ASSESSING A DRONE BASED LAST MILE LOGISTICS SOLUTION

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ABSTRACT

In this communication a general hybrid LMD solution is considered where two types of last mile delivery vehicles are considered to operate in a coordinated way: ground vehicles and UAVs. These types of vehicles are characterized by their respective payload volume and weight capacity, by their nominal speed and by their operating costs (travel cost and energy consumption per unit of distance and load) as well by their mean speeds, loading and unloading times. In this solution, ground logistics vehicles attend off-line the planned demand while UAVs attends on-line unplanned demand. Simplified performance models are proposed to assess the proposed solution in term of cost and time response.

Keywords: last mile logistics (LMD), unmanned aerial vehicles (UAV), sustainability, fleet sizing, BHH theorem, stochastic processes.

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1. INTRODUCTION

Global trend towards increased urbanization and the rise of e-commerce have changed the patterns of the last mile delivery (LMD) in urban areas: according to the United Nations (United Nations, 2018), 60% of people are expected to live in cities by 2030, while the volume of parcels delivered worldwide should reach 200 billion by 2025 (Pitneys Bowe, 2022). Around 86% of the parcels delivered by one of the main actors in urban logistics, Amazon, are lighter than 2.27 kg. Also, the major industrialized countries have engaged in a long-term decarbonization policy while urban logistics are an important contributor to air pollution. Thus, a new organization of urban logistics operations based on less polluting vehicles seems desirable. UAVs appear to be strong candidates to provide, at least in part, an answer to this need.

In this communication a general hybrid LMD solution is considered where two types of last mile delivery vehicles are considered to operate in a coordinated way: ground vehicles and UAVs. These types of vehicles are characterized by their respective payload volume and weight capacity, by their nominal speed and by their operating costs (travel cost and energy consumption per unit of distance and load) as well by their mean speeds, loading and unloading times. Compared to UAVs, ground logistics vehicles have two important advantages: they can transport larger or heavier loads and the scale effect makes it possible to reduce the unit cost of transport. But they contribute in an important way to urban traffic congestion and pollution, they lack flexibility and the urgent transport of individual requests by their means is extremely expensive. Then it appears that ground last mile delivery will remain of interest when it is possible to group together requests known in advance so as to promote the effect of scale, to optimize delivery routes so as to make better use of the fleet and ensure good quality of service.

2. LAST MILE DELIVERY IN URBAN AREAS

A basic Last mile delivery, also known as last mile logistics, is the transportation of goods from distribution hubs to the final delivery destination, in general the address of the customer. Until today this activity has been ground based except some minor exceptions in remote places. The goals of last mile delivery logistics are to deliver at lower cost the packages as quickly and accurately as possible. Last mile delivery is relevant for businesses that deliver products directly to their consumers. For example: direct-to-consumer retail companies, food delivery companies, third-party logistics companies, couriers, supermarkets, pharmacies, restaurants and department stores offering delivery, florists, e-commerce. In the last years e-commerce has boosted B2B (Business-to-Business) and B2C (Business-to-Consumer) last mile deliveries. Ground last mile delivery is the most expensive part of the distribution chain. It represents about 50% of shipment costs. This delivery cost increases the final cost for consumers damaging the attractiveness of this service (demand) and limits the profit margin of sellers. Many factors contribute to this increased cost:

- Lower speeds are used during the last mile delivery operation either because it is in urban areas or because local roads may be used to reach the customers.

- The last mile delivery presents large idling times related to traffic conditions (traffic lights, traffic congestion) and to the final dropping-off of packages.

- Complex routes with a large number of delivery stops may lead to extra miles since it is not easy to deliver thousands of packages to their final destination every day in an efficient way.

- Failed deliveries to final customers are frequent.

- The difficulty to select optimal routes and assign efficiently the fleet of vehicles when demands for delivery happens in real-time and is scattered randomly over the delivery space.

In the last decades last mile delivery was a booming market, but during the current pandemic it has grown even more accelerated. Important perspectives for the development of urban logistics based on the operation of UAVs are consolidating according to recent publications (Bhawesh, Rohit Gupta & Bani-Hani, 2020), (Eun, Song, Lee & Lim, 2019), (Goodchild & Toy, 2018), since they are able to profit from the until now unused urban airspace and alleviate ground traffic by diminishing the needs for ground-based logistic transportation which is one of the main contributors to ground urban traffic congestion and pollution. Previously, many studies have been devoted to the design of efficient UAVs based urban logistics systems, see for example (Park, Kim & Suh, 2018) and (Koiwanit, 2018), where in general, traffic volumes and capacities are not taken as issues. However, other studies (Mora-Camino, Lamiscarre & Mykoniatis, 2021) expect in few decades the occurrence of high traffic densities of drones operating in the common urban airspace, making imperative and urgent its effective design and organization.

When considering the demand for products which are stored in a logistic center, it is assumed that this demand is spread stochastically over the considered urban space and during different periods of the day. Part of this demand is known beforehand due to its periodicity or its prior request, it is the *planned demand*. Another part of the demand appears online and has a stochastic nature, it is the *unplanned demand*. Planned and unplanned demands have common parameters: location for delivery, volume and weight of the package to be delivered, but the performance indexes are different. In the case of planned demand, it is supposed that delivery must be realized within a wide given time window by minimizing delivery costs, while in the case of unplanned demand, delivery must be performed as soon as possible after the issuance of the delivery request.

Considering planned demand, an extensive literature exists for solving vehicle routing problems (VRP) with the objective of minimizing logistics costs through the planning of delivery routes. In (Braekers, Ramaekers, & Van Nieuwenhuyse, 2016) a recent survey of the different variants for the VRP and the corresponding algorithms is presented. However, since here the focus is on the main variables which will influence the performance of a delivery system, no particular routing algorithm is considered and an empirical formula is used to approximate the mean distance to be travelled to serve N points uniformly distributed in a given area from an outside depot. Then given the shares of ground based and of air based LMD operations, it is possible to estimate roughly global delivery costs for the logistics company but also to estimate the environmental impact resulting from the energy used for delivery and from emissions. If different logistics companies operate the same area, the above results can be repeated and added when their demands are independent.

With respect to unplanned demand, it is supposed that each request is attended using an UAV operating in a round trip basis from a depot. It is also supposed that the travelled distances are compatible with the autonomy of the drones and that the operations of recharging and changing the batteries are carried out at the depot. Available statistics about unplanned demand can be used to size the warehouse or the local production unit of the depot which can be supplied periodically by large capacity ground vehicles. Here to treat the problems of sizing a fleet of UAVs operating from a given location and the corresponding energy consumption a stochastic model is adopted to represent demand and delivery service so that analytical results can be obtained with respect to the performance of the UAV based delivery system (service times, waiting times, energy) for a given size of the fleet of UAVs.

Finally, it is possible to compare the considered hybrid solution for LMD with a classical ground-based solution in terms of quality of service, environmental impact and energy.

3. STRATEGY FOR LMD WITH UAVS

For the urban UAVs traffic manager, ground and air, it is of importance to predict what can be the demand for using the available space, so that it is of interest to foresee the way the main users of the 3D urban space will generate traffic demand. This will allow the local authorities to design a traffic plan to structure the 3D urban space which will allow to balance potential traffic demand with societal acceptance and urban quality of life.

For instance, the last mile delivery traffic demand by a logistics company will result from its solution to different inter-related problems:

- location and dimensioning of the logistics centers,
- size and composition of the delivery fleet,
- policy for handling delivery requests,
- fleet management, scheduling and routing,

while the underlying generating process will be the final delivery demand characterized by its spatial and temporal distributions and the nature and physical parameters of the delivered packages. Depending on the considered decision problem, different representations of the logistics urban space are more suitable to contribute to its solution. The logistics urban space can be considered composed of the space in which is performed transport, the urban transport space, and the space where demand is located, the urban demand space. Of course, both spaces have the same geographical references and are closely connected. Discrete or continuous representations can be adopted to represent the urban transport space and the urban demand space. For example, 2D graph representation can be based on the grids of streets and lanes in the city through its ground circulation plan to display the transit opportunities for ground delivery vehicles, while a 3D graph representation can be adopted for a structured airspace. The period of operations can be taken either as a continuum or as a succession of discrete time periods associated with different demand and traffic patterns.

Based on discrete representations of space and time, problems such as scheduling and routing of deliveries either by ground or air, where operations costs have to be minimized while satisfying a known demand, can be tackled using an already existing vast literature in the field of Operations Research treating of the variants of the vehicle routing problem (Gan X., Y. Wang , S. Li and B. Niu, 2012). However, if scores of UAVs are considered in the delivery fleet, numerical complexity issues will arise unless the logistics urban space is divided someway in subareas. Observe that in general these approaches, complexified by time windows delivery and capacity constraints consider only by the side environmental issues.

Here it is considered that the logistics center location is already in an acceptable location and that additional areas for UAVs ground operations are available close to the warehouse at the logistic center. The location of logistic centers is in general chosen to be at the same time close to the delivery area and easily accessible by wholesale supply chains. All this means that the logistics centers associated with the last mile delivery are very often located on the outskirts of urban areas.

Two types of LMD vehicles are considered: ground vehicles and UAVs. They are characterized by their respective payload volume and weight capacity, by their nominal speed and by their operating costs (travel cost per unit of distance and remit cost) as well by their loading and unloading times.

When considering the demand for products which are stored in the logistic center, it is assumed that this demand is spread stochastically over the considered urban space and during different periods of the day. Part of this demand is known beforehand due to its periodicity or its prior request. It is referred to here as *planned demand*. Another part of the demand appears online and has a stochastic nature, it is called here, *unplanned demand*. Planned and unplanned demands have common parameters: location for delivery, volume and weight of the package to be delivered, but the performance indexes are different. In the case of planned demand, it is supposed that delivery must be realized within a wide given time window by minimizing delivery costs, while in the case of unplanned demand, delivery must be performed as soon as possible after the issuance of the delivery request.

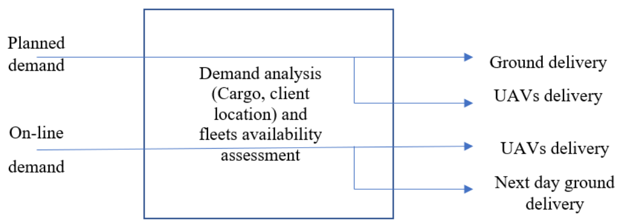

Figure 1 Principle of a cargo dispatcher system

It is assumed that parcels whose volume is greater than V_{max} or whose weight is greater than M_{max} will be delivered on the next day by ground transportation as a planned demand, while smaller or lighter parcels can be delivered either by ground transportation or by UAVs. Observe also that smaller or lighter parcels which are part of the planned demand but are difficult to be reached by ground vehicles or whose introduction into a planned delivery route turns out to be too costly, may be added online to the unplanned request log at a time where UAVs should be available. Then, to improve the effectiveness of the LMD system, it appears of interest to have an intelligent dispatcher system that can classify online any new request in terms of planned or unplanned. Figure 1 outline this process.

4. GROUND LMD FOR PLANNED DEMAND

Extensive literature exists for solving vehicle routing problems (VRP) with the objective of minimizing logistics costs through the planning of delivery routes. For example, in (a recent survey of the different variants for the VRP and the corresponding algorithms is presented. However, since here the focus is on the main variables which will influence the performance of a delivery system, no particular algorithm is considered. With respect to planned demand, an empirical formula (Rifki, Garaix & Solnon, 2021) based on the BHH theorem (Beardwood, Halton and Hammersley, 1959) , can be used to approximate the mean distance to be travelled to serve N points uniformly distributed in a square area A (in square meters) from and outside depot positioned at a distance l of the center of the area (see Figure 2). This formula assumes that the delivery tours minimize travel distances:

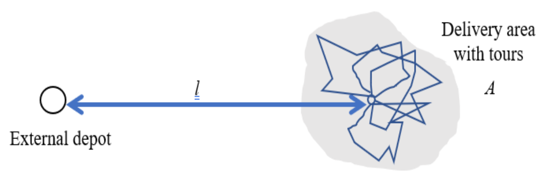

Figure 2 Organization of ground delivery for planned demand

$$L_N = 2\,l \cdot N/C + \rho \cdot N \cdot \sqrt{A}\left(\left(\frac{1}{C}\right) + \left(\frac{1}{\sqrt{N}}\right)\right) \quad (1)$$

where ρ is a shape parameter of the distribution area and C is the capacity of the ground vehicles (equal to the maximum number of standard parcels the vehicle is able to deliver in a single tour). This formula supposes that $N \gg C$. This formula has been used to optimize the shape of delivery sub-areas in the urban space. The first distance term is relative to the connection between the depot and the urban area, the second one $(\rho \cdot N \cdot \sqrt{A}/C)$ is related with the mean distance to reach a delivery point during a tour and the third term $(\rho \cdot \sqrt{AN})$ is related with the mean distance detour needed to reach each delivery point.

Let V_O and V_I be respectively the medium speed adopted to reach from the depot the delivery area and the medium speed used during delivery. Then, the mean duration to serve N delivery points is given by:

$$d_N = 2l \cdot \frac{N}{C \cdot V_O} + \rho \cdot N \cdot \sqrt{A}\left(\left(\frac{1}{C}\right) + \left(\frac{1}{\sqrt{N}}\right)\right)/V_I \quad (2)$$

which is an increasing function of N.

Let T be the daily operations time, then the mean number of delivery points which can be treated by a vehicle of capacity C is such that:

$$N_T = N \cdot T/d_N \quad (3)$$

or

$$N_T = \alpha(A,l,C,V_O,V_I) + \beta(A,l,C,V_O,V_I) \cdot T - \alpha(A,l,C,V_O,V_I)\sqrt{(1+\gamma \cdot T)} \quad (4.0)$$

with

$$\alpha(A,l,C,V_O,V_I) = C^2 \frac{\rho^2 A}{2 \cdot \left(\rho\sqrt{A} + 2l/(\frac{V_O}{V_I})\right)^2} \quad (4.1)$$

$$\beta(A,l,C,V_O,V_I) = \frac{C \cdot V_I}{\left(\rho\sqrt{A} + 2l/(\frac{V_O}{V_I})\right)} \quad (4.2)$$

$$\gamma(A,l,C,V_O,V_I) = \frac{V_I}{C \cdot \rho^2 \cdot A}\left(\rho\sqrt{A} + 2l/(\frac{V_O}{V_I})\right) \quad (4.3)$$

Then the size of the fleet necessary to perform the ground delivery is given by:

$$F_G(T) = D_T/N_T \quad (5)$$

where D_T is the total considered demand during the T period. Then the number of delivery operations is approximated by:

$$D_T/C. \quad (6)$$

The estimated total distance traveled at speed V_O is given by:

$$F_G(T) \cdot 2\,l \cdot (N/C) \quad (7)$$

while the estimated total distance traveled at speed V_I is given by:

$$F_G(T) \cdot \rho \cdot N \cdot \sqrt{A}\left(\left(\frac{1}{C}\right) + \left(\frac{1}{\sqrt{N}}\right)\right) \quad (8)$$

Assuming that the ground vehicles leave the depot at full load C , the total distance travelled in this condition is $F_G(T) \cdot l \cdot (N/C)$, and the same distance will be travelled when there is no load by the ground vehicles. Also it can be

considered that along a delivery tour, the vehicle is unloaded progressively.
All these elements allow not only to estimate roughly global delivery costs for the logistics company but also to estimate the environmental impact resulting from the energy used for delivery and from emissions, if any (electrical vehicles). If different logistics company operate the same area, the above results can be repeated and added when their demands are independent.

5. UAV BASED LMD FOR UNPLANNED DEMAND

With respect to unplanned demand, it is supposed that each request is attended to using an UAV operating in a round trip basis from a depot. It is also supposed that the travelled distances are compatible with the autonomy of the drones and that the operations of recharging and changing the batteries are carried out at the depot.
Available statistics about unplanned demand should be used to size the warehouse or the local production unit of the depot which can be supplied periodically by large capacity ground vehicles. Then, to diminish the time response and delivery costs for unplanned demand, this depot is assumed to be placed inside the urban area to be covered by the delivery service (see Figure 3).

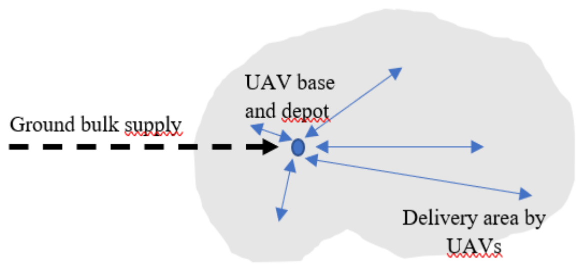

Figure . UAVs delivery for unplanned demand

The problem of the location of the UAV depot is not developed here but it must take in to account the following elements: the geographic distribution of demand, the structure of the airway network which can be used by UAVs in the urban space, the range of the considered UAVs and the available sites.
Here to treat the problem of sizing a fleet of UAVs operating from a given location a stochastic model is adopted to represent demand and delivery service so that analytical results can be obtained with respect to the performance of the UAV based delivery system for a given size of the fleet of UAVs.
It is assumed that requests for delivery are generated by a stochastic process and that once a request appears, a UAV is sent as soon as possible to the request location. It is also supposed that demand is distributed in the urban area according to another stochastic process. Here, it is considered the case in which requests for delivery follow a Poisson process of rate λ while the time to reach the request location follows an exponential distribution of parameter μ. The Poisson assumption for requests timing is a classical one and can be adopted for different periods of time where the flow of requests remains almost constant. Other stochastic models could have been adopted, however, for the sake of simplicity, the above hypothesis have been adopted, leading to analytic developments even if rather complex formulas have finally to be considered. With respect to the demand exponential distribution assumption, this can correspond to the case in which the depot is located centrally in the considered urban area. Considering a fleet of f UAVs used to treat on-line the requests, the adopted assumptions configurate a queuing system of the class $M/M/f$ with some peculiarities.
In this case, once a request has been treated, i.e. a parcel has been delivered by a UAV to a customer, this UAV will have to return to the depot to be available for the treatment of a new request. Considering that the customer starts to be served when the UAVs leaves the depot to attend him, μ can be defined as:

$$\frac{1}{\mu} = 2 \cdot \delta / V_I \qquad (9)$$

where V_I is the means speed adopted by the UAVs during their trip and where δ is the mean distance to the depot. Here the loading and unloading times of the control on the UAV are assumed to be very small compared to the duration of the journey and are not taken in to account.
If $f > \lambda/\mu$ it can be considered that the delivery process reaches a probabilistic stationary state, the waiting time to be served (in the queue) is given by [15]:

$$W_q = \pi_0 \frac{\rho\,(f \cdot \rho)^f}{\lambda \cdot (1-\rho)^2 \cdot f!} \qquad (10)$$

where ρ is the utilization level and π_0 is the probability that no client is waiting for the assignment of an UAV to his request. They are given by:

$$\rho = \frac{\lambda}{f \cdot \mu} \quad (11)$$

and

$$\pi_0 = 1/\left(\sum_{k=0}^{f-1} \frac{(\frac{\lambda}{\mu})^k}{k!} + \frac{(\frac{\lambda}{\mu})^f}{f!} \frac{1}{1-(\lambda/f\mu)}\right) \quad (12)$$

The average response time for a customer to receive his parcel is given by:

$$T_U = \frac{1}{2\mu} + \pi_0 \frac{\rho\,(f \cdot \rho)^f}{\lambda \cdot (1-\rho)^2 \cdot f!}. \quad (13)$$

The probability for a client to wait more than *t* to get a parcel is given by:

$$P(W > t) = e^{-\mu t}\left(1 + \frac{\pi_0 \cdot (\frac{\lambda}{\mu})^f}{f!(1-\rho)} \cdot \frac{1-e^{-\mu t(f-1-\lambda/\mu}}{f-1-\lambda/\mu}\right) \quad (14)$$

These two last indexes can be used to choose the size of the fleet according to a level of service given by a value of T_U or by a value *p* such that:

$$P(W > t_{max}) < p\,, \qquad p \in]0, 1[\quad (15)$$

where t_{max} is a guaranteed delivery time.

It can be also show that T_U and $P(W > t_{max})$ are decreasing functions of *f* and V_I so that ways to reduce the average response time or the probability of a timeout, is either to increase the size of the UAV fleet or to increase the flying speed of the UAVs.

The mean total distance d_U travelled at speed V_I by the UAVs during a period Δt is given by the formula:

$$d_U = 2\delta\,\mu \cdot \left(\sum_{n=0}^{f-1} n \cdot P_n + f \sum_{n=f}^{+\infty} P_n\right) \cdot \Delta t \quad (16)$$

where P_n, the probability of having *n* requests is given by the classical formula of *M/M/f* :

$$P_n = \begin{cases} \pi_0 \cdot \left(\frac{\lambda}{\mu}\right)^n / n! & for\ 0 \le n < f \\ \pi_0 \cdot \left(\frac{\lambda}{\mu}\right)^n / (f! \cdot f^{n-f} & for\ n \ge f \end{cases} \quad (17)$$

Observe that when *f* is very large, d_U tends to $2\delta \cdot \lambda \cdot \Delta t$ which corresponds to the situation in which no request is left over on the considered time period.

6. CONCLUSION

This paper has focused on the development of a methodology to design last mile logistics based on a hybrid solution composed of ground vehicle, addressed to planned demand, and on UAVs processing unplanned demand. This approach allows to join the scale effects of ground vehicles performing multiple deliveries and the flexibility and responsiveness of UAVs devoted to delivery. The ground last mile delivery routing and scheduling activities have been considered globally using an empirical formula relating minimum cost route operation in a dense urban area with the mean length necessary to serve a customer, while the UAV LMD activity has been analyzed globally using a stochastic model. In both cases, the generated traffic has been estimated and performance indexes, related with the quality of service and the environmental impact, have been produced. At this stage, it appears of interest to guarantee the effectiveness of the proposed hybrid solution, to design an intelligent dispatcher system that can classify online any new request either planned or unplanned. Finally, it is expected that, as the performances of UAVs in terms of safety, range and payload improve, they will occupy a growing LMD market share.

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