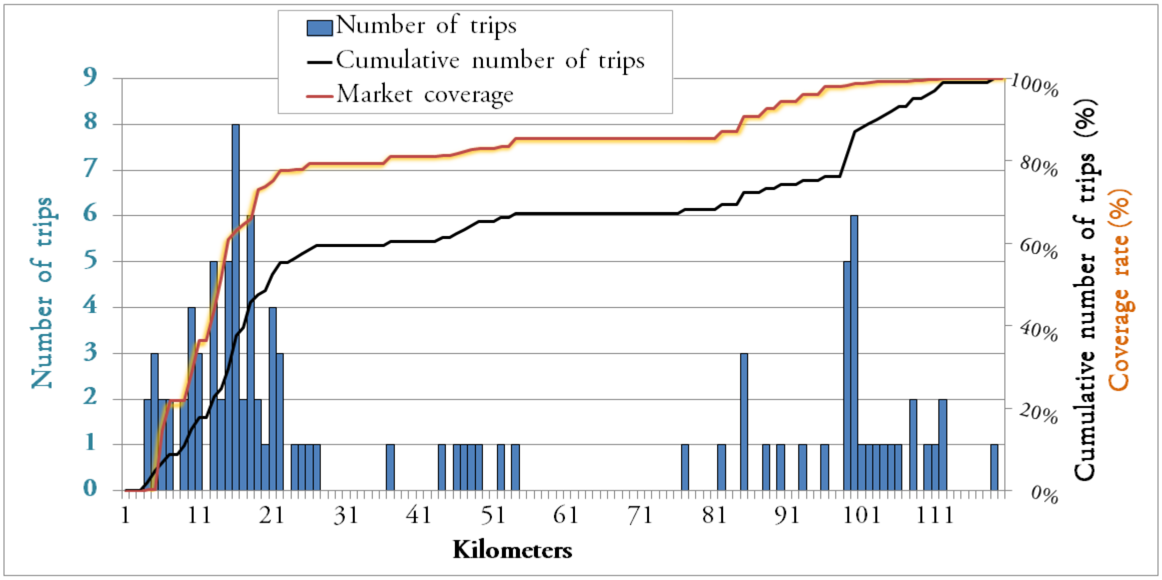

Figure 8: Number of trips by travelled distances and the demand satisfaction rate, scenario 1.

Figure 9 represents the locations of the bases and the trips that are made by drones. Two bases are open. The base located north of Charleroi (504) has a set-up cost of 920€ and is responsible for all Curepath activities and for the southern paths, i.e., 446 paths. The other base in Saint Gilles (425) has a set-up cost of 1362€ and ensures the distribution of blood products (from Rhisnes) to hospitals in Brussels and all the northern paths, which is a total of 2237 paths. Note that the two largest customers attract established bases.

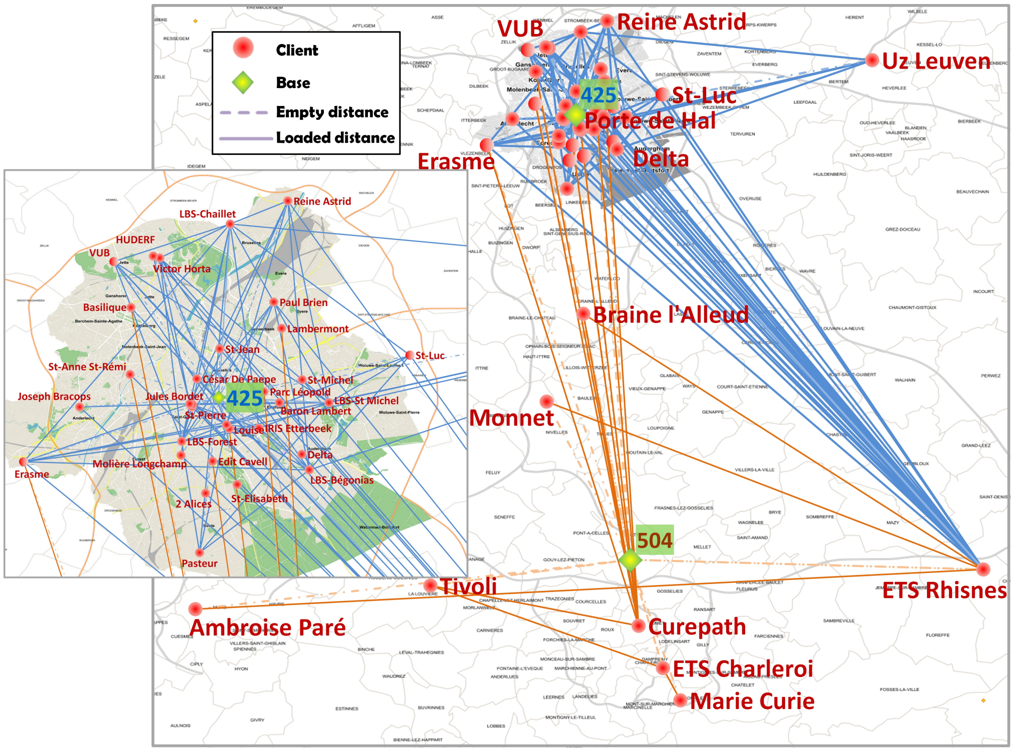

Figure 9: Map of the optimal locations of UAV bases and paths (scenario 1). Dashed lines and solid lines correspond to sections of the trips with the UAV empty or loaded, respectively. Colour of the lines indicates the origin base of UAV for corresponding trip.

Location	Set-up cost	Number of	
		Departures	Arrivals
South of Erasme (337)	920€	480	200
Jette (392)	920€	715	102
Saint Gilles (425)	1362€	1372	1938
Charleroi (508)	920€	56	443
Rhisnes (893)	920€	60	0

Table 5: Optimal locations, scenario 2.

6.1.2. Scenario 2

The optimal solution obtained in 159 s. results in a total cost of 37342€ including 32300€ for the trips and 5042€ for the bases. Figure 10 shows that the distances of the complete trips have been considerably reduced. In addition, the use of two types of drones with different levels of flying range would be possible. The first for small operating ranges (<23 km) would cover 59% of the lines and 79% of the market in terms of products. The second would cover the largest range of action. This solution could be adopted as part of a gradual deployment of the activity. However, the consequences of this solution on modelling are out of the scope of this paper. Indeed, considering a non-VTOL drone that is suited for larger ranges may lead to extra equipment, such as catapults, which would modify the cost structure assumptions and results.

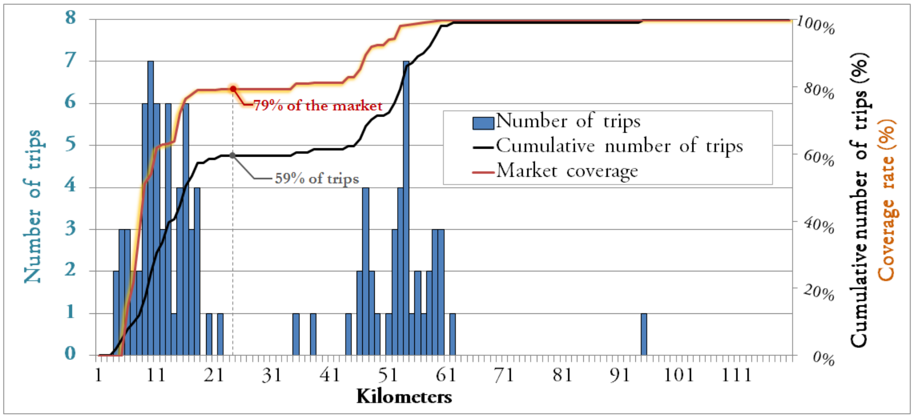

Figure 10: Map of the optimal locations of UAV bases and paths (scenario 1).

The first column of Table 5 is the optimal locations of bases, and the second/third columns are the number of UAV departures/arrivals from/to the bases.

Since the drone is not forced to return to its initial base after a delivery anymore, the distance that is covered when empty decreases to 13490 km. However, an imbalance in the number of drones per base is observed. Indeed, some bases have deficient numbers of drones, such as base 893, which only serves as a launch base for the distribution blood products from Rhisnes, and other bases have excess numbers of drones. This is the case for the base in Charleroi (508), which mainly collects drones that have delivered from Curepath, as shown in Figure 11.

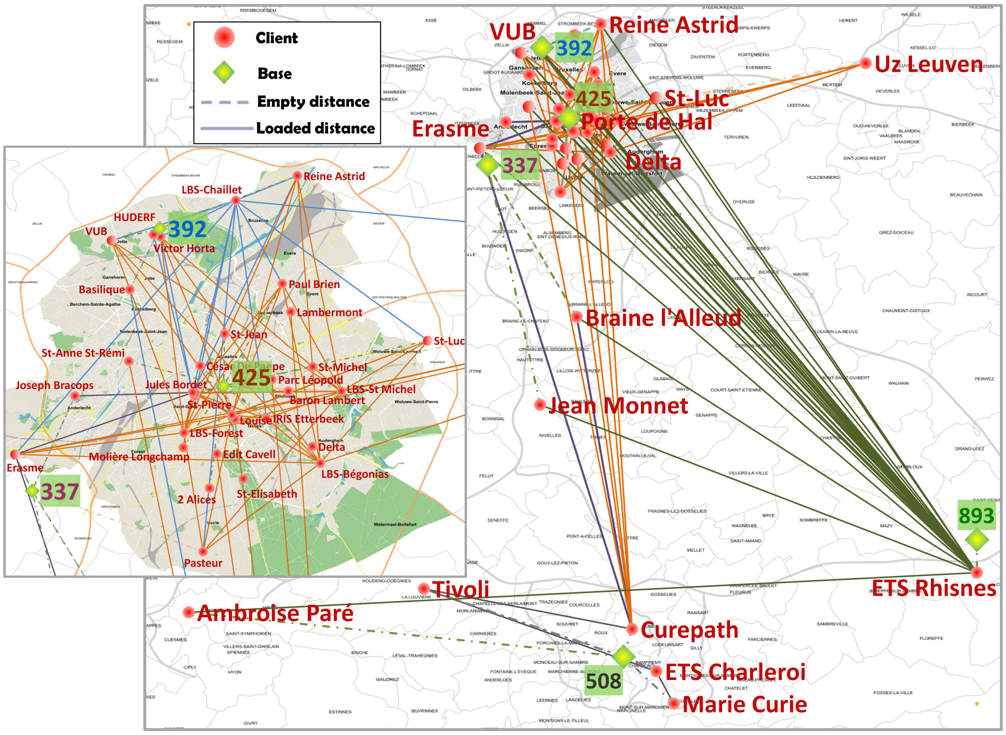

Figure 11: Map of the optimal locations of UAV bases and paths (scenario 2).

6.1.3. Scenario 3

In this scenario, a 23 km range constraint is taken into account. As already highlighted in Figure 5, this kind of UAV can cover 65% of the number of lines that are to be served, which is 83% of the market in terms of products. That is the reason why the considered satisfaction rate of the demand must necessarily be less than 83%. Actually, the maximum coverage is 81.65% due to the assumption of the discretization of space. Nevertheless, determining the optimal satisfaction rate is not a trivial task. Therefore, in our experiment, the satisfaction rate τ goes from 5 to 80% at a 5% step.

All the optimal solution are obtained in less than 7 s. At the 5 and 10% of satisfaction rates, only one base in Forest is opened at a setup cost of 1140.8 €; 192 lines at 5% and 269 lines at 10% are served by this facility with transportation costs of 664 € and 1229.4 €, respectively. From 15% to 80%, it is interesting to note that the locations of the bases are stable and therefore are compatible with a gradual increase in activity. The 15% rate leads to the start of activity at the base in Saint Gilles (425). This will be continued up to 79% with the opening of a base in Jette (392) when the rate hits 45% and then a base in Anderlecht (335) when the rate hits 60%.

Those three bases are enough to satisfy up to 79% of the demand at a total cost of 16811.6€. Figure 12 shows the result corresponding to a coverage rate of 79% and drones with ranges of 23 km. All activity is concentrated in Brussels since trips involving a customer outside Brussels are out of the reach of UAVs.

At 80%, i.e., as close to the flying range limit, two new bases have to be opened to cover the longest distances: the bases in La Louvière near Tivoli 295 (with 0 arrival and 48 departures) and in Charleroi 508 (with 52 arrivals and 48 departures). The facility costs and

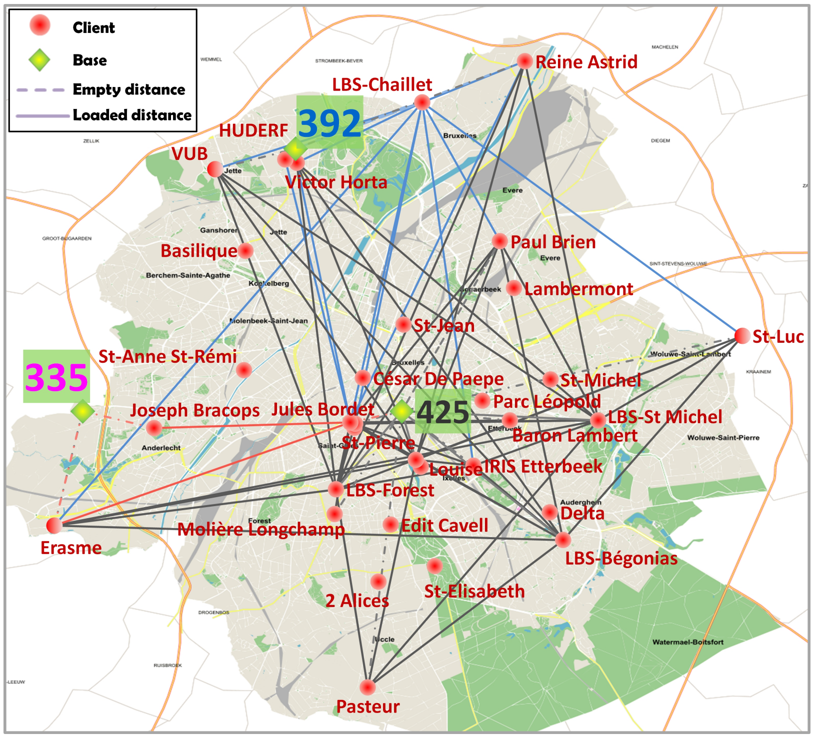

Figure 12: Map of the optimal locations of UAV bases and paths (scenario 3) with UAVs with a 23 km range and a 79% satisfaction rate.

consequently the total costs (19027.8 €) are significantly increased with a slight increase in the demand satisfaction. Figure 13 represents the costs according to the satisfaction rate. Red dots correspond to the total cost for a given satisfaction rate, i.e., the sum of transportation cost (orange dots) and drones bases costs. Bases costs are a function of the number of bases opened, from light green (one base open) to dark green (5 bases open).

Figure 14 illustrates how the expansion is achieved. Black lines represent the global market in terms of the number of different trips (i.e., a distance from a loading location to an unloading location) to be achieved by drone for each kilometric segment. Blue coloured segments correspond to the trips achieved for a corresponding satisfaction rate (in terms of products transported): from light blue (first trips achieved, usually corresponding to small distances), to dark blue (corresponding to longer trips). White segments correspond to trips that cannot be achieved with an autonomy limit of 23 km. First, the activity is developed on small lines ($<$ 6 km for 15% activity), and then it is extended (all lines less than 8 km are covered at 75% activity).

6.1.4. Scenario 4

The possibility to recharge the UAVs does not change the results of scenario 3 for a satisfaction rate less than 80%. All the optimal solutions are obtained in less than 7 s. At 80% (Figure 15), a base in Neder-over-Heembeek (452) is added to the three bases that are located in Saint Gilles (425), Jette (392) and Anderlecht (335) and a recharging station is used at location 723 (Leuven West). The number of UAVs that is recharged over the period is 24, which remains acceptable in view of the assumptions that are made for the charging stations (2 charging systems per station). This configuration is obtained in 51s and costs

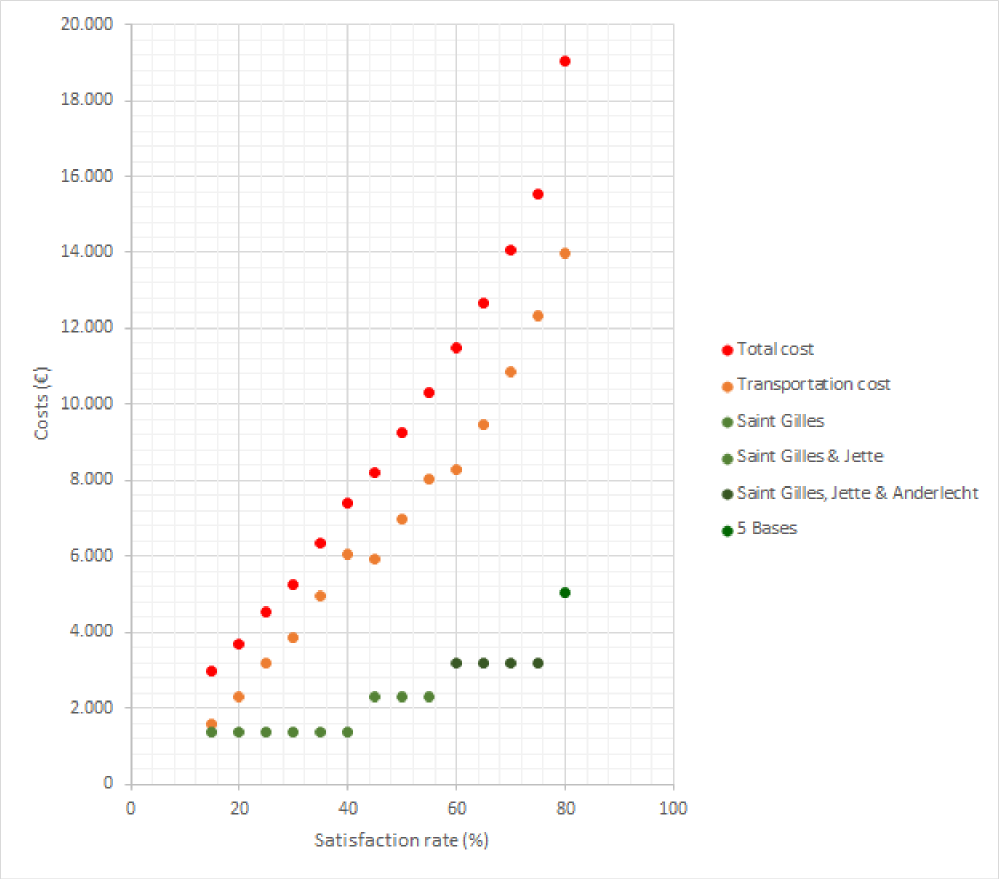

Figure 13: Costs according to the satisfaction rate.

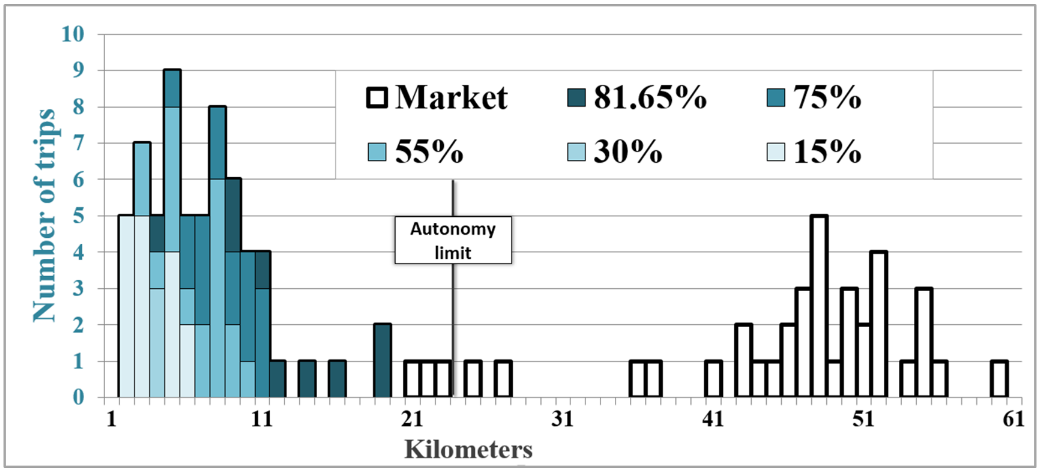

Figure 14: Expansion of activity as a function of distance.

17906.5€ (including 13627.9€ for the transportation, 4121.6€ for the bases and 157€ for the recharging stations) instead of 19027.8€ without recharging stations.

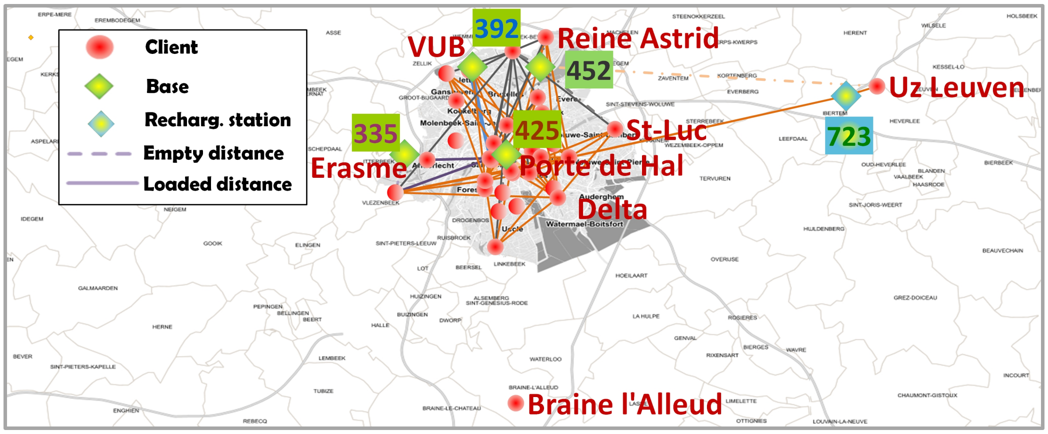

Figure 15: Map of the optimal locations of UAV bases, recharging station and paths (scenario 4) with UAVs with a 23 km range and a 80% satisfaction rate.

With 22795.4€, 85% of the demand can be served using seven facilities, including five bases and two recharging stations, with one facility being used both as a base and a recharging station. This result is obtained in 47s.
In this scenario, 87.1% of the demand can be served, but since the distances of some lines are close to the flying range limit, bases and recharging stations with low activity rates are opened, which results in substantially increased costs.

6.1.5. Summary

The results are summarised in Table 6. Column named NB shows the optimal number of bases, whereas RS is the number of recharging stations located at a different location than the optimal location of the bases. As the solutions are the same for scenario 3 and 4 for a satisfaction rate less than 80%, only the results of scenario 3 are displayed.

6.2. Additional instances

We test some instances with a variety of sizes.

6.2.1. Description of the instances

The coordinates of the potential pickup and delivery sites are randomly selected: the latitude in [50.4,50.9] and longitude in [3.9,4.8]. The resulting area is similar to the one studied in the case of Brussels and is square-patterned with a grid of potential bases or potential recharging stations every 2 km. The pickup-delivery pairs (P-D) are randomly generated with a probability of 5, 10, 20 and 40% excluding pairs with the same pickup and delivery location. Their flows are also randomly generated in [1,200]. The 10 instances are summarised in Table 7.

The UAVs characteristics are the following: a range of 23 km and the operating costs per km are 0.7€ empty and 0.75€ loaded. The cost of setting up a base is assumed to be 1000€, and the one for a recharging station is 150€. Scenarios 3 and 4 are also tested with a flying range of a UAV increased to 35 km which could be reached by improved technologies or reduction of the payload, for example. The limit of the computation time is set to 3600s.

Scenario	Flying range	τ	Transportation costs	Set-up costs	NB	RS	Time (s)
1	∞	1	48062	2282	2		131
2	∞	1	32300	5042	5		159
3	23 km	0.05	664.4	1140.8	1		4
		0.10	1299.4	1140.8	1		6
		0.15	1604.3	1361.6	1		5
		0.20	2323.5	1361.6	1		3
		0.25	3190.0	1361.6	1		6
		0.30	3872.0	1361.6	1		5
		0.35	4979.1	1361.6	1		3
		0.40	6047.7	1361.6	1		6
		0.45	5919.4	2281.6	2		4
		0.50	6961.1	2281.6	2		3
		0.55	8022.4	2281.6	2		6
		0.60	8296.6	3201.6	3		4
		0.65	9459.9	3201.6	3		6
		0.70	10857.1	3201.6	3		6
		0.75	12325.1	3201.6	3		5
		0.80	13986.2	5041.6	5		6
4	23 km	0.80	13627.9	4278.6	4	1	51
		0.85	17439.8	5355.6	5	2	47
		0.87	18803.1	6570	6	2	48

Table 6: Summary of the results obtained for the case of Brussels

Instance	Potential customers	Total flows	P-D
I-40-74	40	7356	74
I-40-175	40	17589	175
I-40-297	40	29096	297
I-40-490	40	47793	490
I-40-647	40	65282	647
I-50-118	50	11387	118
I-50-242	50	24837	242
I-50-509	50	50951	509
I-50-688	50	67152	688
I-50-942	50	92735	942

Table 7: Instances.

6.2.2. Scenario 1

Table 8 shows that, in 4 instances out of 10, the optimal solution is not reached within the limit of the computation time. For these instances, the best integer, the best bound, and the CLPEX Gap are provided to identify how close the obtained solutions are to the optimal one.

Instance	Number of bases	Best integer	Best bound	CLPEX Gap (%)	Optimal	Time (s)
I-40-74	4				129559.28	72.59
I-40-175	8				420589.85	324.63
I-40-297	9				615786.38	833.38
I-40-490	11				1146526.00	3533.08
I-40-647	15	1403515	1402631	0.06	-	3600
I-50-118	6				355815.78	577.99
I-50-242	8				694048.99	1104.66
I-50-509	13	1619624	1616393	0.20	-	3600
I-50-688	18	1985851	1981704	0.21	-	3600
I-50-942	28	2507130	2495762	0.45	-	3600

Table 8: Results of scenario 1.

6.2.3. Scenario 2

Relaxing the constraints related to the destination bases allows to significantly reduce the computation time (Table 9).

Instance	NB	Optimal	Time (s)
I-40-74	11	86700.92	7.50
I-40-175	17	248140.61	9.84
I-40-297	23	360722.05	15.28
I-40-490	25	648700.66	29.95
I-40-647	26	794902.95	38.19
I-50-118	18	213169.37	18.19
I-50-242	27	401416.72	17.28
I-50-509	31	900242.52	32.67
I-50-688	33	1102875.03	42.84
I-50-942	32	1384853.27	54.70

Table 9: Results of scenario 2.

6.2.4. Scenario 3

In our experiments, the satisfaction rate τ is set to 0.25, 0.5, and 0.75. The infeasible solutions are represented by ✗ in Table 10. Solving the problem considering a flying range of 35 km increases computation time.

<table>
<tr><th colspan="2"></th><th></th><th colspan="2">Optimal</th><th colspan="2">Time (s)</th></tr>
<tr><th>Instance</th><th>τ</th><th>NB</th><th>23 km</th><th>35 km</th><th>23 km</th><th>35 km</th></tr>
<tr><td rowspan="3">I-40-74</td><td>0.25</td><td>2</td><td colspan="2">9449</td><td>3.94</td><td>7.2</td></tr>
<tr><td>0.50</td><td>4</td><td colspan="2">22280</td><td>4.53</td><td>5.25</td></tr>
<tr><td>0.75</td><td>7</td><td colspan="2">38854</td><td>3.22</td><td>5.75</td></tr>
<tr><td rowspan="3">I-40-175</td><td>0.25</td><td>6</td><td colspan="2">24129</td><td>5.92</td><td>13.28</td></tr>
<tr><td>0.50</td><td>9</td><td colspan="2">54094</td><td>4.63</td><td>10.58</td></tr>
<tr><td>0.75</td><td>13</td><td>✗</td><td>119370</td><td>✗</td><td>11.7</td></tr>
</table>

I-40-297	0.25	6	31486		10.44	27
	0.50	11	78680		7.69	15.11
	0.75	17	✗	152210	✗	20.11
I-40-490	0.25	8	51892		19.66	33.98
	0.50	14	128909		8.88	33.28
	0.75	20	✗	290684	✗	25.26
I-40-647	0.25	9	61333		24.31	46.38
	0.50	16	157437		13.11	38.70
	0.75	21	✗	328183	✗	41.14
I-50-118	0.25	4	16996		4.03	12.08
	0.50	9	42798		4.47	13.47
	0.75	✗	✗		✗	✗
I-50-242	0.25	6	32012		15.25	16.64
	0.50	14	78067		8.88	24.45
	0.75	21	✗	182525	✗	53.31
I-50-509	0.25	12	61410		26.55	51.89
	0.50	21	159672		25.39	64.85
	0.75	✗	✗		✗	✗
I-50-688	0.25	12	75808		29.84	76.05
	0.50	24	193672		33.5	85.05
	0.75	✗	✗		✗	✗
I-50-942	0.25	15	91079		45.75	88.17
	0.50	22	241925		45.16	107.16
	0.75	30	✗	579666	✗	55.59

Table 10: Results of scenario 3.

6.2.5. Scenario 4

Table 11 displays the optimal solution for a satisfaction rate τ ranging from 0.75 to 1 at a 0.05 step. In this scenario, UAVs can be recharged at any bases or at a recharging station. Columns named RS show the number of recharging stations located at a different location than the optimal location of the bases.

Those recharging possibilities allow increasing the satisfaction rate compared to scenario 3. In all the tested cases, the solutions obtained for $\tau = 0.75$ are the same in both scenarios. Interestingly, two configurations are observed for instance I-40-490 (τ=0.75) with a flying range of 35 km. Indeed, in scenario 3, the solution is obtained with 20 bases, whereas in scenario 4 only 19 bases are open, 4 of them also serving as recharging stations resulting in lower set-up costs but higher transportation costs.

		23 km				35 km			
Instance	τ	NB	RS	Optimal	Time (s)	NB	RS	Optimal	Time (s)
I-40-74	0.75	7	0	38854	6.63	7	0	38854	15.06
	0.8	8	0	44483	11.73	8	0	44483	25.06
	0.85	8	0	51179	12.62	8	0	51124	11.52
	0.9	9	1	60812	16.51	9	0	60554	51.59
	0.95	11	3	72077	11.20	11	1	71677	137.41

	1.00	✗	✗	✗	✗	11	2	87040	12.61
I-40-175	0.75	13	1	119675	33.88	13	0	119370	44.55
	0.8	14	2	140177	31.97	14	0	139688	40.84
	0.85	15	3	161696	51.09	15	0	161004	114.98
	0.9	16	4	185302	26.62	16	0	184580	70.77
	0.95	✗	✗	✗	✗	17	1	214242	115.95
	1.00	✗	✗	✗	✗	17	3	248715	53.28
I-40-297	0.75	17	0	152216	33.70	17	0	152210.41	88.11
	0.8	18	1	182104	68.77	18	0	181833	103.27
	0.85	19	1	215487	40.84	19	0	215094	113.64
	0.9	19	3	252103	56.16	19	0	251466	90.55
	0.95	✗	✗	✗	✗	21	2	301253	125.76
	1.00	✗	✗	✗	✗	23	3	361388	134.69
I-40-490	0.75	19	1	291127	124.77	19	0	290684	104.60
	0.8	21	3	344504	81.83	21	0	343862	86.89
	0.85	22	3	400344	88.70	22	0	399520	87.41
	0.9	24	5	467235	83.17	24	1	466171	113.7
	0.95	✗	✗	✗	✗	25	2	551298	235.34
	1.00	✗	✗	✗	✗	25	4	649539	223.02
I-40-647	0.75	21	0	328287	73.87	21	0	328183	185.27
	0.8	23	1	396914	80.33	23	0	396379	148.30
	0.85	24	4	471314	88.56	24	0	470525	161.08
	0.9	25	4	555445	294.64	25	1	554423	282.50
	0.95	✗	✗	✗	✗	26	1	667780	284.88
	1.00	✗	✗	✗	✗	26	5	795906	357.76
I-50-118	0.75	15	1	105296	35.47	13	0	104659	159.25
	0.8	18	2	126475	38.93	14	0	124853	228.30
	0.85	✗	✗	✗	✗	14	1	144906	148.55
	0.9	✗	✗	✗	✗	15	1	166405	160.38
	0.95	✗	✗	✗	✗	16	1	189192	104.11
	1.00	✗	✗	✗	✗	18	1	213447	47.11
I-50-242	0.75	21	2	183010	119.73	21	0	182525	151.74
	0.8	22	2	218662	105.27	22	1	217941	558.53
	0.85	✗	✗	✗	✗	24	1	259855	141.72
	0.9	✗	✗	✗	✗	24	1	305066	97.47
	0.95	✗	✗	✗	✗	26	2	352655	383.95
	1.00	✗	✗	✗	✗	27	1	401987	125.84
I-50-509	0.75	28	5	426913	100.61	28	2	426053	508.05
	0.8	30	7	511537	213.27	28	2	510402	504.23
	0.85	✗	✗	✗	✗	31	2	598542	509.08
	0.9	✗	✗	✗	✗	31	3	693438	358.36
	0.95	✗	✗	✗	✗	31	4	793276	2871.23
	1.00	✗	✗	✗	✗	31	6	901226	1995.27
I-50-688	0.75	30	4	497268	242.12	30	1	496398	352.22
	0.8	31	10	603018	411.31	31	3	601832	541.5
	0.85	✗	✗	✗	✗	32	2	715981	784.44

	0.9	✗	✗	✗	✗	32	4	837691	488.81
	0.95	✗	✗	✗	✗	32	3	965865	3061.56
	1.00	✗	✗	✗	✗	33	5	1103933	1196.41
I-50-942	0.75	30	2	580235	566.36	30	0	579676	347.84
	0.8	31	6	700956	635.11	31	1	699929	748
	0.85	✗	✗	✗	✗	31	2	851757	1460.56
	0.9	✗	✗	✗	✗	31	3	1018882	1826.06
	0.95	✗	✗	✗	✗	32	4	1195156	1760.42
	1.00	✗	✗	✗	✗	32	6	1386108	2067.48

Table 11: Results of scenario 4.

7. Conclusion

For UAVs to obtain a clear advantage over traditional transport schemes, we underline the importance of various variables with higher weights accorded to the most significant ones. The model and results are of interest as decision-support tools for the process of UAV network deployment for biological material transport since they help to evaluate the consequences of strategic choices.

The PESTEL analysis identifies the evolution of the regulations relating to the operation of UAVs and their technological development and related systems as the main factors that may have significant impacts on the UAV market. Nevertheless, concerning medical transport, societal aspects may be a measure through which one can obtain derogations. Indeed, UAVs may compete with respect to rapidity, which is an essential criterion due to the nature of the products that are transported and the urgency that is inherent in the sector. Furthermore, the use of UAVs opens up new possibilities for setting up traceability while reducing transportation costs.

Four innovative location models are proposed. We illustrate the practicality of our model with an application related to the transportation of units of blood or medical samples in the Brussels area. In addition to the results that are presented for Brussels, this research on the optimal location of the bases highlights the importance of the technical characteristics of UAVs (range, speed, and payload). The results of the study show the following.

- If the return to the launching base is required, the total distance is greater than that if this constraint is relaxed. This is a crucial point regarding the limited range of UAVs. However, the latter implies repositioning UAVs due to imbalances.
- The use of charging stations is useful for extending the mission ranges and increasing market share.
- Concerning a progressive deployment, the first results show the possibility of gradually implementing the bases without requiring any major changes such as closing a base.

This study has set the foundations of a UAV network for biological material transportation in the city of Brussels. Some of the choices made in this study (the type of drone, material transported, collect and delivery on customer sites), are identical to a similar project tested in the city of Antwerp (MEDRONA project, Neuray (2020)). Implementation of such drone-powered solution would likely be progressive:

- A progressive installation of UAV bases, with consideration of demand uncertainty for a choice of the first bases open that minimises the risks.
- With the support of a traditional road transport solution for potential customers out-of-range of the drones, and as a backup for emergency requests during unfavorable weather conditions.

Also, the model would require to consider more parameters in order to refine the solutions and be more realistic (e.g., the use of specific corridors rather than direct paths).

Future research directions are related to the management of the bases. Indeed, as departure and arrival bases can be different, this could lead to an imbalance (lack of UAV in some bases, excess in others). Repositioning can be investigated either by the UAVs itself or by using an inland vehicle. Consequently, the temporal aspect of the management of the fleet of UAVs is of interest; it is essential to determine an appropriate number of UAVs for each base, consistent with the demand and the degree of urgency.

We illustrate the practicality of our model with an application related to the Brussels area. Thus, future contributions might analyze the case of another region (or of a set of regions) to examine potential variation between distinct contexts. As future perspectives, more accurate costs, as well as updated freight demand data, would undoubtedly help draw conclusions that are better suited to the actual practices in UAV transport nowadays.

Finally, as a research outlook, this work could be further developed by considering the impact of other attributes of transport such as quality of service, reliability, accessibility, safety, security, flexibility, or environmental impact. Moreover, external costs or externalities could also be integrated, as in the analysis of Merchan et al. (2019) for inland freight transport in Belgium. Nevertheless, depicting such developments requires a lot of data.

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