On the optimal micro-hub locations in a multi-modal last-mile delivery system

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Short summary

Last-mile delivery is one of the most polluting parts of the supply chain. In this work, we propose a multi-modal logistics system for last-mile delivery that combines the use of trucks, metro and micro-mobility. The envisioned system uses the metro to distribute the parcels to micro-hubs across the network and uses micro-mobility for the final part of the parcel's itinerary. We focus on finding the optimal micro-hub locations in such a system. We use a continuum approximation of the operational decisions which includes routing of the micro-mobility vehicles. The whole problem is than modelled as a Mixed Integer Linear Programming model for the strategic and tactical decisions regarding the micro-hubs, which include location, capacity, and fleet-assignment decisions. We evaluate the results on a case study of the city of Madrid, which illustrates that a multi-modal last-mile delivery system can significantly improve a traditional last-mile delivery system both in terms of operational costs and pollution.
Keywords: Last-mile delivery, Location problems, Multi-modal transportation, Mixed integer linear programming, Continuum approximation

1 Introduction

Traditionally, last-mile delivery of parcels to customers is performed by delivery trucks. Generally, these trucks are heavily polluting (Lack et al., 2011; Zhang et al., 2017). This can be severely problematic in urban areas where, as a consequence, they are not allowed to enter zero or low-emission zones. A shift is observed to electric vehicles, but these are typically more expensive to operate because of higher purchase and maintenance costs and because the limiting battery capacity adds a restriction on the routing. On top of that, some cities are banning heavy delivery vehicles alltogether. For example, the city of Amsterdam has banned heavy vehicles from the urban city center (City of Amsterdam, 2021). Besides their effect on pollution, trucks contribute to traffic congestion in urban areas, particularly during peak hours and in areas with high commercial activity. Their frequent stops for deliveries and service-related activities can disrupt traffic flow, leading to delays, increased travel times, and increased frustration among commuters. Holguín-Veras et al. (2006) identify the impacts of time of day pricing on the behavior of freight carriers in a congested urban area, based on a research project in New York and New Jersey. Hammami (2020) study the impacts of freight delivery in urban areas and its impact on urban congestion through double parking versus dedicated delivery areas. To avoid these issues and adapt to stricter regulations, delivery companies are looking for sustainable alternatives to traditional last-mile delivery.

One of these more sustainable modes that can enter urban areas without suffering from restrictions on pollution, size or weight is micro-mobility. Last-mile delivery in urban areas can be performed by small vehicles such as (electric) bikes, scooters, or small walking carts. These vehicles are substantially less polluting, but also have lower capacities and can be slower than larger moterized vehicles. For this reason, a large fleet size is necessary and many tours need to be made with relatively few parcels on board.

To increase the efficiency of last-mile delivery systems through micro-mobility (also referred to as micro-delivery in the rest of this paper), a multi-modal logistics system can be utilized. In this case, parcels can be transported in large quantities by existing transport systems with high capacities to the edge of the urban area. The parcels are then stored at micro-hubs from where they are taken into the city by micro-mobility vehicles with lower capacities. Such a multi-modal logistics system benefits from the sustainability aspect of micro-delivery, while benefiting from the efficiency of larger trucks.

In this work, we focus on the optimal micro-hub locations in a multi-modal last-mile delivery system. The system we consider consists of three stages: truck, metro, and micro-mobility. We divide the urban area into zones around metro stops. The costs of opening facilities (i.e., operating micro-hubs) and assigning zones to the nearest open micro-hub are approximated through a classical Continuum Approximation approach. We formulate the problem as a Mixed Integer Linear Programming problem (MILP). The formulation contains similarities to a Facility Location Problem (FLP), extended with constraints on capacity and fleet assignment across the three stages.

The remainder of this paper is organized as follows. The problem is described in more detail in Section 2. Section 3 provides the mathematical formulation of the problem and the approximation method for the cost structure. Results based on a case study of the city of Madrid are provided in Section 4 and the paper is concluded in Section 5.

2 Problem Description

We consider a three stage delivery process for last-mile delivery that combines truck, metro, and active transport modes (such as bikes or walking). This three-stage process, which is graphically depicted in Figure 1, is envisioned to replace a direct delivery by trucks, to reduce the presence of delivery trucks in urban areas. In this new system, trucks are only involved in the transport from the consolidation center to the metro depot. These metro depots are mainly located outside the urban areas, in an attempt to limit the effect of trucks on congestion and pollution. From there, parcels are transported by metro to micro-hubs where they are stored before dedicated drivers deliver the parcels using active modes or transport. Typically, these are bikes or walking carts with a relatively small capacity of packages.

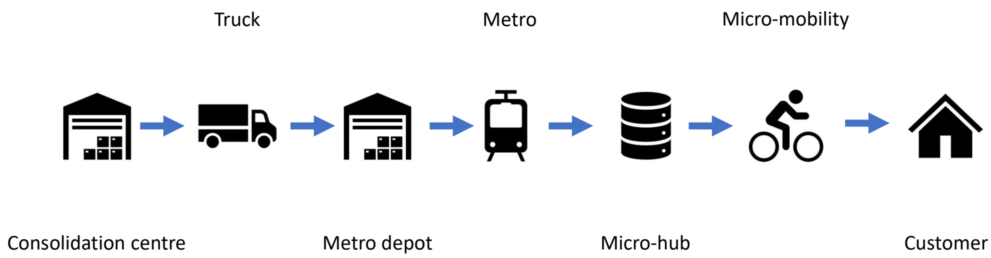

Figure 1: Schematic representation of last-mile delivery process

In this work, we wish to determine where micro-hubs should be opened. Micro-hubs are opened at metro stops, which limits the set of potential locations. Metro routes do not influence the costs, as we assume these are running anyway independent of the distribution of micro-hubs throughout the network. However, both metros and trucks have a maximum capacity. This means that the total number of parcels that can be transported to micro-hubs on the same metro can be limited by this capacity. In addition to this, the distribution of dedicated drivers across the micro-hubs may also form a constraint, as fleet size is usually limited. The cost components that are considered in this work are the costs of opening micro-hubs (i.e., operating costs and rental of the location) and the routing of trucks and micro-delivery couriers. To approximate the routing costs, the network is divided into a set of zones around metro stops. The routing costs depend on the zone itself, as well as the micro-hub it is assigned to and are approximated through a Continuum Approximation (CA) approach.

The zonal division of the network allows the costs to be approximated a-priori. In this way, the lower-level operational costs can be divided into intra-zonal and inter-zonal components. The intra-zonal component is exogenous and does not depend on the strategic micro-hub locations. Therefore, only the inter-zonal line-haul component is endogeneous and thus influences these locations. This component is therefore integrated into the mathematical formulation of the problem.

3 Methodology

Micro-hub location problem

We formulate the problem as a Mixed Integer Linear Programming (MILP) problem. The problem carries similarities to a Facility Location Problem (FLP), extended with capacity and fleet assignment constraints on the different decision-making levels. This problem is especially difficult due to the relation between the strategic micro-hub location decisions and the operational costs, as well as the direct connection between the three modes in the multi-modal system. We consider I the set of zones in the network, R the set of metro lines and W the set of warehouses. We construct subsets $K_r \subset I$ of zones where metro line $r \in R$ makes a stop. If stations are on multiple metro lines, they are part of multiple subsets K_r. The following decision variables are considered:

- y_i (binary) - equal to 1 if micro-hub in zone $i \in I$ is opened.
- x_{ij} (binary) - equal to 1 if zone $j \in I$ is served from a micro-hub in zone $i \in I$.
- z_{irw} (integer) - the number of parcels designated to micro-hub $i \in I$ that are originating from warehouse $w \in W$ and travelling there through line $r \in R$.
- o_{wr} (integer) - the number of trucks needed to serve line $r \in R$ from ware-house $w \in W$.
- s_i (integer) - the fleet size assigned to micro-hub $i \in I$.

The costs of opening a micro-hub in zone $i \in I$ are defined by f_i. These costs can be associated both to rental of space at the metro stops, or one-time investments to improve accessibility of the metro stations to faciliate smooth pickups of parcels. Especially for the latter case, the cost parameters have to be properly weighted with the operational costs in the second two terms. The costs of micro-delivery in zone $j \in I$ from a micro-hub in zone $i \in I$ are defined as c_{ij}. The costs associated to running trucks between warehouse $w \in W$ and the metro depot of line $r \in R$ is denoted as c_{wr}^{truck}. Let p be the maximum number of micro-hubs that can be opened. The capacity of the metro serving line $r \in R$ is denoted as Q_r and the capacity of a truck is denoted as Q^{truck}. Let d_i be the demand for parcels in region $i \in I$, out of which d_{iw} originates from warehouse $w \in W$, such that $\sum_{w \in W} d_{iw} = d_i$. Every courier can deliver q parcels and in total at most S employees can be distributed across the microhubs. Parameter M is an arbitrarily large number.

The problem is formulated such that the expected operational and tactical decisions, regarding assignment of parcels to metro lines and micro-hubs and the distribution of staff, and strategic decisions of where to open micro-hubs are incorporated into the same formulation. The three transportation stages denoted in Figure 1 are therefore connected through the decision variables x_{ij}, z_{irw}, and o_{wr}. The problem is then formulated as follows:

$$minimize \sum_{i \in I} f_i y_i + \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{w \in W} \sum_{r \in R} c_{wr}^{\text{truck}} o_{wr} \quad (1)$$

s.t.

$$\sum_{i \in I} y_i \leq p \quad (2)$$

$$\sum_{i \in I} x_{ij} = 1 \qquad \forall j \in I \quad (3)$$

$$x_{ij} \leq y_j \qquad \forall i, j \in I \quad (4)$$

$$\sum_{j \in I} d_{jw} x_{ij} = \sum_{r \in R} z_{irw} \qquad \forall i \in I, w \in W \quad (5)$$

$$\sum_{w \in W} \sum_{i \in K_r} z_{irw} \leq Q_r \qquad \forall r \in R \quad (6)$$

$$o_{wr} \geq \frac{\sum_{i \in I} z_{irw}}{Q^{\text{truck}}} \qquad \forall r \in R, w \in W \quad (7)$$

$$\sum_{j \in I} d_j x_{ij} \leq q s_i \qquad \forall i \in I \quad (8)$$

$$s_i \leq S y_i \qquad \forall i \in I \quad (9)$$

$$\sum_{i \in I} s_i \leq S \quad (10)$$

$$y_i \in \{0, 1\} \qquad \forall i \in I \quad (11)$$

$$x_{ij} \in \{0, 1\} \qquad \forall i, j \in I \quad (12)$$

$$z_{irw} \in \{0, 1, \ldots, Q_r\} \qquad \forall i \in K_r, r \in R, w \in W \quad (13)$$

$$z_{irw} = 0 \qquad \forall i \notin K_r, r \in R, w \in W \quad (14)$$

$$o_{rw} \in \{0, 1, \ldots, M\} \qquad \forall r \in R, w \in W \quad (15)$$

$$s_i \in \{0, \ldots, S\} \qquad \forall i \in I \quad (16)$$

The objective in (1) is to minimize the costs of opening microhubs, micro-delivery and truck routing. Constraint (2) ensures the maximum number of micro-hubs is not exceeded. Constraints (3) ensure that every zone is assigned to one micro-hub and Constraints (4) ensure that zones are only assigned to open micro-hubs. Constraints (5) ensure that the number of parcles that enter the micro-hub (right-hand side) is the same as the number of parcels that exit the micro-hub (left-hand side). Constraints (6) ensure that the capacity of the metro lines and trucks is satisfied. Constraints (7) regulate the number of trucks that are required between the warehouse and the metro depot. This constraint together with the introduction of decision variable o_{rw} is an implict linearization of the number of trucks on the right-hand side of Constraints (7), which would otherwise require a ceiling function to satisfy the integrality constraint. The connection of the origin (warehouse $w \in W$) and destination (zone $i \in I$) of parcels to metro lines and metro depots is made through decision variables z_{irw}. Constraints (13) and (14) ensure that a parcel can only be transported through a metro line if the destination zone is on that line. The connection to the warehouse is then made through Constraints (7). Constraints (8) ensure that the fleet assigned to a micro-hub (right-hand side) is sufficient to serve all the parcels assigned to that micro-hub (left-hand side). Constraints (9) ensure that staff members are only assigned to open hubs and Constraint (10) ensures that the total fleet size is not exceeded. We note that Constraints (9) are not strictly required to ensure feasibility. However, in this case the costs of staff members are not included in the cost function. Due to this, when the maximum number of staff members is not a binding constraint, we use Constraints (9) to ensure staff is only assigned to open micro-hubs.

Zonal division and cost approximation

The formulation of the problem is grounded in a zonal division of the network. Given that the last step of the delivery process is executed using micro-mobility, the proximity of the final destination of a parcel to the metro station is important. Therefore, we divide the network into zones depending on the closest metro station. That is, a point belongs to zone $i \in I$ if the metro station in zone i is closer than any other metro stations in zones $j \in I \setminus \{i\}$. To this end, we construct a Voronoi diagram on the city network around all metro stations. The network is then made up out of a set of Voronoi polygons around every metro station. Every polygon constitutes to a zone in the set I. To approximate the costs of delivery in every zone, the area of each zone is computed using Delauney's triangulation.

To approximate the costs of micro-delivery we use a classical CA approach (Daganzo, 1984). We separately determine the inter and intra-zonal costs. For this, we emphasize that this is done to make the approximation tractable. The intra-zonal costs are computed by solving a classical continuum approximation of the vehicle routing problem inside a zone. Inter-zonal costs consists of line hauls from a micro-hub to a zone. For a detailed explanation of the CA approach to approximate the costs, the reader is reffered to the full paper.

4 Results

Case study

We evaluate the results on a case study of the city of Madrid, Spain. The case study consists of two warehouses (W), five metro depots (M) and eight metro lines (R). All of these components are graphically in Figure 2. Warehouses are located relatively far from the citycenter of Madrid in the province of Toledo. The five metro depots are scattered throughout the city of Madrid, with most of them being on the outskirts of the city center. A region around every metro station is identified as a zone (I) using a Voronoi diagram. The demand for every zone is known and based on historical data from a local last-mile delivery company. We consider two types of trucks that differ in terms of costs and emissions. The remaining parameters are chosen as realistically as possible based on the input from a local micro-delivery company.

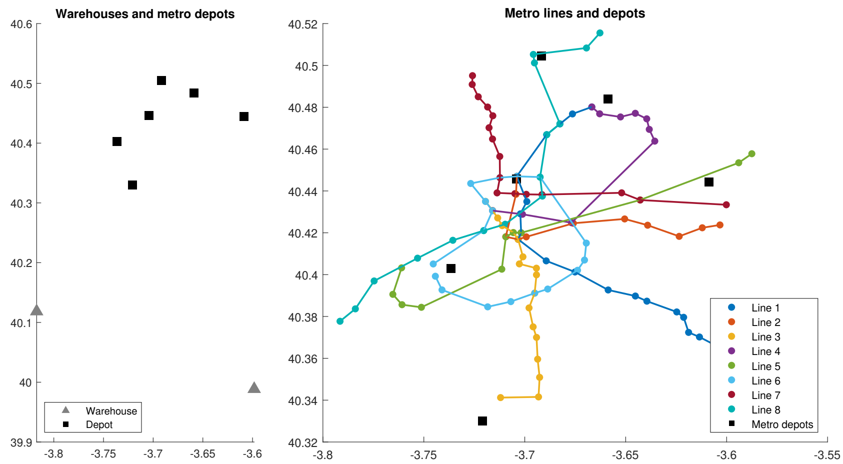

Figure 2: Graphical representation of warehouses, metro depots, and metro lines

Comparison to tradtional delivery

To evaluate the performance of the multi-modal last-mile delivery system, we compare it to a benchmark of a traditional truck routing problem modeled as a Capacitated Vehicle Routing Problem (CVRP). The CVRP instances are solved using the VRPy package in Python developed by Montagné & Torres Sanchez (2020). For the benchmark and the multi-modal system we compare different vehicle sizes. In addition to this, we compare two variants of micro-delivery (MD): by foot and by bike. The results are displayed in Table 1.

The results indicate that both for the multi-modal delivery and for the traditional benchmark, the use of small trucks has a cost advantage, whereas the use of large trucks has an advantage in terms of emissions. Clearly, as bikers are faster than walkers and are therefore able to deliver significantly more parcels within the same amount of time, the cost is substantially lower when using bikers. As the truck routes remain approximately the same, the difference between the cost of trucking and the emissions are almost negligible. We highlight that multi-modal delivery is not necessarily more cost efficient than traditional delivery. Only when the micro-delivery couriers are efficient enough, the multi-modal delivery method forms a competitive alternative. On the other hand, in terms of emissions the multi-modal delivery method always outperforms traditional delivery. This also indicates that in case a pollution costs is introduced, the multi-modal delivery would be more attractive.

Table 1: Comparison of multi-modal to traditional delivery

Truck	MD	Cost of trucking (€)	Cost of MD(€)	Total cost(€)	Total emissions (CO2 KG)
			Multi-modal		
small	foot	1789.84	6408.98	8198.82	382.26
small	bike	1788.46	2115.51	3903.97	381.96
large	foot	1826.72	6410.63	8237.35	304.45
large	bike	1826.72	2115.51	3942.23	304.45
			Traditional		
small		4803.87		4803.87	1025.97
large		5101.88		5101.88	850.31

Evaluation of different number of micro-hubs

In this section, we evaluate the effect of a different number of micro-hubs on the geographical location of these micro-hubs, the distribution of staff members over these micro-hubs and the total costs involved in the complete last-mile delivery process. The geographical locations of the opened micro-hubs are displayed in Figure 3. Here, opened micro-hubs are indicated by a red bubble, where the size of the bubble is determined by the number of staff members that are assigned to that bubble.

The results indicate that when only a small number of micro-hubs are opened, they are mostly opened in the city center. The reason for this is that demand for parcels here is the highest and thereby the outskirts can be reached from this central locations in separate tours. When more hubs are opened, these are scattered throughout the city, with them initially being mostly in the city center and later also towards the outskirts. With respect to the distribution of staff members, most staff members operate in the city center. Again, the reason for this is that demand is higher in the city center. We also see that the total number of staff members slightly increases when the number of micro-hubs increases, even though the total demand remains constant. The reason for this is that slight inefficiencies start to exist when demand is spread over multiple micro-hubs, which causes staff members to more frequently operate less-than-full loads. In this way, slightly more staff members are needed to serve all the demand.

Figure 4 provides three key features of the system for a varying number of micro-hubs. For this comparison, the smaller trucks have been used and micro-delivery couriers are assumed to travel by foot. The first frame displays the total cost. It shows that the first micro-hubs are the most influential in reducing the total cost. For later micro-hubs, we observe decreasing marginal benefits. The number of staff members remains relatively constant, although a slight non-monotonic increase is observed when staff members have to be distributed over various micro-hubs. The occupancy of staff members shows a similar pattern as the total cost. It is important to note that for a relatively low number of micro-hubs, the occupancy of staff members is too high. In case a staff member has to bike for more than 100 KM per day, their schedule can typically be considered as not workable. This means that at least four micro-hubs are necessary to get a good average walking distance. Here, we emphasize that some tours may still be significantly longer and to reach a feasible schedule for all staff members it may be required to reposition staff members from one micro-hub to another throughout the day. Given their connection to metro stations, this is generally do-able.

5 Conclusions

In this paper we studied a multi-modal alternative for last-mile delivery in urban areas where trucks, metros and micro-delivery are combined. We focused on the strategic problem of determining the optimal location of micro-hubs, as well as on the tactical problem of fleet and staff allocation. Whether the designed multi-modal transportation system is less costly than traditional

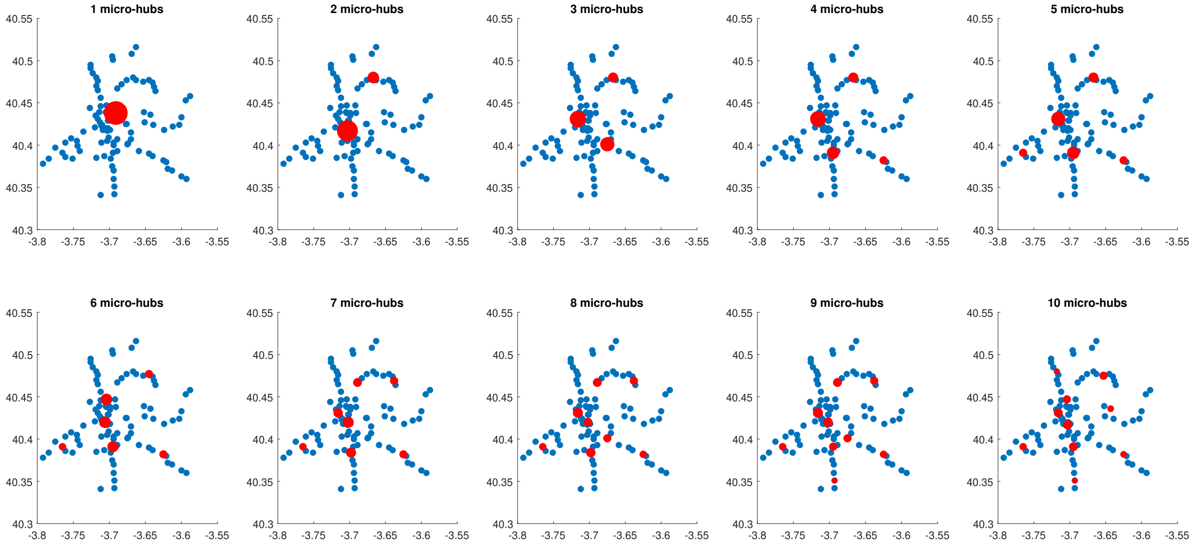

Figure 3: Geographical location of hubs and distribution of staff members across hubs.

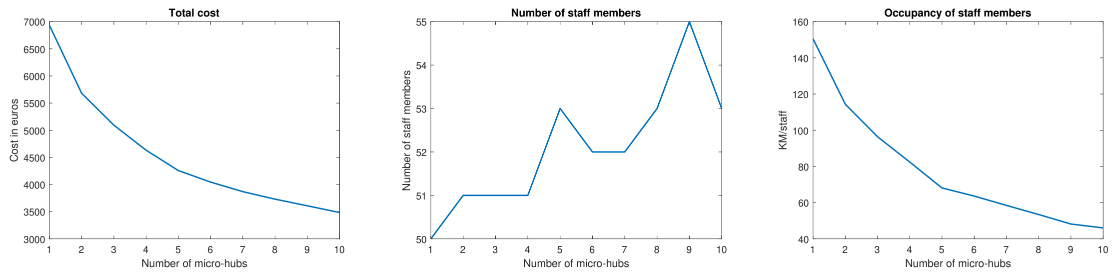

Figure 4: Statistics for different number of micro-hubs

delivery is highly dependent on the efficiency of micro-delivery couriers. However, the multi-modal delivery system shows to be significantly less polluting than traditional delivery. Micro-hubs are strategically positioned throughout the network. Clearly, they are distributed geographically, but also taking into account the demand in each region. In addition to this, locations that lie on the intersection of multiple metro lines are more attractive to construct micro-hubs. These results, together with the more detailed results of the full paper, provide promising perspectives for future developments of multi-modal transportation systems for last-mile delivery.

Acknowledgements

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