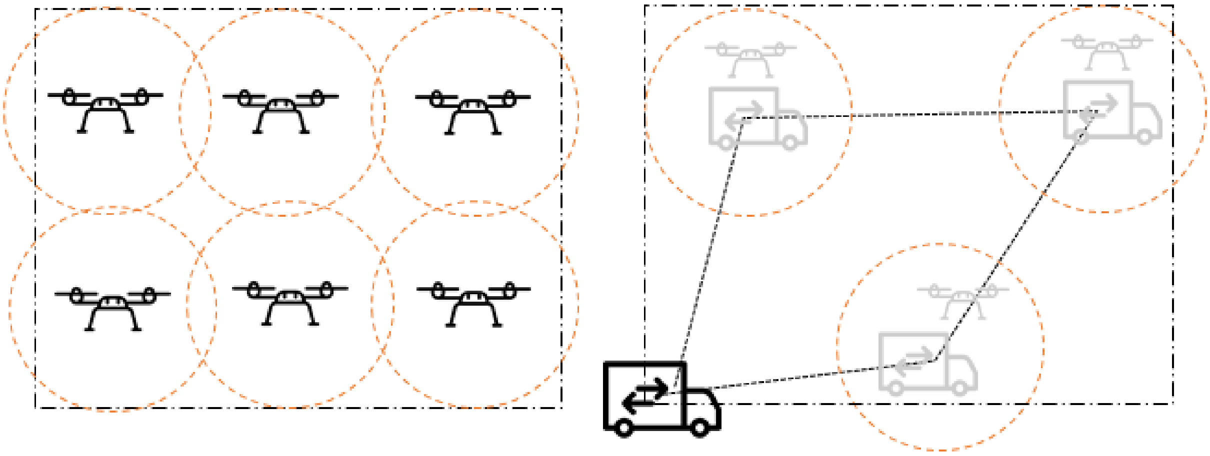

Logistic deliveries with Drones. State of the art of practice and research

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May 2019

STRC

19th Swiss Transport Research Conference
Monte Verità / Ascona, May 15 – 17, 2019

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May 2019

Abstract

New technologies are transforming facilities and vehicles into intelligent systems that will significantly modify logistics deliveries. With the appearance of automated vehicles, multiple new technological possibilities appear to perform deliveries. One example is the use of Unmanned Aerial Vehicles (UAV), or Drones, that might trigger different delivery networks or might boost new delivery services. This work will focus on the use of UAVs for logistic deliveries, including both a research state of the art and state of practice. Multiple researchers have already investigated several optimization problems that can appear when performing deliveries assisted with drones. For instance, the flying sidekick traveling salesman problem, where a drone is used in combination with vans to improve the service. Another example is the study of the optimal drone placement to provide cost-efficient coverage. However, multiple factors affect the market adoption of drones in logistic, like technical features, airspace regulation, or users' preferences, amongst others. That is why the work will also include a review on the latest industry trends and tests, to be able to identify potential optimization research gaps.

Keywords

Drones, Autonomous, Logistic, Urban Freight

1 Introduction

In recent years, the drone technology has been capturing a lot of attention from multiple industries to exploit its potential in several civil applications: inspection, agricultural, mapping, disaster response or delivery to name a few. The drone global market is estimated to grow from $2 billion in 2016, to nearly $127 billion in only 4 years (Moskwa, 2016). On the other side, research on optimization has been also intensively envisioning future problems where drones could replace or could be used in combination with tradicional delivery networks in urban areas.

This article tries to summarize the latest advances both on practical and research state of the art. From this point, we try to identify potential gaps for research in optimization in urban delivery networks. This state of the practice is not aimed at providing a comprehensive summary of all the tests in logistic services in urban areas with drones, rather than selecting the most promising with a future operational view and ready to soon be implemented in practice. From the research point of view, the selection is also not aimed to be comprehensive. The focus is rather on the works that tackle problems related to the optimization of urban delivery networks, that is, with an strategic and operational approach.

2 State of practice

Since the first famous announcement of Amazon Prime developing a fleet of UAVs for small parcel deliveries (Rose, 2013), multiple companies (DHL, Google, UPS, among several others) (Madrigal, 2014, Dillow, 2015) have been further developing the technology and adapting to multiple regulations to be able to bring the potential of UAVs to the field of urban logistics. In the following, the most important advances will be summarized. Focus will be given to tests with a future business operational view and that are close to implementation as permanent solutions.

It is important to mention, that from a combination of technological progress and economic activity, Giones and Brem (2017) still situates UAVs for small package deliveries in the first stage of the path to industry: the concept validation phase. Whereas other civil applications of UAVs, like inspection services or agricultural are situated one step furter (in product growth) and photography/videography are situated already in the market growth phase.

In the case of Switzerland, the Federal Office of Civil Aviation (FOCA) has been working for many years to offer an opportunity to UAVs to operate in a safely manner. Their advanced regulation has enabled to bring pioneers in the sector to Switzerland. In other locations, regulations have been adapted or special exceptions have been granted to allow tests to happen.

2.1 Drones in the medical sector

Swiss Post with Matternet have been very sucessfully testing and implementing the use of drones to complement the service offered with tradicional modes of transportation. First tests started in 2015, but most of the public presentation has been done from mid 2017 and is ongoing. In particular, their focus has been in the transportation of blood samples between hospitals or laboratories located in urban regions.

The firsts tests were performed in Lugano, and the operation has been since September 2017 established as a permanent solution. Two hospitals are located in a very small region, the big one is permanently open. The small one offers emergency services between 9h and 22h mondays to fridays but the laboratory service is not always operating. Previously, if a patient required an emergency blood analysis, the sample was sent to the big hospital with a taxi. This transport is now performed with the use of a drone between 14h and 22h (Swiss Post, 2017). Figure 1a shows a photograph with a drone carrying blood samples from the test. Similar concepts have been tested in two pairs of hospitals/laboratories in Zürich (Swiss Post, 2018a,c) and between one pair of hospitals in Bern (Swiss Post, 2018b). In Zürich (location 1), between Zentrallabor and Hirschlanden im Park, the drones fly above the lake, which avoids the congested point of "Quaibrücke". The other test (location 2), connects University Hospital and University Zürich Irchel, the Medical Virology Institute. There is regular service mornings and evenings to transport the biggest quantities of blood samples. During the rest of the day, a drone is available for on-demand emergency transport. Figure 2a) presents a scheme of the service.

Table 1 summarizes the operation in the different tests. Distance and travelled time between origin and destination are estimated in both alternatives. In a ground vehicle, like a car (C), or with the use of a drone (D). The dates that the tests have been active and their main goal is also included.

Even though the operation has so far been limited in spatial scope (only connecting pairs of hospitals) and in type of product (only blood samples). The operation could be expanded to build a network between multiple hospitals and laboratories, and to include the transport of other medical material, medicines, or urgent laboratory samples like perioperative biopsies. Other potential future applications within the medical sector include: pharmacies in the transport of same-day delivery of medicaments and blood or stem cell emergency requirements within

Table 1: Information from Switzerland Drone tests for blood samples

Location	Distance(km)	Time (min)	Test	Goal
Lugano	C: 3.6	C: 30-45	Mar-Aug17	Substitute taxi service
	D: 1-1.34	D: 3	Sep17-Permanent	
Zürich 1	C: 6	C: 20-25	Jun18-Jan19	Test quality of blood samples
	D: 5.8	D: 7	Apr19-Ongoing	Investigate permanent
Zürich 2	C: 3.1	C: 10-15/ 60	Dec18-Jan19	Investigate potential
	D: 5.97	D: 7	Apr19-Ongoing	
Bern	C: 5.4-6.7	C: 10-15	Jun18	Assess a possible
	D: 5.62	D: 6.5		solution

a) b)

Figure 1: a) Drone from Matternet in a test for Swiss Post transporting blood samples in Lugano. Source: Swiss Post. b) Drone and van in the test in Zürich. Source: Dailmer

multiple locations.

2.2 Drones and vans for e-commerce

During September 2017, Mercedes-Benz vans, US drone systems developer Matternet and Siroop online marketplace developed a pilot project with title *Vans and drones* in Zürich. The innovative concept was to use vans as mobile landing platforms for drones with the objective to test on-demand delivery and its acceptance by retailers and public. The combination of vans and drones allows to connect customers and retailers faster, enhances efficiency and service level and can reduce congestion.

During the three-week pilot, customers were able to order for the same-day selected products from the online marketplace suitable for transport by drone, mainly consumer electronics and other small items from e-commerce. The drones were loaded at the retailer warehouse and flew to a van located in one of the four pre-defined points. At the van, the driver took the product and performed the final delivery to the customer, meanwhile the drone returned to the retailer. (See Figure 2b). The idea is that with a combination of drone and vans the delivery time and service level associated with on-demand delivery can be improved. During 10 days, 50 packages were successfully delivered and services always took less than 2h between ordering and delivery. Safety was ensured and all deliveries were tracked to collect data. Figure 1b) shows a picture of the landing of the drone on the roof of the van.

2.3 Drones with backyard delivery

Wing is an initiative from Alphabet, that uses delivery drones to provide an innovative new service. They have been testing a system to conveniently transport small packages quickly. For the moment, they have been partnering with delivery residents and business to provide food and beverages, over-the-counter chemist items, and locally made coffee and chocolate. Tests have been performed in Canberra, Australia, among multiple regions. And tests in Helsinki, Findland are scheduled to start soon. Multiple benefits are claimed, in especial the reduction of traffic in the streets and the subsequent increased saftey. But also the expansion of the reach of local business serving food and beverages (Bass, 2019).

Citizens and retailers in the neighborhood have contradictory viewpoints. Both families and business involved in the tests are thrilled about their potential. Whereas other neighbours are actively trying to avoid this operation to be brought to permanent practice. Detractors' concerns are mainly the noise and the violation of the private sphere. Wing (and other companies) are working to reduce the noise level of their drons. Regarding the recording of images, most of the flights are mainly guided with GPS waypoints. Low-image recording resolution is only for a backup purposes.

Flytrex in partnership with AHA, one of Iceland's largest e-commerce, is testing in Reykjavik, Island, new and efficient ways to deliver goods to customers. Due to the geopgraphic barrier of a wide river, drone deliveries between the river-separated parts of the city can represent a dramatic improve for deliveries. Deliveries are performed in the customers' backyard, with the drone hovering 15 meters above the ground and releasing a wire with the package attached to

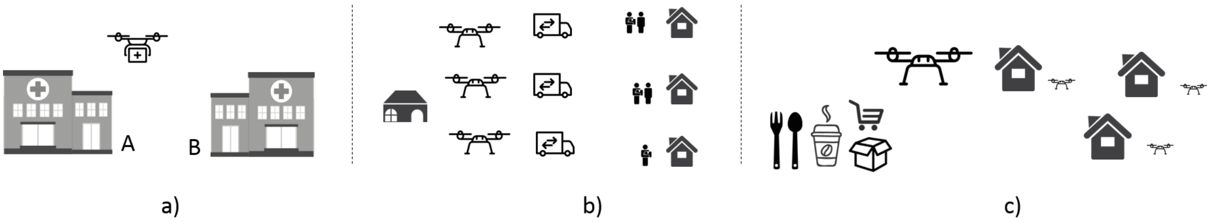

Figure 2: Tests performed with drones in urban environments. a) Within two hospitals. b) Drones from retailers with drones and vans c) Drone service for food and coffee direct to homes with backyard/landing space

it, slowly lowering it down until soft landing. The regulations allow Flytrex to fly 13 different routes arround Reykjavik, and the drones can make detours of up to 700m in order to reach customers. This provides effective coverage of around half the city (Nichols, 2018). Given the physical barriers existing in the area, drones can significantly reduce the distance of the trip, and subsequently the delivery time. For example, reducing a 7km and 20min drive, to a flight of around 7min. Figure 2c presents a schematic representation this use of drones for urban deliveries.

2.4 Strenghts and Weaknesses

After reviewing the above, and reading many more experiences of the use of drones in urban logistics, this section synthetizes the strenghts and weaknesses in the operation of drones as logistic solutions in urban environtments.

One of the essential strengths of drones in the urban logistic market is their capability to fly over traffic, giving them the competitive advantatge of providing a very fast service between locations. This is especially true if the alternative needs to drive through congested points of the urban area. For that reason, drones are identified as a very competitive alternative in urgent/emergency services, short time service (few hours) or at most same-day delivery. Services like next-day delivery are already performed very efficiently in urban areas though classical network deliveries.

Another claimed strength of drones is their environmental impact when transporting a small packages. A drone can weight up to around 15kg, containing a package up to 2kg and uses electric energy. Evidently, this advantatge needs to be compared to the alternative transport. But their advantatge is particularly attractive in urgent deliveries, when a courier might need to perform an addicional exclusive trip to fulfill the request.

Finally, in an emergency situation drones have the ability to access urban areas that might be blocked to all other modes of transportation. Offering a unique opportunity to provide urgent medical or any kind of light material to the blocked area.

Multiple drone features can be identified as weaknesses, some of them are currently hindering them to expand faster. However, several of them have already been solved, they might not represent real weaknesses in some contexts or solutions are already being discussed.

Although some UAVs can carry big packages, the UAVs suited for urban areas have a small shipping capacity, maximum around up to 2.5kg. Moreover, flight range is limitied (approx. 15km with load). Nonetheless, that still leaves them with potential marked. In particular, Amazon claims that in the case of e-commerce, 86% of the packages weighted less than 5 pounds (Rose, 2013). In terms of distance, Walmart claims that 70% of the customers were located within 5 miles from a center (Layne, 2015).

In order to secure all operations, guaranteeing safety to all involved subjects the country organization responsible for flight operations imposes strict flight safety regulations, especially in the operation beyond visual line of sight (BVLOS). Moreover, currently special permits might still be needed to have authorization to fly at certain pre-defined routes in many countries. However, parallel advances are being made to discusse the air highways (NASA, 2019) or the U-space (FOCA, 2019). Air highways would create a similar network as the street network to organize air traffic. Another approach is the U-space, where authorizations to flight requests are planned to be responded immediately.

Different UAVs offer alternative launching and landing alternatives without the need of supervision, using launching/landing pads, or hovering and releasing the package with a wire from a safe altitude. In urban environments, the final delivery of packages to recipients can become a challenge due to the urban landscape. Current tests use either deliveries to big buildings (e.g. hospitals), where landing could be performed without problems, landing in the rooftop of vans with incorporated landing pads and safely operating 2m over the floor, or hovering in the backyards or open spaces in suburban and less dense areas.

The UAVs used in the previous test mainly use GPS guided trajectories to perform their deliveries. Although they need to have alternatives in case no GPS is available, e.g. safe emergency landing. Some of the UAVs perform low-resolution image recording that might be used as a backup, ensuring to fulfill data protection policies. Moreover, to guarantee safe flighs UAVs should incorporate air communication systems, which can raise the price of commercial UAVs.

Lastly, but still somehow important is the noise. UAVs noise emission might be not accepted by residents. UAVs noise is recognized as new noise in the urban context, possibly raising higher rejection. Moreover, different sensitivities can arise depending on the neighborhood or flight

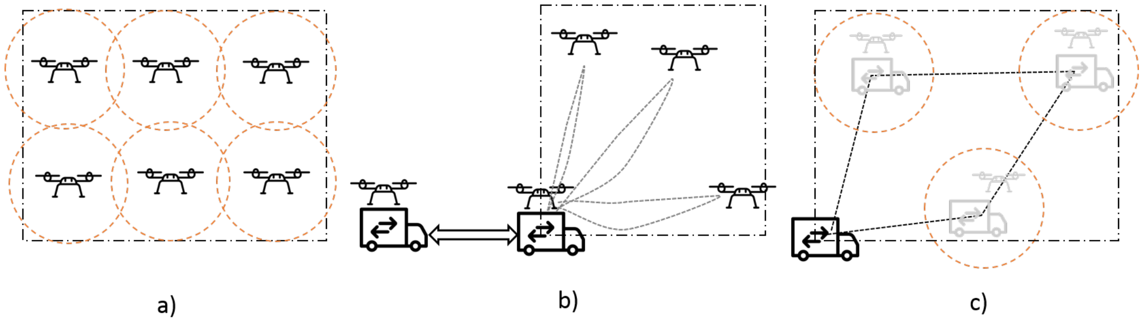

Figure 3: Problems studied in the operation research literature of the delivery with drones

puproses (e.g. rescue helicopter vs leisure flights). It still remains a doubt until what extend the noise might be accepted by residents. In the future, in order to regulate the noise levels in the different urban regions, UAVs might need to adapt their flights to respect noise boundaries limitations.

3 State of research

In this section, we will summarize the most studied optimization problems involving drones that can be used for urban deliveries. With a significantly broader aim, Otto *et al.* (2018) reviews the literature providing a good overview of both the most promising aerial drone applications and a literature survey on optimization approaches to civil applications of UAVs.

In this paper, the works will be classified in three groups and discussed in the following sections. The first group contains the coordinated use of trucks and UAVs. That is when together trucks and drones perform delivery services in a coordinated way. The second group reviews the works where drones are assisted by other vehicles to perform their services. In this case, drones are the only vehicles that bring packages to final deliveries, and the other vehicles are used as a launching platform, or to help the drones reach the desired targets. The third group focuses on the works where drones work alone or with the only support of fixed infrastructure, like distribution centers or depots. Figure 3 presents a schematic description of the three main groups of studied problems.

After the review of the existing works, an additional section discusses the estimated benefits of the use of drones. Several works focus only on the minimization of completion service time, while multiple other factors like cost, energy consumption or emissions can be even more important in some applications.

3.1 Coordinated use of trucks and UAVs

Murray and Chu (2015) were the first to study the operational problem of parcel delivery with a drone-van tandem. Murray and Chu (2015) proposed two different operational problems that could appear in drone-assisted parcel delivery. The most known has been the flying sidekick traveling salesmen problem (FSTSP), where the classical traveling salesman problem (TSP) is modified to incorporate the drone-assisted deliveries. In the FSTSP, drones can perform missions to visit feasible UAVs customers. Drones might flight from/to the depot or the van, and they can only visit a single customer at each mission. Several reasonable assumptions further restrict the operation of drones. Additionally, another problem is presented, the parallel drone scheduling traveling salesman problem (PDSTSP), where a significant portion of the customers are located within UAV's flight range from de distribution center. Where both the truck and a fleet of drones operate from the distribution center.

The seminal work of Murray and Chu (2015) has given place to multiple modifications of the FSTSP. As Murray and Chu (2015) consider the problem with a single pair truck-drone, extensions have considered the incorporation of multiple drones (Ferrandez and Sturges, 2016, Murray and Raj, 2019, Kitjacharoenchai *et al.,* 2019) and of multiple trucks and drones, the vehicle routing problem with Drones (VRP-D) (Wang *et al.,* 2017, Poikonen *et al.,* 2017). Moreover, multiple operational considerations have been incorporated to replicate the future realistic operation like the battery consumption depending on package weight or the drone flight detouring to avoid no-flying areas (Jeong *et al.,* 2019). Different assumptions on launching/-landing points, number of deliveries per flight, battery recharge operations or customer requests appear dynamically. At the same time, several efforts have been devoted to design solution algorithms to obtain better solutions of the above described problems (Agatz *et al.,* 2018, Ha *et al.,* 2018, de Freitas and Penna, 2018), which are demonstrated to be NP-hard (Murray and Chu, 2015).

Continuous models have also been explored to strategically design the system optimization of vans and drones (Campbell *et al.,* 2017, Li *et al.,* 2018). Campbell *et al.* (2017) proposes a strategic design for home deliveries with trucks and drones, where drones are used to complement the tradicional delivery trucks. The work is based on the design of tours along swaths of optimal width (Daganzo, 1984). The model allows to find the optimal parameters to design the best combined delivery system, such as the optimal number of truck and drone deliveries per route, the optimal number of drones per truck. The combined delivery system has the most potential in suburban areas, and the key parameters are the relative operating costs per mile for trucks and drones, the relative stop costs for trucks and drones, and the spatial density of customers. Li *et al.* (2018) designs joint delivery systems organized in a three-tier system, with one distribution center and multiple depots, as bases for trucks and drones. The model divides the region into hexagons containin a central depot each. At each region, the truck delivers packages from the inner circle, and leave the outer packages to the drone. The results shows that the combined delivery system is advantatgeous for low customer density, while at higher densities truck-only systems outperform.

3.2 UAVs assisted by other vehicles

Most of the published works study the problems related to coordinated deliveries with drons and trucks. However, in some other works, drones are the single vehicles reaching the recipients, and other vehicles, such as trucks, are used to bring the drones closer to the recipients, or as recharge stations. The multi-visit drone routing problem proposed in Poikonen (2018) considers a tandem between a truck and a drone. The drone can perform multiple packages deliveries per mission and uses the truck as a service station, where the truck can be launched or land and swap/recharge batteries. Dukkanci *et al.* (2019) minimizes a combination of truck delivery cost and drone energy consumption, where trucks are only used as lauching/landing pads for the drones. The model proposed allows the drone to carry multiple packages and allows to consider drone energy drain functions.

Within the context of health applications, the problem of the transport of emergency medical supply is studied by Scott and Scott (2017) . The drones need to work in combinations with land-based transportation located on warehouses to provide minimal service time. The problem lies on how to position the warehouse and the drone nests to serve the last-mile delivery to the area of need.

3.3 UAVs fleet from fixed launching stations

Chauhan *et al.* (2019) studies the maximum coverage capacitated facility location problem with range constrainted drones. Given a set of demand and potential facility locations, the objective is to find the number of capacitated facilities and the assignment of drones to facilities to optimally serve the demand. The problem accounts for battery limitations, and contains a case study in a Portland Metropolitan Area, US. With a different approach Hong *et al.* (2018) proposes a network of recharging stations to allow the extension of coverage to a wider area.

Cheng *et al.* (2018), Dorling *et al.* (2017) deal with the multi trip drone routing problem. Due to multiple operational characteristics, such as recharge planning and energy consumption, multi-trip operation planning is a challenging problem. Moreover, among other features the problems considered include time windows (Cheng *et al.,* 2018) and cuts to avoid linear simplifications for energy calculation (Dorling *et al.,* 2017). Oh *et al.* (2017) studies the problem task allocation for multiple UAVs in cooperative parcel delivery to carry packages with weight is higher than the allowed for a single UAV.

3.4 Benefits estimations

Most of the mentioned works use the minimization of service time as the objective function. However, this objective is usually questioned, as the underlying optimization criteria of logistic deliverys needs to consider other factors, such as operation cost or emissions, or include costs related to time factors.

Goodchild and Toy (2018) analyze from the CO_2 emmisions perspective. Detecting that drones can be advantatgeous in zones that are either closer to the depot or have a small number of recipients, or both. Figliozzi (2017) includes in the study a lifecycle modelling and assessment of UAVs, comparing to ground vehicles (electric vehicles or trycicles) including vehicle phase emissions. The comprehensive comparison presents in detail when UAVs might be more CO_2 efficient compared to multiple modes. The advantatgeous cases are significantly reduced, specially with electric vehicles and ground service consolidating multiple packages.

Unfortunately, even the delivery drone market has significatively advanced as it has been previously described, an accurate comprehensive cost analysis is not yet feasible. Multiple factors can have a decisive importance when determine the cost operation of UAVs (UAV technology, maintenance, insurance, manpower or operational costs), and which ones might be needed in each specific problem or region is difficult to foresee.

Cost estimations so far result in very optimistic values (D'Andrea, 2014, Sudbury and Hutchinson, 2016). Nontheless multiple uncertainties of the still unsolved challenges might limit the posititive numbers. Like the number of controllers per drone, or the regulation of the airspace (Wang, 2016). However, when the use of drones might allow to rethink and change further the supply chain or the needs of infrastructure, they can bring significant benefits. In particular, Wang (2016) concludes that "UAVs are suited for cargo that is small, light, valuable, and time-sensitive, where cost is much less of a factor."

4 Discussion

Although both research and practice state of the art have recently made huge advances, there seam to be some mismatches. Only in very special situations will drones be able replace tradicional urban delivery methods, but they emerge as another option to complement exisiting delivery networks.

The results from the tests indicate that their strongest asset is their very competitive delivery time in a point-to-point service, especially when the ground deliveries are affected by congestion. In controversy, the most studied problem in research is the combined delivery of drones and trucks, where drones are mainly used to provide a higher delivery capacity. Unfortunately, this service does not look implementable in the near future in urban areas. Drones accessing without restriction final recipients is still unresolved at least in dense urban areas. On the other hand, the use of drones to accelerate the supply chain from the warehouses to vans has not been deeply discussed in the research context. Moreover, the design of a future drone network has only been studied from either a emergency coverage approach or in order to fulfill operational constraints (e.g. batteries). However, the authors were not able to find any work focused on an urban network design that exploits the competitive drone fast service.

Acknowledgement

We wish to acknowledge the support by Christoph Derrer from Swiss Post.

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