Delft University of Technology

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

Stokkink, Patrick; Geroliminis, Nikolas

DOI
10.1016/j.tre.2025.104344

Publication date
2025

Document Version
Final published version

Published in
Transportation Research Part E: Logistics and Transportation Review

Citation (APA)
Stokkink, P., & Geroliminis, N. (2025). On the optimal micro-hub locations in a multi-modal last-mile delivery system. *Transportation Research Part E: Logistics and Transportation Review*, *203*, Article 104344. https://doi.org/10.1016/j.tre.2025.104344

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Transportation Research Part E 203 (2025) 104344

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

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

Patrick Stokkink [a,c,*], Nikolas Geroliminis [b,c]

[a] Faculty of Technology, Policy and Management, TU Delft, Netherlands
[b] École Polytechnique Fédérale de Lausanne (EPFL), Urban Transport Systems Laboratory (LUTS), Switzerland
[c] MobiLysis Sarl, Switzerland

A R T I C L E I N F O

Keywords:
Last-mile delivery
Location problems
Multi-modal transportation
Mixed integer linear programming
Continuum approximation

A B S T R A C T

Last-mile delivery is one of the most polluting parts of the supply chain. This is partially caused by increased congestion in urban areas and repetitive stop-and-go traffic. One possible alternative to this is to use micro-mobility to replace large motorized vehicles. However, these vehicles are usually slower and have lower capacity. In this work, we propose a multi-modal logistics system for last-mile delivery that combines the use of trucks, metro and micro-mobility. This innovative type of system uses the metro to distribute the parcels to micro-hubs across the network and uses micro-mobility only for the final part of the parcel's itinerary from the micro-hub to the front door of the customer. We focus on finding the optimal micro-hub locations in such a system. We use a continuum approximation of the operational and tactical decisions which includes routing of the micro-mobility vehicles. The whole problem is then modeled as a Mixed Integer Linear Programming (MILP) model for the strategic decisions regarding the micro-hubs, which include location, capacity, and fleet-assignment decisions. We evaluate the results of 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 in terms of operational costs and pollution.

1. Introduction

Traditionally, last-mile delivery of parcels to customers is performed by delivery vans and 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 altogether. For example, the city of Amsterdam has banned heavy vehicles from the urban city center (City of Amsterdam, 2021). As a consequence, delivery companies are looking for sustainable alternatives to traditional last-mile delivery.

Besides their effect on pollution, another reason for getting rid of delivery trucks in urban areas is their effect on traffic congestion. 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

* Corresponding author at: Faculty of Technology, Policy and Management, TU Delft, Netherlands.
E-mail addresses: p.s.a.stokkink@tudelft.nl (P. Stokkink), nikolas.geroliminis@epfl.ch (N. Geroliminis).

https://doi.org/10.1016/j.tre.2025.104344
Received 4 November 2024; Received in revised form 25 June 2025; Accepted 21 July 2025
Available online 5 August 2025
1366-5545/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

the impacts of freight delivery in urban areas and its impact on urban congestion through double parking versus dedicated delivery areas.

One of these more sustainable modes that is commonly used nowadays and 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) cargo bikes, scooters, or small walking carts. These vehicles are substantially less polluting, but also have lower capacities and can be slower than larger motorized 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 (or even into the urban areas, if permitted). 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 strengths of these modes, while omitting their weaknesses. The envision system uses the economies of scale and efficiency of larger delivery trucks and metros, while omitting their polluting character and entrance restrictions. At the same time, the system benefits from the sustainability and flexibility micro-delivery, while largely omitting their constraint of restricted capacity.

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. A review of the relevant literature is provided in Section 2. The problem is described in more detail in Section 3. Section 4 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 5 and the paper is concluded in Section 6.

2. Literature review

Multi-modal transport of goods is a rather common practice for long-distance transport. Although traditionally these systems operate separately, recent work has been done on integrating the design and operations of multi-modal freight transport network. Yu and Jiang (2021) and Zhu-jun et al. (2022) investigate network design and operational planning, respectively, for an integrated system of air and rail transport. For container shipping, it is common that a part of the supply chain is maritime (de Bok et al., 2018; Woo et al., 2018; Archetti et al., 2022). Similarly, the integration of road and rail transport is rather common for long-distance transportation (Crisalli et al., 2013; de Miranda Pinto et al., 2018).

Whereas multi-modal freight transport is common for long-distance transport, it is still uncommon for last-mile delivery. Janjevic et al. (2021) design a multi-tier, multi-service-level, and multi-modal last-mile distribution network for e-commerce products. Their modes are connected through satellite stations. Bayliss et al. (2023) consider a multi-modal last-mile delivery system to facilitate the use of greener transportation modes such as electric cargo bikes. Others consider a multi-modal trip where last-mile delivery can be executed by UAVs/drones (Moshref-Javadi et al., 2020; Li et al., 2023; Gao et al., 2023) or through crowd-shippers/occasional couriers (Mousavi et al., 2022; Stokkink et al., 2024; He and Zhen, 2025). The integration of conventional transport with e-mobility has been considered by Babaee Tirkolaee et al. (2024). Although microdelivery is not commonly modeled for last-mile delivery, micromobility is often considered as a first- and last-mile passenger transport solution (Yin et al., 2024; Gao and Li, 2024; Roig-Costa et al., 2024).

Another alternative is to use the empty capacity on public transport services to fulfill a part of the multi-modal last-mile trip. When people and freight share the same transport services, this is referred to as Integrated Passenger and Freight Transport (IPFT). Cavallaro and Nocera (2022) provide a literature review on IPFT. Elbert and Rentschler (2022) focus on urban areas and performed a systematic literature review on the integration of freight with public transport.

The existence of IPFT systems is highly correlated with the territorial scale of the system. IPFT is most common for long-haul transport, for example using ferries, planes, or trains. Back in 1997, research for using planes to combine passenger and freight transport was already done by Peeters et al. (1997). In practice, according to US Department of Homeland Security (2023), almost all domestic commercial passenger flights also carry cargo in the cargo hold of the aircraft. Integrating railway transport for passengers and freight was studied by, among others, Bollapragada et al. (2018) and Huang et al. (2019). More recently, IPFT systems have been considered for short-haul trips in rural areas (Bruzzone et al., 2021; Cavallaro and Nocera, 2022; Feng et al., 2023; He and Guan, 2023). A practical example can be found in Switzerland, where the Swiss PostBus carries commuters, schoolkids, tourists, letters and parcels to more remote areas of the country (House of Switzerland, 2021).

IPFT systems for short-haul transport in urban areas are rarely seen in practice, but have more recently been considered in the literature. Existing studies integrate these systems using taxis (Li et al., 2014), subways (Cochrane et al., 2017), busses (Masson et al., 2017), and rapid-busses (Fatnassi et al., 2015). According to Cavallaro and Nocera (2022), those works that consider actual implementations of IPFT on an urban level are rare exceptions, such as Van Duin et al. (2019) and Wosiyana (2005). A common issue with the adoption of IPFT systems is security. It is considered unsafe for passengers and freight to directly share the same compartment of a vehicle, which makes the direct implementation of these systems difficult. To avoid this problem, in this paper,

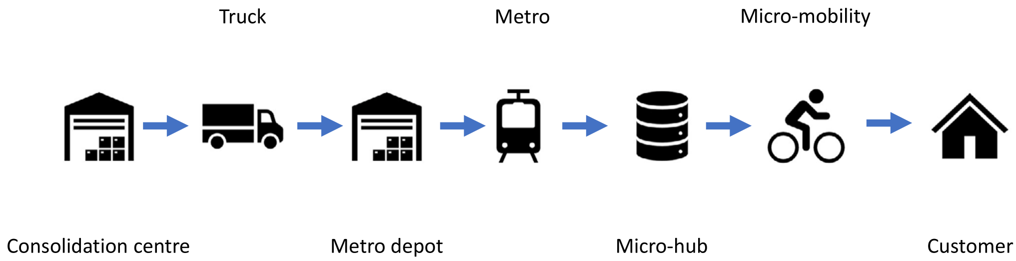


Fig. 1. Schematic representation of last-mile delivery process.

we consider a partially integrated system where passengers and freight use the same infrastructure but not at the same time. This means that metro lines as well as metro carriages are used to transport freight only before the passenger service starts. This is an early-stage solution to avoid safety issues and allows for adaptation to a fully IPFT system when the correct safety measures are in place.

Whereas existing research has primarily focused on the operational aspect of multi-modal systems, in this paper, we focus on strategic and tactical decisions. The strategic decisions regard the locations of micro-hubs. This problem is closely related to facility and hub location problems. Facility location problems were introduced by Cornuéjols et al. (1983) and have been applied in freight transport by, among others, Fernandes et al. (2014), Gendron et al. (2016), Osorio-Mora et al. (2020) and Ambrosino and Sciomachen (2016). Hub location problems have been studied before in the context of passenger transportation (Aydin et al., 2022; Blad et al., 2022; Yatskiv and Budilovich, 2017). In multi-modal systems, hub location problems have been previously studied by Zhao et al. (2018), Ji et al. (2020) and Stokkink and Geroliminis (2023). The tactical decisions regard the assignment of fleet and capacity to different locations. Both of these problems separately are special cases of the Generalized Assignment Problem (GAP). The GAP knows many applications, of which a survey is provided by Öncan (2007).

We approximate the lower-level routing decisions through a continuum approximation (Li and Ouyang, 2010; Wang and Ouyang, 2013; Stokkink and Geroliminis, 2023). This approximation allows us to obtain an approximation of the costs of routing couriers in the final stage of the problem. The strategic and tactical decisions (i.e., location of micro-hubs and assignment of capacity and fleet) are then formulated as a Mixed Integer Linear Programming (MILP) problem. This approach carries some similarities to Janjevic et al. (2021) and Stokkink and Geroliminis (2023) for the network design of a crowd-shipping system, where the lower-level assignment decisions are approximated using CA. In Stokkink and Geroliminis (2023) the lower-level decisions strongly rely on the higher-level decisions, which require the two levels to be solved jointly. In this work, we decompose the cost function into an exogenous and endogenous component, which allows for a more efficient formulation of the problem.

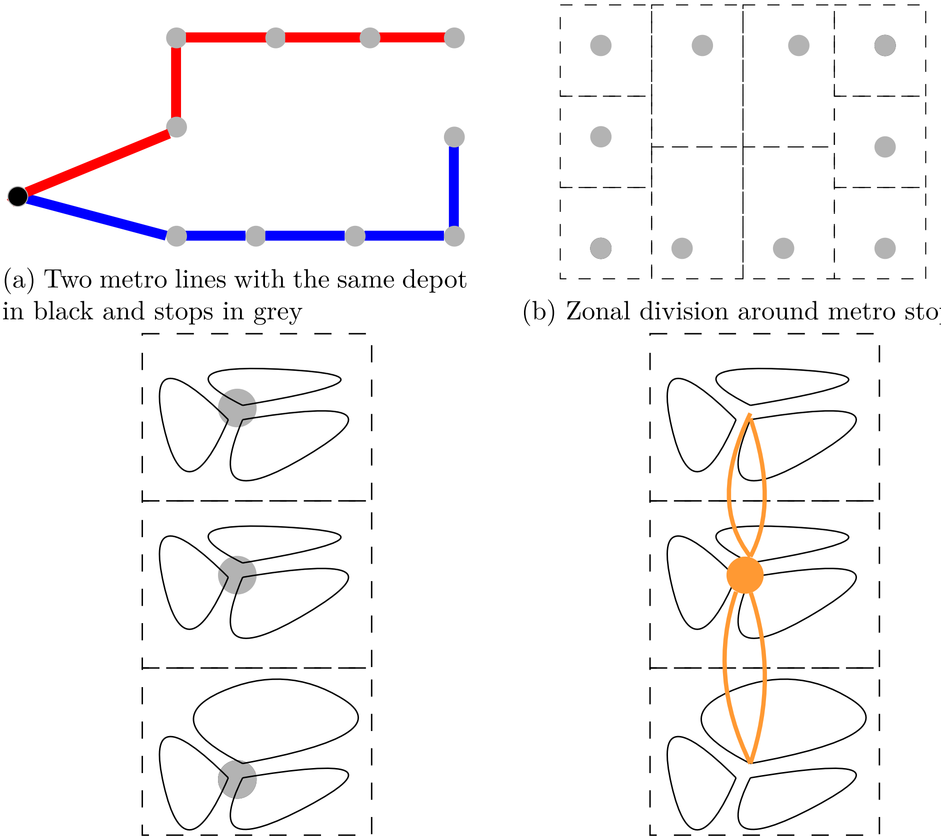
The contributions of this paper are fourfold. First, we introduce a new multi-modal last-mile delivery system for urban areas, combining trucks, metro, and micro-delivery. In this way, we exploit the economies of scale of larger trucks and metros, while using the sustainability advantage of metro and micro-delivery. Second, we formulate the *strategic hub location* and *tactical staff assignment* problems as an integrated MILP problem. In this intricate problem, CA is used to decompose the cost function. To the best of our knowledge, we are the first to consider this combined problem for a multi-modal last-mile delivery system. Third, we evaluate the overall efficacy of the multi-modal LMD system in terms of costs and emissions. Fourth, we provide insights into the optimal hub location and staff distribution in a multi-modal system.

3. Problem description

We consider a three-stage delivery process for last-mile delivery that combines truck, metro, and active transport modes (such as cargo bikes or walking carts). This three-stage process, which is graphically depicted in Fig. 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 cargo bikes or walking carts with a relatively small capacity of packages. Due to the limited size of these micro-delivery vehicles, we focus on small to medium-sized parcels that are transportable by micro-delivery vehicles with relative ease. We look into e-commerce rather than grocery or food delivery, given the higher flexibility of these delivery services.

In terms of timing, the metro is typically operational for passenger transport starting at 6:00 in the morning. This means it can be used for parcel transportation between 5:00 and 6:00, which requires the trucks to arrive at the metro depot by 5:00 or 5:30. Micro-delivery can commence around 6:00, which allows for a full regular working shift, but in general leads to most deliveries being completed by noon. Time windows for customers are outside the scope of this work, but can easily be incorporated given the realistic working shift of micro-delivery couriers. As time windows generally reduce the efficiency of routes, it would likely require additional couriers.

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. Both metros and trucks have a maximum capacity, which means that the total number of parcels



(a) Two metro lines with the same depot in black and stops in grey

(b) Zonal division around metro stops

(c) VRP for micro-delivery in a single zone

(d) Micro-hub in orange with line-haul to unopened zones

Fig. 2. Schematic depiction of process to select the optimal micro-hubs. Grey circles denote metro stops that are potential micro-hub locations. An orange circle indicates a metro stop for which a micro-hub is actually opened. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that can be transported to micro-hubs on the same metro can be limited by this capacity. 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. Costs for transporting parcels by metro are measured based on the distance between the depot and the micro-hub that the parcel is delivered to. To approximate the routing costs, the network is divided into a set of zones around metro stops as indicated in Fig. 2a and b. 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 as depicted in Fig. 2c and d. The line-haul components are part of the trip of the micro-delivery couriers. For three tours, this means that the two-directional line-haul is traversed three times by micro-delivery couriers. Details of this approximation are described in Section 4.3. 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 zonal division of the network, which is detailed in Section 4.2, 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 endogenous and thus influences these locations. This component is therefore integrated into the mathematical formulation of the problem.

4. Methodology

A mathematical formulation of the problem is provided in Section 4.1. For this formulation, a zonal division of the network is required. Section 4.2 discusses a generic method to divide the network into zones around metro stations. The cost parameters associated with the operational level are approximated using a continuum approximation approach, which is explained in Section 4.3. The benchmark to which our multi-modal system will be compared is outlined in Section 4.4.

4.1. 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 traveling there through line $r \in R$.
- o_{wr} (integer) - the number of trucks needed to serve line $r \in R$ from the warehouse $w \in W$.
- 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 with rental of space at the metro stops, or with one-time investments to improve accessibility of the metro stations to facilitate 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} and the time it takes to perform this delivery is defined as τ_{ij}. The cost associated with running trucks between warehouse $w \in W$ and the metro depot of line $r \in R$ is denoted as c_{wr}^{truck}. The cost of delivering a parcel from the depot of line $r \in R$ to micro-hub $i \in I$ is denoted as c_{ri}^{metro}. 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}. Microhub capacity is not considered, given that the capacity of a metro is typically lower than the capacity of a metro station. Nevertheless, this can be easily incorporated into the formulation for other applications. Let d_{iw} be the demand for parcels in region $i \in I$ that originates from warehouse $w \in W$. Every courier can work for at most τ^{shift} time units. Parameter M is an arbitrarily large number and ϵ an arbitrarily small 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 Fig. 1 are therefore connected through the decision variables x_{ij}, z_{irw}, and o_{wr}. The problem is then formulated as follows:

$$\min \sum_{i\in I} f_i y_i + \sum_{i\in I}\sum_{j\in I} c_{ij}x_{ij} + \sum_{r\in R}\sum_{i\in I}\sum_{w\in W} c_{ri}^{metro} z_{irw} + \sum_{w\in W}\sum_{r\in R} c_{wr}^{truck} o_{wr} + \sum_{i\in I}\epsilon s_i \tag{1}$$

s.t.

$$\sum_{i\in I} y_i \le p \tag{2}$$

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

$$x_{ij} \le y_j \quad \forall i,j \in I \tag{4}$$

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

$$\sum_{w\in W}\sum_{i\in K_r} z_{irw} \le Q_r \quad \forall r \in R \tag{6}$$

$$o_{wr} \ge \frac{\sum_{i\in I} z_{irw}}{Q^{truck}} \quad \forall r \in R, w \in W \tag{7}$$

$$\sum_{j\in I} \tau_{ij}x_{ij} \le \tau^{\text{shift}} s_i \quad \forall i \in I \tag{8}$$

$$y_i \in \{0,1\} \quad \forall i \in I \tag{9}$$

$$x_{ij} \in \{0,1\} \quad \forall i,j \in I \tag{10}$$

$$z_{irw} \in \{0,1,\dots,Q_r\} \quad \forall i \in K_r, r \in R, w \in W \tag{11}$$

$$z_{irw} = 0 \quad \forall i \notin K_r, r \in R, w \in W \tag{12}$$

$$o_{rw} \in \{0,1,\dots,M\} \quad \forall r \in R, w \in W \tag{13}$$

$$s_i \in \{0,\dots,S\} \quad \forall i \in I \tag{14}$$

The objective in (1) is to minimize the costs of opening microhubs, micro-delivery, metro transportation and truck routing. Constraint (2) ensures the maximum number of micro-hubs is not exceeded. A small penalty is added to ensure the number of couriers is not higher than necessary to serve all demand. 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 parcels 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 implicit 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 (11) and (12) 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, on average, the maximum shift duration of staff members assigned to micro-hub $i \in I$ is not exceeded.

4.2. Zonal division

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.

After the construction of the Voronoi diagram, the network is 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, as will be explained in detail in Section 4.3, the area of each zone needs to be computed. For every Voronoi polygon, we obtain the vertices that make up the polygon using Delauney's triangulation. For polygons on the edge of the network, no exact vertex to define the polygon exists (it is a ray instead). To approximate the area in this case, we set the area of this polygon to the maximum area of any other polygon in the network. Using the coordinates of these vertices, we use the shoelace formula, also known as the Surveyor's eye formula (Braden, 1986), to approximate the area of the polygon. The area of zone $i \in I$, is denoted as A_i.

4.3. Approximation of costs

To approximate the costs of micro-delivery we use a classical CA approach (Daganzo, 1984). One of the main advantages of this method is that the estimates are based on aggregated data and are theoretically and empirically shown to be robust in case of uncertainties and fluctuations (Daganzo, 1984; Huang et al., 2013; Merchán and Winkenbach, 2019). We separately determine the inter and intra-zonal costs. For this, we emphasize that this is done to make the approximation tractable. In reality, drivers can serve parcel requests in different zones during the same tour. Recall that I is the set of zones and d_i the demand in zone $i \in I$. Let q^{tour} be the capacity of a dedicated driver on a single tour. We emphasize that a driver may perform multiple tours, as long as it is feasible within their maximum shift duration τ^{shift}. Let A_i and n_i be the area of zone $i \in I$ and the number of stops needed to be made in zone $i \in I$, respectively. Based on the vehicle capacity and the total demand in a zone, the minimum number of tours that need to be performed is $m_i = \lceil \frac{d_i}{q^{\text{tour}}} \rceil$. This is independent of the number of drivers as they can perform multiple tours, as long as it does not exceed the total number of parcels that can be delivered by the dedicated number of drivers. This independence also aids the decomposition of the problem, as the number of drivers is only used in the mathematical formulation and is not required for the cost approximation.

Let every tour then cover an equal portion of the area and an equal number of stops, such that the area is equal to $\frac{A_i}{m_i}$ and the number of stops is equal to $\frac{n_i}{m_i}$. Then, the tour length can be approximated as

$$l_i = k\sqrt{\frac{A_i}{m_i}}\sqrt{\frac{n_i}{m_i}} = k\frac{\sqrt{A_i n_i}}{m_i} \tag{15}$$

The total length traveled inside the zone is then equal to $L_i = m_i l_i = k\sqrt{A_i n_i}$.

The inter-zonal costs h_{ij} of a delivery from micro-hub in zone $i \in I$ to destinations in zone $j \in I$ depends on the distance between the two zones (approximated by the distance between the centroids of the zone) which is equal to t_{ij} and the number of tours that need to be performed in zone $j \in I$, m_j. That is, the total line-haul distance is between zones i and j is given as $h_{ij} = 2t_{ij}m_j$. Given that the line-hauls are performed by micro-delivery couriers, the distance is multiplied by the number of tours. By definition, the line-haul distance is negligible for a zone that has a micro-hub, i.e., $h_{ii} = 0$. When the number of micro-hubs is small, this generally leads to long line-haul costs by micro-delivery vehicles. As this is time-consuming and costly, this will typically favor solutions with more micro-hubs.

These components can be used in turn to determine the time τ_{ij} and the costs c_{ij} in the formulation in Section 4.1. Let ρ be the cost for every unit of distance traveled by a dedicated driver. The time and costs are then equal to:

$$\tau_{ij} = h_{ij} + L_j \tag{16}$$

$$c_{ij} = \rho(h_{ij} + L_j) \tag{17}$$

We can use the total number of tours and the tour length, compared to the obtained number of staff members s_j from Section 4.1 to determine the average workload per staff member at every micro-hub. The average number of tours per staff member working from micro-hub j is equal to $\frac{m_j}{s_j}$ and the average distance traveled is equal to $\frac{h_{ij}+L_j}{s_j}$.

Trucks are used between the warehouse and the metro depots. Given the limited number of metro depots and the relatively large loads that need to be transported to each depot, we route the trucks according to a Full Truck Load (FTL) principle. This means every truck is filled with parcels for a dedicated warehouse and metro depot. Another important reason for this is the limited time that is available for serving the metro depots in the morning, which means that it is more efficient to dispatch the trucks at the same time. As such, the costs can be approximated as line-haul costs. For this, let ρ^{truck} denote the cost for every unit of distance traveled by a truck, such that the costs are equal to:

$$c_{wr}^{\text{truck}} = 2\rho^{\text{truck}} t_{wr}, \tag{18}$$

where a truck travels a distance t_{wr} back and forth between a warehouse and a metro depot and is hence multiplied by two. For transportation by metro, a similar approach is used. Denote t_{ri} the distance between the metro depot on line $r \in R$ and micro-hub $i \in I$, and ρ^{metro} as the cost for every unit of distance traveled per parcel by metro, then the cost of metro transportation is computed as:

$$c_{ri}^{\text{metro}} = \rho^{\text{metro}} t_{ri}. \tag{19}$$

4.4. Benchmark: Truck routing problem

As a benchmark, we use traditional delivery where trucks are used between the warehouse and the front door of all customers. As we only have zone-based demand data, rather than the exact destination location of parcels, we use a continuum approximation of the costs similar to the one described in Section 4.3. We distinguish between the intra-zone routing costs, which are approximated by a continuum approximation, and inter-zone routing costs which are approximated by solving separate Capacitated Vehicle Routing Problems (CVRP) from each warehouse.

The intra-zone routing costs are associated to the distance the truck travels within the zone and the corresponding stops that the truck makes. Let ψ^{stop} be the cost of stopping at a customer and ψ^{dist} the cost per unit of distance traveled. Given the size of the trucks, we assume a truck can serve all the demand inside a zone. That is, only a single truck needs to travel into a zone from each warehouse. Given that separate trucks come from separate warehouses, we consider parameter n_{iw} as the number of stops in zone $i \in I$, with demand from warehouse $w \in W$. We note that here we differentiate between the multiple warehouses. For the multi-modal case, all parcels from different warehouses are aggregated at the micro-hub and therefore the differentiation does not need to be made in the routing of micro-delivery couriers. The intra-zone routing costs for zone i from warehouse w can be computed as:

$$\psi^{\text{dist}} k \sqrt{A_i n_{iw}} + \psi^{\text{stop}} n_{iw} \tag{20}$$

The inter-zone routing costs are associated with the distance between the zones and to reach the zones from the warehouses. For this, a CVRP is solved for each warehouse separately. Truck capacity is equal to Q^{truck}, the set of nodes is made up of the set of zones I and demand in each zone is equal to d_{iw}. Every truck starts and ends at the warehouse $w \in W$. Let $CVRP(w)$ denote the corresponding distance traveled from warehouse w to visit all customers and let $V(w)$ denote the number of trucks needed from warehouse w. We can then compute the total costs associated with inter-zone routing from warehouse w as:

$$\psi^{\text{dist}} CVRP(w) \tag{21}$$

The total costs of the benchmark of traditional truck routing can then be approximated as:

$$\sum_{w \in W} \left[\psi^{\text{dist}} CVRP(w) + \sum_{i \in I} \left(\psi^{\text{dist}} k \sqrt{A_i n_{iw}} + \psi^{\text{stop}} n_{iw} \right) \right] \tag{22}$$

5. Results

In this section we evaluate the performance of the envisioned multi-modal last-mile delivery system. We detail the case study in Section 5.1. We compare the envisioned delivery system to a traditional last-mile delivery system in Section 5.3. The effect of varying the number of micro-hubs is evaluated in Section 5.4. Sensitivity analysis on the number of staff members and the number of operating lines and warehouses are performed in Sections 5.5 and 5.6, respectively.

5.1. Case study

We evaluate the results on a case study of the city of Madrid, Spain. Data for this case study has been provided by the relevant stakeholders: DHL, Metro de Madrid, and KOIKI (a Spanish micro-delivery company). These stakeholders have also actively participated in the tuning of the parameters, to accurately represent reality. The case study consists of two warehouses (W), five metro depots (M), and eight metro lines (R). All of these components are graphically depicted in Fig. 3. Warehouses are indicated by a grey triangle and are located relatively far from the city center of Madrid in the province of Toledo. The five metro depots, indicated by black squares, are scattered throughout the city of Madrid, with most of them being on the outskirts of the city center. Every metro line has a unique color, with every station that could potentially function as a micro-hub indicated by a colored circle. Recall that every station on line $r \in R$ is included in the set K_r. It can be noted that the metro depots do not necessarily align with the start or end station of a line. The reason for this is that a metro depot is used to store metros and their spare parts. These depots

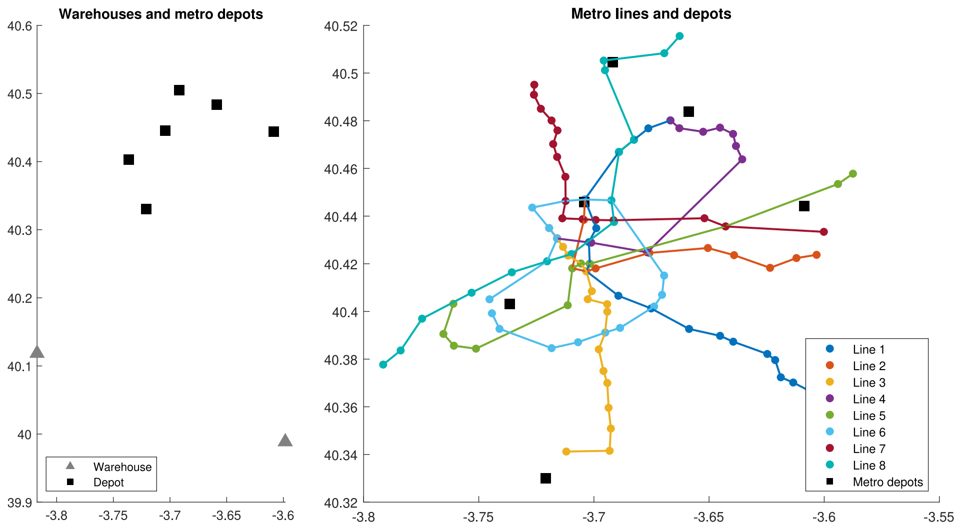


Fig. 3. Graphical representation of warehouses, metro depots, and metro lines in a geographic coordinate system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

therefore require a space that is not always directly available, which means they may be located slightly further away. Naturally, they are connected by tracks, but as they do not carry passengers on these tracks, these are not indicated in the metro network.

In total, the network consists of 99 unique stations, where we note that some stations can be served by multiple lines. For every station, we identify the region around that station through a Voronoi diagram, as indicated in the left-hand side of Fig. 4, such that we have 99 regions (I). The demand for every region is known and based on historical data from a last-mile delivery company, indicated by d_i. The values of d_i range from 10 to 300 and are displayed on the right-hand side of Fig. 4. The capacity of each metro line (Q_r), imposed by the size of the metro, ranges from 1000 on line 2 to 4500 on lines 6 and 8. We consider two types of trucks: small trucks with a capacity Q^{truck} of 400, a cost ρ^{truck} of €1.40 per km and emissions e^{truck} of 299 grams per km, and large trucks with a capacity Q^{truck} of 600, a cost ρ^{truck} of €2.10 per km and emissions e^{truck} of 350 grams per km. For the benchmark policy, we choose $\phi^{\text{dist}} = \rho^{\text{truck}}$ and $\phi^{\text{stop}} = 0.00$. The cost per parcel of transporting that parcel by metro is typically small given the relatively high capacity of the metro and the limited effort of staff (in this case study, carts with parcels only need to be pushed on and off the metro). For this, we choose $\rho^{\text{metro}} = €0.01$.

The remaining parameters are chosen as realistically as possible based on the input from a microdelivery company. The base number of staff members (S) is set to 200. The number of parcels that can be delivered per tour (q^{tour}) is assumed to be equal to 12. A tour lasts approximately two hours, meaning that 4 tours can be executed during a workday. As such, q^{shift} is set equal to 48 parcels. The cost per hour is approximately €10,00. At a walking speed of 5 km/h, this means ρ is equal to €2.00 per km. At a cycling speed of 15 km/h, this means ρ is equal to €0.66 per km. The increased speed typically also increases the number of tours that can be performed by a staff member. A micro-hub is operated at a constant cost f_i is set equal to €60,00.

The mathematical model has been implemented in Java (Java SE-10) and is solved using CPLEX version 12.6.3. All instances are solved up to a 2% optimality gap. Given the strategic and tactical nature of our problem, solution time of the problem does not form a strict burden. Nevertheless, a single problem instance can be solved within seconds or minutes. Instances for which staff constraints are less tight are generally faster to solve, whereas instances for which the maximum fleet size forms a tighter constraint are more difficult to solve.

5.2. Computational efficiency

The problem considered in this paper is a mix between a strategic and tactical problem. Although real-time computation is not necessary, we analyze the scalability of the solution approach in this section. All instances that are considered in this paper are solvable within seconds or minutes. Nevertheless, there are some components that are influential on the size of the model and on the solving times. In this section, we evaluate two aspects. The first is an aspect that directly influences the size of the model, like the number of metro lines or the number of zones. The second aspect does not influence the size of the model, but influences the complexity in finding a solution and with that the computation times. To quantify both aspects, we perform two sets of experiments. Table 1 displays the number of constraints, variables and computation time for a varying number of metro lines. Table 2 displays the number of constraints, variables and computation time for a varying number of maximum micro-hubs. All instances are solved up to a 2% optimality gap.

When varying the number of metro lines, the number of constraints and variables increases steadily. With this, the computation time also increases from less than a second for one line, to 21 s for 8 lines. The complexity of the model evolves similarly when

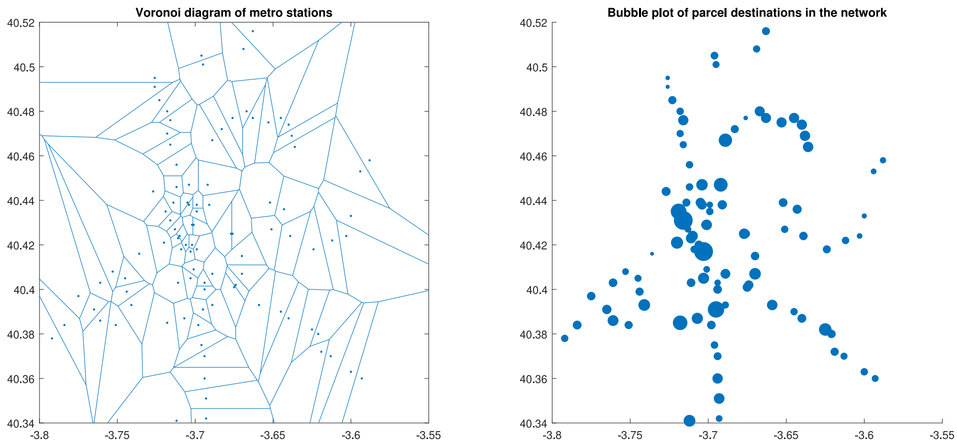


Fig. 4. Voronoi diagram and bubble plot of metro stations in a geographic coordinate system.

Table 1
Model properties for varying number of metro lines.

Lines	Constraints	Variables	CPU time (s)
1	2 143	2 062	0.14
2	3 064	2 995	0.44
3	4 801	4 750	2.22
4	5 620	5 580	4.82
5	6 439	6 412	12.58
6	7 768	7 761	8.22
7	9 199	9 209	13.94
8	10 222	10 251	20.92

Table 2
Model properties for varying number of micro-hubs.

Micro-hubs	Constraints	Variables	CPU time (s)
1	10 222	10 251	4.95
2	10 222	10 251	2.83
3	10 222	10 251	7.54
4	10 222	10 251	17.30
5	10 222	10 251	10.91
6	10 222	10 251	7.03
7	10 222	10 251	8.43
8	10 222	10 251	11.46
9	10 222	10 251	51.43
10	10 222	10 251	61.21

varying the number of demand regions. When varying the maximum number of micro-hubs, the number of constraints and variables remains constant. The only change to the problem formulation is through the parameter p in Constraint (2). Clearly, the number of constraints and variables remains constant upon a change in p. Nevertheless, the feasible region increases and therefore computation time still shows a (non-monotonic) increasing trend. Similar effects can be observed when changing other model parameters. Nevertheless, solution times remain reasonable especially given that the considered problem is strategic and therefore does not require real-time decision-making. All in all, the results indicate the computational strength of the model.

5.3. Comparison to traditional 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, as described in Section 4.4. The CVRP instances are solved using the VRPy package in Python developed by Montagné and 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 walking cart and by cargo bike. We compare both methods in terms of costs and pollution. For the multi-modal system, six micro-hubs are used and located optimally according to the formulation in Section 4.1. Given the fixed number of micro-hubs, $f_i = 0$ without loss of generality for a constant cost of micro-hubs throughout the network. The results are displayed in Table 3.

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

Table 3
Comparison of multi-modal to traditional delivery.

Truck	MD	Truck cost (€)	Metro cost (€)	MD cost (€)	Total cost (€)	Emissions (CO2 kg)	Staff	Shift (h)
Multi-modal								
Small	Foot	2032.37	419.78	6501.65	8953.80	434.06	84	7.7
Small	Bike	1846.05	346.35	2252.89	4445.29	394.26	32	7.1
Large	Foot	1905.05	457.11	6558.67	8920.83	317.51	86	7.6
Large	Bike	1909.66	352.72	2213.53	4475.91	318.28	31	7.2
Traditional								
Small		4803.87			4803.87	1025.97		
Large		5101.88			5101.88	850.31		

Note: The table displays the results of multi-modal and traditional delivery. The top rows represent the multi-modal case, the bottom rows represent the traditional case. The first two columns mark the settings of the instance: the type of truck and the type of micro-delivery (if applicable). The third, fourth and fifth column denote the cost of trucking, metro, and micro-delivery (if applicable) with the total cost denoted in the sixth column. Total emissions are denoted in the seventh column and are expressed in kilograms of CO2. The final two columns denote the number of micro-delivery staff members and the average shift duration of staff members in hours.

and are therefore able to deliver significantly more parcels within the same amount of time, the cost is significantly lower when using bikers. Besides influencing cost of micro-delivery, the speed of couriers also indirectly influences the costs of trucking and metro, given that different hub locations are chosen. 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 cost is introduced, the multi-modal delivery would be more attractive.

The efficiency of staff members is also visible from the number of staff members that are required. This is significantly higher if staff members travel by foot, rather than by cargo bike. With staff shortages being a prominent issue in last-mile delivery, this is an important aspect to be considered. The average shift duration is between 7 and 8 h, making the shifts highly feasible. Shift durations are similar for staff members assigned to different micro-hubs. Nevertheless, the number of parcels delivered by staff members may differ significantly across micro-hubs given the different line-haul distances that influence tour duration.

5.4. 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 Fig. 5. 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 (see Fig. 4) and thereby the outskirts can be reached from this central location 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.

Fig. 6 provides three key features of the system for a varying number of micro-hubs. For this comparison, smaller trucks have been used, and micro-delivery couriers are assumed to travel by cargobike. 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 steep decrease is observed due to higher efficiency in staff members for the first micro-hubs. Spreading more micro-hubs throughout the network drastically reduces the line-haul distances. This also explains the sharp decrease in the number of staff members. Less staff members are needed to serve the same demand because the line-haul distances are reduced. This implies that more parcels can be delivered within the same shift duration. We also observe a decrease in the occupancy of staff members. The reason for this is that spreading out the parcels and staff members across micro-hubs may introduce some slight inefficiencies, with staff members operating shorter shifts.

The spread of micro-hubs and specifically the optimal number of micro-hubs is influenced by the operating cost of a micro-hub (f_i). When we increase the operating costs of a micro-hub from €60.00 to €120.00, we observe that total costs are reduced up to 8 micro-hubs, but after this, no cost reduction is obtained by opening additional micro-hubs. This tells us that the optimal number of micro-hubs, and with that the overall profitability of a multi-modal system, depends on the specific features of the micro-hub. For example, micro-hubs that do not require full-time attendance by a staff member are generally cheaper to operate, and will therefore lead to different system configurations.

A more detailed inspection of the flow of parcels through the network gives us more insights. First, the maximum truck capacity sometimes implies that it is better to transport parcels to a suboptimal metro-depot in terms of location, because sending an extra truck is too costly. Second, we observe that although some parcels go from the warehouse to different metro depots, they may thereafter end up in the same micro-hub. The reason for this is again the maximum truck capacity. Third, we observe that three out of six micro-hubs are located on an intersection of two or three metro lines. This grants the solution extra flexibility. In addition to

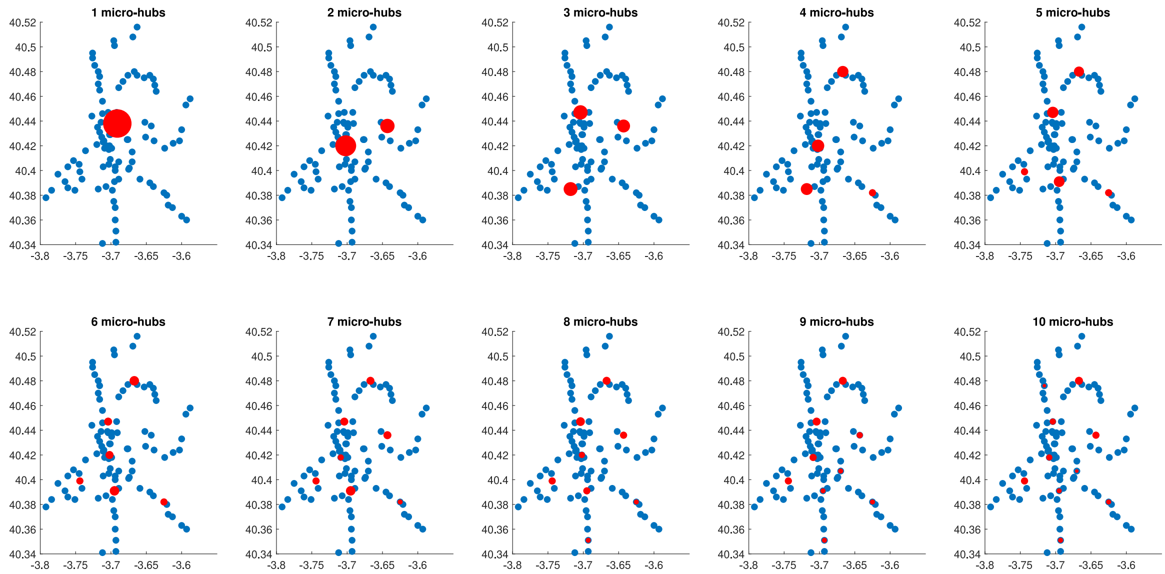


Fig. 5. Geographical location of hubs and distribution of staff members across hubs in a geographic coordinate system. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

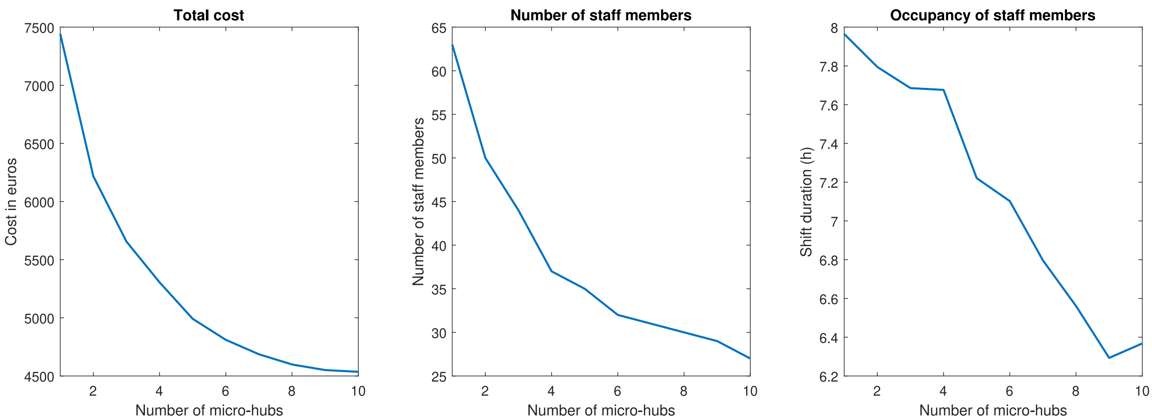


Fig. 6. Statistics for different number of micro-hubs.

this, this allows for more robustness in the system. In case one line is closed, the parcels can still be sent through that micro-hub via another line. We also observe that two depots remain unused. This indicates that opening these lines is not effective in improving the performance of the system. Further analysis of this phenomenon is performed in Section 5.6.

5.5. Sensitivity analysis on staff effort

Throughout this work, we have considered a maximum shift duration of 8 h, which is consistent with full-time employment in many countries. In this section, we vary the shift duration to evaluate the effect on the number of staff members and the total costs. A sensitivity analysis is performed by varying the shift duration between 2 and 12 h considering staff that walk and bike. Changing the shift duration influences τ^{shift} but also influences the number of parcels that can be delivered during a shift.

In terms of operational costs, we observe no significant changes. The reason for this is that we assume staff is paid for the hours they actually work, not for the total duration of their shift. The required number of staff members, on the other hand, changes significantly for varying shift durations. The number of required staff members for a varying maximum shift duration are displayed in Table 4. The number of required staff members is significantly higher if the staff uses walking carts rather than cargo bikes. The reason for this is that staff using cargo bikes can deliver more parcels in the same amount of time. The total number of required staff decreases with the increase in shift duration. Nevertheless, the maximum number of available hours (i.e., shift duration multiplied by staff members) increases. This signals that for higher maximum shift durations, more staff members execute shifts that have a shorter duration than the maximum.

Table 4
Number of staff members for varying shift duration.

Shift duration (h)	Required staff	
	Walk	Bike
2	331	118
4	165	60
6	112	41
8	84	32
10	69	26
12	57	22

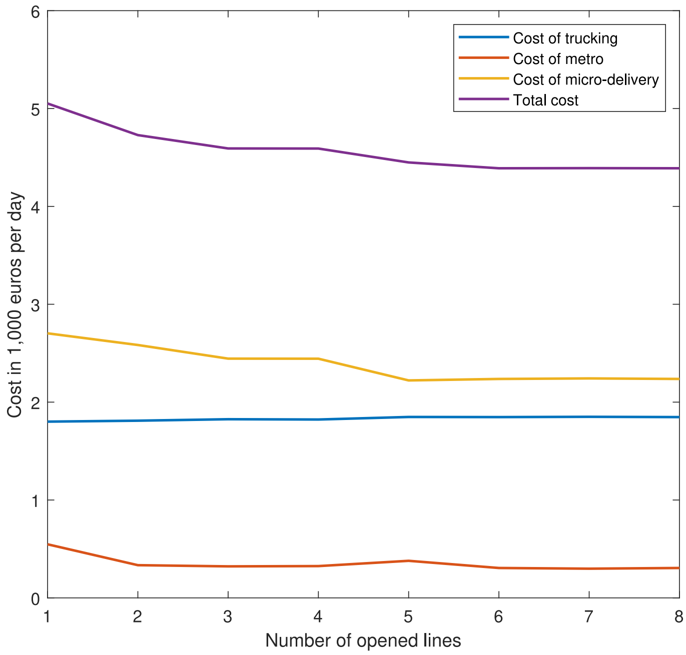


Fig. 7. Effect of opening additional metro lines.

5.6. Evaluation of lines, depots, and warehouses

In the prior sections, we assumed that each of the eight metro lines could be used to transport parcels. In this section, we evaluate the effect of the number of metro lines (and with that the metro depots they start from) on the operational costs. By increasing the number of metro lines and metro depots, parcels can be more easily distributed over the micro-hubs in the network. In addition to this, it allows for a larger set of reachable micro-hubs given that new lines may reach different parts of the network. On the other hand, the cost of trucking may increase given that separate trucks need to be dispatched to separate metro depots. To quantify this effect, we explore how the costs associated with trucking and micro-delivery change when a limited number of metro lines is used. To ensure feasibility, the capacity of metro lines (Q_r) is ignored in this case. Furthermore, to ensure comparability among the instances, fixed hub costs f_i have been set to 0. Metro lines are opened based on their number in Fig. 3. That is, when one line is opened it is only Line 1, when two lines are opened these are Line 1 and Line 2, etc.. The results of this experiment are displayed in Fig. 7.

The results clearly indicate that opening extra metro lines allows for a reduction of the overall costs. The reason for this is that the costs of micro-delivery decrease faster than the costs of trucking increase. We also observe that some lines have limited influence. Specifically, Lines 7 and 8 do not contribute to a further reduction of the costs. By taking a closer look, it appears that no micro hubs are opened on those lines, which therefore implies that the solution to the optimization problem remains identical. The cost of metro transportation generally tends to decrease, although not monotonously. For some additional lines, a change in hubs leads to an increase in metro transportation, which is countered by a larger decrease in the costs of micro-delivery. In general, the costs associated with using the metro decrease, suggesting that micro-hubs are chosen that are closer to the metro depots to reduce the distance traveled by metro.

Operating everything from a single warehouse allows the system to benefit from economies of scale. Rather than sending out vehicles from each warehouse to the opened depots, vehicles only need to be sent out from a single warehouse. This allows to reduce the number of required trucks and with that the costs of trucking. The influence of the number of warehouses on the costs of micro-delivery is marginal, given that this component is only indirectly affected through the choice of opened metro depots. This makes that a multi-modal system benefits less from economies of scale in trucking than a traditional delivery system. In the multi-modal case, these effects may be rather marginal compared to the benefits of splitting the warehouses from the perspective of warehouse optimization. For separate warehouses, order picking and storage may be more efficient, which could reduce the overall costs of the logistics operation.

6. Conclusion

In this paper, we studied a multi-modal alternative for last-mile delivery in urban areas. Although multi-modal delivery is common for long-haul transportation, it is not common for short-haul transportation of parcels, especially in urban areas. We study a framework where trucks, metros, and micro-delivery (by walking cart or cargo bike) are combined using depots and micro-hubs. We focus on the strategic problem of determining the optimal location of micro-hubs, as well as on the tactical problem of fleet and staff allocation across the network. We formulate the problem as a Mixed Integer Linear Programming (MILP) problem, which is solved using CPLEX.

This problem is especially difficult due to the intertwined strategic, tactical, and operational stages. To tackle this, we approximate the operational stage, the movement of micro-delivery couriers through the city, using a continuum approximation approach. The costs associated with the operational stage are implicitly integrated in the mathematical formulation. The strategic and tactical stages (micro-hub location and staff and fleet assignment, respectively) are then explicitly incorporated in the mathematical formulation.

The results indicate that the costs highly depend on the efficiency of micro-delivery couriers. In case the couriers travel by foot, the costs of our multi-modal system are higher than that of a traditional system using delivery trucks. In case the couriers travel by cargo bike, efficiency is increased significantly and with that the costs are decreased below that of traditional delivery. In terms of pollution, the multi-modal delivery system shows to be significantly less polluting than traditional delivery, independent of which mode of transport is used by micro-delivery couriers.

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. Increasing the number of micro-hubs and the number of lines can lead to cost reductions with decreasing marginal returns to scale. The average occupancy of couriers shows that, in the network of Madrid for couriers traveling by foot, at least four micro-hubs are necessary for the schedules to be workable, with respect to the average number of kilometers traveled by couriers. When time windows for parcels are considered, the mathematical formulation will remain unchanged but the approximated costs and shift durations may change, which may lead to different network configurations. An analysis of the influence of time windows, as well as an influence of potential disruptions and fluctuations, is marked as an interesting direction of further research.

Further research is needed to explore the willingness of stakeholders to participate in such a multi-modal system. This is especially important since transport companies that typically focus on transport of passengers, need to extend their service to transporting parcels, which may even require investments in infrastructure. After that, real-life implementations should be considered in combination with simulation studies to evaluate the impacts of this modal shift on congestion and emissions. Specifically in the case of Madrid, a real implementation of the envisioned system is foreseen by the involved stakeholders. Finally, collaboration between the stakeholders under heterogeneous objectives should be considered, to answer questions regarding the division of costs and profits.

CRediT authorship contribution statement

Patrick Stokkink: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nikolas Geroliminis:** Writing – original draft, Validation, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was conducted as part of the DELPHI project, which is funded by the European Union, under grant agreement No. 101104263. This work has received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI). We are also grateful for industrial insights and the proposed case study by DELPHI partners from DHL, Metro de Madrid, and KOIKI.

References

Ambrosino, D., Sciomachen, A., 2016. A capacitated hub location problem in freight logistics multimodal networks. Optim. Lett. 10 (5), 875–901.

Archetti, C., Peirano, L., Speranza, M.G., 2022. Optimization in multimodal freight transportation problems: A survey. European J. Oper. Res. 299 (1), 1–20.

Aydin, N., Seker, S., Özkan, B., 2022. Planning location of mobility hub for sustainable urban mobility. Sustain. Cities Soc. 81, 103843.

Babaee Tirkolaee, E., Cakmak, E., Karadayi-Usta, S., 2024. Traveling salesman problem with drone and bicycle: multimodal last-mile e-mobility. Int. Trans. Oper. Res..

Bayliss, C., Bektaş, T., Tjon-Soei-Len, V., Rohner, R., 2023. Designing a multi-modal and variable-echelon delivery system for last-mile logistics. European J. Oper. Res. 307 (2), 645–662.

Blad, K., de Almeida Correia, G.H., van Nes, R., Annema, J.A., 2022. A methodology to determine suitable locations for regional shared mobility hubs. Case Stud. Transp. Policy 10 (3), 1904–1916.

Bollapragada, S., Markley, R., Morgan, H., Telatar, E., Wills, S., Samuels, M., Bieringer, J., Garbiras, M., Orrigo, G., Ehlers, F., et al., 2018. A novel movement planner system for dispatching trains. Interfaces 48 (1), 57–69.

Braden, B., 1986. The surveyor's area formula. College Math. J. 17 (4), 326–337.

Bruzzone, F., Cavallaro, F., Nocera, S., 2021. The integration of passenger and freight transport for first-last mile operations. Transp. Policy 100, 31–48.

Cavallaro, F., Nocera, S., 2022. Integration of passenger and freight transport: A concept-centric literature review. Res. Transp. Bus. Manag. 43, 100718.

City of Amsterdam, 2021. Stricter rules for heavy vehicles. https://www.amsterdam.nl/en/traffic-transport/stricter-rules-heavy-vehicles/.

Cochrane, K., Saxe, S., Roorda, M.J., Shalaby, A., 2017. Moving freight on public transit: Best practices, challenges, and opportunities. Int. J. Sustain. Transp. 11 (2), 120–132.

Cornuéjols, G., Nemhauser, G., Wolsey, L., 1983. The Uncapicitated Facility Location Problem. Technical Report, Cornell University Operations Research and Industrial Engineering.

Crisalli, U., Comi, A., Rosati, L., 2013. A methodology for the assessment of rail-road freight transport policies. Procedia-Soc. Behav. Sci. 87, 292–305.

Daganzo, C.F., 1984. The length of tours in zones of different shapes. Transp. Res. Part B: Methodol. 18 (2), 135–145.

de Bok, M., de Jong, G., Tavasszy, L., Van Meijeren, J., Davydenko, I., Benjamins, M., Groot, N., Miete, O., Van den Berg, M., 2018. A multimodal transport chain choice model for container transport. Transp. Res. Procedia 31, 99–107.

de Miranda Pinto, J.T., Mistage, O., Bilotta, P., Helmers, E., 2018. Road-rail intermodal freight transport as a strategy for climate change mitigation. Environ. Dev. 25, 100–110.

Elbert, R., Rentschler, J., 2022. Freight on urban public transportation: A systematic literature review. Res. Transp. Bus. Manag. 45, 100679.

Fatnassi, E., Chaouachi, J., Klibi, W., 2015. Planning and operating a shared goods and passengers on-demand rapid transit system for sustainable city-logistics. Transp. Res. Part B: Methodol. 81, 440–460.

Feng, W., Tanimoto, K., Chosokabe, M., 2023. Feasibility analysis of freight-passenger integration using taxis in rural areas by a mixed-integer programming model. Soc.-Econ. Plan. Sci. 87, 101539.

Fernandes, D.R., Rocha, C., Aloise, D., Ribeiro, G.M., Santos, E.M., Silva, A., 2014. A simple and effective genetic algorithm for the two-stage capacitated facility location problem. Comput. Ind. Eng. 75, 200–208.

Gao, J., Li, S., 2024. Synergizing shared micromobility and public transit towards an equitable multimodal transportation network. Transp. Res. Part A: Policy Pr. 189, 104225.

Gao, J., Zhen, L., Wang, S., 2023. Multi-trucks-and-drones cooperative pickup and delivery problem. Transp. Res. Part C: Emerg. Technol. 157, 104407.

Gendron, B., Khuong, P.-V., Semet, F., 2016. A Lagrangian-based branch-and-bound algorithm for the two-level uncapacitated facility location problem with single-assignment constraints. Transp. Sci. 50 (4), 1286–1299.

Hammami, F., 2020. The impact of optimizing delivery areas on urban traffic congestion. Res. Transp. Bus. Manag. 37, 100569.

He, D., Guan, W., 2023. Promoting service quality with incentive contracts in rural bus integrated passenger-freight service. Transp. Res. Part A: Policy Pr. 175, 103781.

He, X., Zhen, L., 2025. Column-and-row generation based exact algorithm for relay-based on-demand delivery systems. Transp. Res. Part B: Methodol. 196, 103223.

Holguín-Veras, J., Wang, Q., Xu, N., Ozbay, K., Cetin, M., Polimeni, J., 2006. The impacts of time of day pricing on the behavior of freight carriers in a congested urban area: Implications to road pricing. Transp. Res. Part A: Policy Pr. 40 (9), 744–766.

House of Switzerland, 2021. PostBus: A Swiss icon.

Huang, M., Smilowitz, K.R., Balcik, B., 2013. A continuous approximation approach for assessment routing in disaster relief. Transp. Res. Part B: Methodol. 50, 20–41.

Huang, W., Zhang, Y., Shuai, B., Xu, M., Xiao, W., Zhang, R., Xu, Y., 2019. China railway industry reform evolution approach: Based on the vertical separation model. Transp. Res. Part A: Policy Pr. 130, 546–556.

Janjevic, M., Merchán, D., Winkenbach, M., 2021. Designing multi-tier, multi-service-level, and multi-modal last-mile distribution networks for omni-channel operations. European J. Oper. Res. 294 (3), 1059–1077.

Ji, Y., Zheng, Y., Zhao, J., Shen, Y., Du, Y., 2020. A multimodal passenger-and-package sharing network for urban logistics. J. Adv. Transp. 2020, 1–16.

Lack, D.A., Cappa, C.D., Langridge, J., Bahreini, R., Buffaloe, G., Brock, C., Cerully, K., Coffman, D., Hayden, K., Holloway, J., et al., 2011. Impact of fuel quality regulation and speed reductions on shipping emissions: implications for climate and air quality. Environ. Sci. Technol. 45 (20), 9052–9060.

Li, A., Hansen, M., Zou, B., 2023. Uav scheduling strategies in multi-modal last-mile urban parcel delivery. In: Fifteenth USA/Europe Air Traffic Management Research and Development Seminar. Atm2023.

Li, B., Krushinsky, D., Reijers, H.A., Van Woensel, T., 2014. The share-a-ride problem: People and parcels sharing taxis. European J. Oper. Res. 238 (1), 31–40.

Li, X., Ouyang, Y., 2010. A continuum approximation approach to reliable facility location design under correlated probabilistic disruptions. Transp. Res. Part B: Methodol. 44 (4), 535–548.

Masson, R., Trentini, A., Lehuédé, F., Malhéné, N., Péton, O., Tlahig, H., 2017. Optimization of a city logistics transportation system with mixed passengers and goods. EURO J. Transp. Logist. 6 (1), 81–109.

Merchán, D., Winkenbach, M., 2019. An empirical validation and data-driven extension of continuum approximation approaches for urban route distances. Networks 73 (4), 418–433.

Montagné, R., Torres Sanchez, D., 2020. VRPy. https://github.com/Kuifje02/vrpy.

Moshref-Javadi, M., Hemmati, A., Winkenbach, M., 2020. A truck and drones model for last-mile delivery: A mathematical model and heuristic approach. Appl. Math. Model. 80, 290–318.

Mousavi, K., Bodur, M., Roorda, M.J., 2022. Stochastic last-mile delivery with crowd-shipping and mobile depots. Transp. Sci. 56 (3), 612–630.

Öncan, T., 2007. A survey of the generalized assignment problem and its applications. INFOR Inf. Syst. Oper. Res. 45 (3), 123–141.

Osorio-Mora, A., Núñez Cerda, F., Gatica, G., Linfati, R., 2020. Multimodal capacitated hub location problems with multi-commodities: An application in freight transport. J. Adv. Transp. 2020, 1–9.

Peeters, P., Tensen, D., Sleurink, R., Peeters, P., Tensen, D., Sleurink, R., 1997. Airships for passenger and freight transport in The Netherlands. In: 12th Lighter-than-Air Systems Technology Conference. p. 1424.

Roig-Costa, O., Marquet, O., Arranz-López, A., Miralles-Guasch, C., Van Acker, V., 2024. Understanding multimodal mobility patterns of micromobility users in urban environments: insights from Barcelona. Transportation 1–29.

Stokkink, P., Cordeau, J.-F., Geroliminis, N., 2024. A column and row generation approach to the crowd-shipping problem with transfers. Omega 103134.

Stokkink, P., Geroliminis, N., 2023. A continuum approximation approach to the depot location problem in a crowd-shipping system. Transp. Res. Part E: Logist. Transp. Rev. 176, 103207.

US Department of Homeland Security, 2023. Air cargo program.

Van Duin, R., Wiegmans, B., Tavasszy, L., Hendriks, B., He, Y., 2019. Evaluating new participative city logistics concepts: The case of cargo hitching. Transp. Res. Procedia 39, 565–575.

Wang, X., Ouyang, Y., 2013. A continuum approximation approach to competitive facility location design under facility disruption risks. Transp. Res. Part B: Methodol. 50, 90–103.

Woo, S.-H., Kim, S.-N., Kwak, D.-W., Pettit, S., Beresford, A., 2018. Multimodal route choice in maritime transportation: the case of Korean auto-parts exporters. Marit. Policy Manag. 45 (1), 19–33.

Wosiyana, M., 2005. The use of light delivery vehicles (ldv's) for the conveyance of people. SATC 2005.

Yatskiv, I., Budilovich, E., 2017. A comprehensive analysis of the planned multimodal public transportation HUB. Transp. Res. Procedia 24, 50–57.

Yin, Z., Rybarczyk, G., Zheng, A., Su, L., Sun, B., Yan, X., 2024. Shared micromobility as a first-and last-mile transit solution? Spatiotemporal insights from a novel dataset. J. Transp. Geogr. 114, 103778.

Yu, S., Jiang, Y., 2021. Network design and delivery scheme optimisation under integrated air-rail freight transportation. Int. J. Logist. Res. Appl. 1–17.

Zhang, Q., Jiang, X., Tong, D., Davis, S.J., Zhao, H., Geng, G., Feng, T., Zheng, B., Lu, Z., Streets, D.G., et al., 2017. Transboundary health impacts of transported global air pollution and international trade. Nature 543 (7647), 705–709.

Zhao, L., Li, H., Li, M., Sun, Y., Hu, Q., Mao, S., Li, J., Xue, J., 2018. Location selection of intra-city distribution hubs in the metro-integrated logistics system. Tunn. Undergr. Space Technol. 80, 246–256.

Zhu-jun, L., Yun, B., Yao, C., 2022. Integrated optimization of train service planning and shipment allocation for airport expresses under mixed passenger and freight transportation. J. Transp. Syst. Eng. Inf. Technol. 22 (5), 154.