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An Analysis on Shared Charging Hubs for Eco-Friendly Vehicles in Urban Logistics

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Abstract: Using electric vehicles in urban freight distribution generates opportunities (e.g., zero emissions in urban areas) and challenges (e.g., range of electric vehicles). Their adoption implies that operators need to change the approach to freight distribution. As an example, the reduced range of an electric vehicle substantially reduces the kilometers traveled before a recharging stop. This implies a redefinition of routes, fleet size, personnel, and vehicle charging management. This research investigates the changes that operators must make when using shared charging hubs. Given the interest of logistic companies in reducing both their fixed and operating costs, the use of shared recharging hubs for electric vans and trucks constitutes a relevant applied research theme. This paper explores the pre-feasibility of some possible concrete scenarios. In more detail, the investigated scenarios involve charging hubs located in three different settings: at the depot, based on client distribution, and scattered across the area. The aim is to assess the performance of each scenario under the assumption that the position of the charging hub reflects the choices of operators on the usage of electric freight vehicles. The indicators considered for comparison are the delivery service time, the charging time and the number of routes.

Keywords: Electric freight vehicles, charging hubs, city logistics, urban freight, vehicle routing problem

1. Introduction

Urban freight represents 15-20% of vehicular traffic [1,2], which negatively contributes to greenhouse gases (GHG) emissions. Although the new generation of eco-friendly vehicles (e.g., electric or hybrid vehicles) offers the opportunity to improve the environmental performance [3,4], diesel fueled vehicles remain the preferred option for companies. In fact, in the first three quarters of 2024, 84.6% of purchased were diesel fueled, while the electric and hybrid freight vehicles account for only 5.7% and 2.0%, respectively [5]. Furthermore, scaling up the use of these vehicles requires a system perspective on the availability of renewable energy and alternative fuels (e.g., electricity and hydrogen, [6]), grid capacity, and charging/refueling infrastructure.

The European Commission clearly states that ensuring a smart, sustainable and resilient transport system against future crises should be a key goal of European transport policy [7]. However, there are some barriers to overcome (as shown in section 3). Among them, one of the key factors is the reduced range and the long recharging time (with respect to the available technology) of electric vehicles (EVs) compared to vehicles with internal combustion engines. Furthermore, for a carrier, it may not be convenient to have its own charging area. This can occur, for example, when the volume of deliveries handled does not justify the expense or when their hubs are far from the delivery areas, resulting in additional travels that reduce the energy available for the real delivery operations. One possible solution could be a third-party managed charging hubs (located barycentrically) where different carriers could charge the vehicles. This allows them to benefit both from improved operations and reduced installation costs.

The implementation of charging hubs and related charging strategies [8] could be a significant lever to help operators renovate their fleet faster, bringing benefits to the city through the reduction of emissions. Furthermore, the possibility of recharging vehicles multiple times during delivery tours reduces the number of vehicles requested for the service [9]. To analyze this aspect, this paper explores some scenarios related to charging hubs, considering different situations, and assuming that the position of charging hub reflects the choices of operators on the usage of electric freight vehicles. In fact, it is assumed that the fleet consists only of electric vehicles, the management of which varies depending on the scenario considered. The basic idea is that vehicles start at the carrier's depot for delivery service and, when necessary, go to the hub to recharge in a place that allows them to reduce time loss. Different situations can arise depending on the number of deliveries, the vehicle range, and the recharging strategy (Fig. 1), for example:

1. the vehicle starts from the carrier's hub, performs the deliveries, and goes back to the depot; there is no need to recharge given the service to perform;

2. the vehicle starts its travel, makes some deliveries, stops at the hub for recharging, and then continues delivering; however, it has not finished all its planned deliveries yet and needs to recharge before continuing the service.

Note that these scenarios are truly effective when the energy needed to recharge batteries is produced from renewable sources. When this is not the case, the problem of polluting emissions shifts from the urban center to the energy production area.

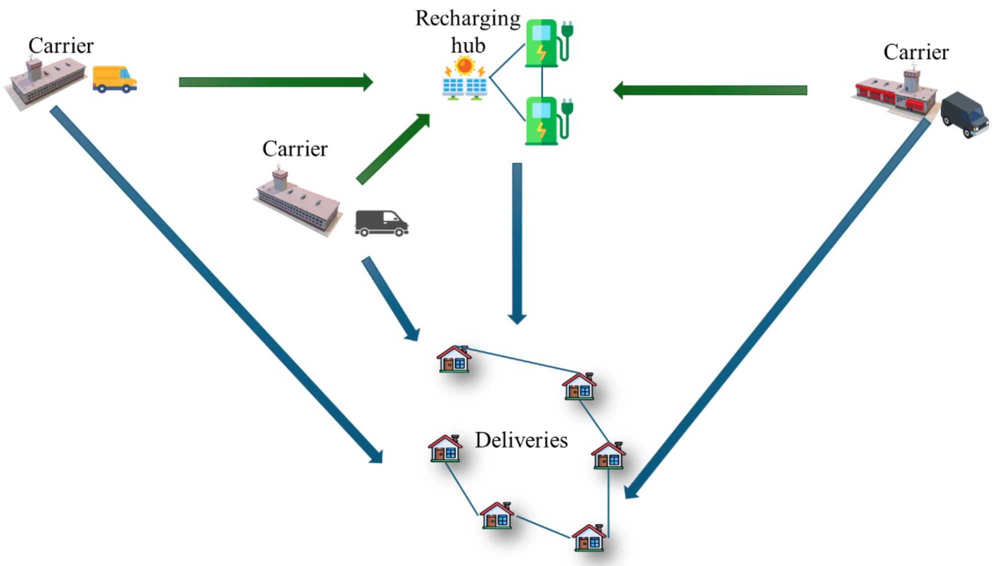

Fig. 1 Shared charging stations. Source: authors

2. Literature Review

Adopting alternative-fueled freight vehicles for urban deliveries is an effective policy in reducing pollution in urban areas. However, replacing conventional freight vehicles (e.g., diesel fueled vehicles) with electric ones can encounter barriers related to technology and the attitudes of the transport operators. As an example, the transport operators consider the probability of waiting in a queue to recharge the vehicle and the need to have charging stations inside the warehouse as some of the barriers when converting the fleet. Other barriers are based on the characteristics of an electric vehicle, such as payload and range, which can be less than that of a conventional vehicle [10,11].

Some works in literature have explored the willingness to adopt an alternative fueled vehicle. Gillström [12] grouped barriers to urban freight fleets into four clusters: (i) practical and technological, (ii) financial, (iii) institutional, social and (iv) cultural, and highlights that the importance of barriers due to the characteristics of the transport operator. The conclusion was that the transition could be advantaged by collaboration among operators (e.g., different collaborative operators could schedule the deliveries related to the availability of recharging service, reducing the queue time at recharging hubs). Saxena and Yadav [13] examined barriers to electrification in India by classifying the factors affecting the adoption of electric vehicles. This study concluded that vehicle range, charging time, and vehicle purchase costs are key factors influencing the choice of transport companies. Melander et al. [14] conducted a study in Stockholm to understand the drivers and barriers to adopt electric freight vehicles. They summarized barriers into internal (referring to the characteristics of the transport operator), external (referring to market), or government policies (referring to regulations, subsidies, taxes). Similarly, İmre et al. [15] classified the factors (barriers and drivers) influencing the adoption of such vehicles in Turkey. Barriers included driving range, inadequate charging infrastructure, and high vehicle / battery costs. The drivers included expected low operational and maintenance costs, improved reputation of the transport operator, and the expected decline in battery prices.

Quak et al. [16] identified some drivers affecting the adoption of electric freight vehicles by transport operators, such as the attitude of the carriers, the technological features (performance and reliability of the vehicles), the promotion policies (e.g., no parking fees, using bus lanes, free access to restricted zones), the financial incentives (generally, the purchase cost of an electric vehicle is greater than the cost of a similar traditional vehicle) and the logistics organization (new organization dictated by the switch from traditional vehicle to electric vehicles). Schiffer et al. [17] evaluated the viability of adopting electric freight vehicles considering investment decisions, transport operators' requirements, and technical limitations. They generated a set of scenarios that forecast future vehicles, charging stations and battery characteristics. Focusing on the short food supply chain, Galati et al. [18] pointed out that in this particular sector of analysis, electric freight vehicles (but with a range greater than 120 kilometers and a payload greater than 100 kilograms) were suitable for food transportation. Other aspects that can push operators to adopt such a type of vehicle are the external spaces of farms for installing charging points, the cost of electricity lower than that of other fuels, and the possibility of using self-produced energy (from wind or sun).

Martínez et al. [19] discussed the impacts deriving from the electrification of the postal fleet considering as a case study of Madrid City and taking into account the (new) routes used by electric vehicles (which can be different from the route of traditional vehicles) and the impact of such vehicles on the electrical network. The main finding is that the use of decentralized postal hubs reduces energy consumption (and consequently the impact on the electric grid). Utomo et al. [20] analyzed how the grocery delivery service is affected by different charging strategies, and an agent-based simulation approach that incorporates the use of electric vehicles in the model. The analysis focused on grocery delivery, and the aim was to maximize the reliability of delivering the parcels (this aspect of the problem depends on the charging time). Wang et al. [21] proposed some hypothetical scenarios where charging stations to reduce the total management costs and number of vehicles were considered.

3. Methodology

From previous sections, it has emerged that the transition of freight vehicles from conventional vehicles (internal combustion engine, ICE) to electric is possible but constrained due to the different characteristics of the vehicles. Therefore, it is necessary to modify some aspects of freight distribution to accelerate this transition. In particular, a detailed design of the routes of the vehicles is requested to make the most of the vehicle range and load capacity. This design procedure includes the strategy to charge (even partially) the vehicle during service. Different scenarios can be considered in relation to the policy adopted for recharging operations, and these scenarios include: (i) the use of their own recharging infrastructures and (ii) the use of the charging infrastructure which is shared with other operators. In terms of route optimization, this can be translated into the position of charging hubs relative to the headquarters of the logistics company.

Starting from these considerations, the proposed problem is a multi-depot electric vehicle routing problem with charging stations, where the position of the charging stations depends on the scenario considered. Additionally, a fleet of homogeneous vehicles is considered, both in terms of load capacity and range. The aim is to minimize the total time spent on the delivery service, considering three components: travel time, charging time and operation time. Energy consumption is evaluated in terms of vehicle range, i.e. when the vehicle travels a distance equal to a rate of the range the recharge is required.

In formulating the problem, it is considered an oriented graph $G(N, L)$ where N is the set of nodes (it contains depots, clients, and charging stations) and L is the set of links. The problem is formulated as a vehicle routing problem (e.g., see [21]), with the aim to optimize the travel time spent for service operations and battery charging as follows, equation (1):

$$\text{Minimize } \left(\sum_{v \in V} \sum_{i \in B} \sum_{j \in B} \left(t_{ijv} + t_j\right) \cdot x_{ijv} + \sum_{v \in V} \sum_{s \in C} \tau_{vs} \cdot y_{sv}\right), \quad (1)$$

s.t.

$$\sum_{v \in V} \sum_{i \in B \cup D} x_{ijv} = 1 \qquad \forall j \in B, \quad (2)$$

$$\sum_{i \in A} x_{ijv} = \sum_{i \in A} x_{jiv} \quad i \neq j;\ \forall j \in B; \forall v \in V, \quad (3)$$

$$d_{ij} \cdot x_{ijv} \leq R_v \ \ \forall v \in V; \forall i, j \in A, \quad (4)$$

$$\sum_{i \in B} \sum_{j \in B} q_i \cdot x_{ijv} \leq w_v \ \ \forall v \in V, \quad (5)$$

$$\left(\sum_{i \in A} \sum_{j \in A} \left(t_{ijv} + t_j\right) \cdot x_{ijv} + \sum_{s \in C} \tau_{vs} \cdot y_{sv}\right) \leq TT_{max} \quad \forall v \in V, \quad (6)$$

$$LE_{ij} = E_v \ \ \forall i \in D \cup C;\ \forall v \in V, \quad (7)$$

$$x_{ijv} \in [0,1];\ y_{vs} \in [0,1], \quad (8)$$

where: A is the set of all nodes (clients, depots and charging stations); B is the set of clients; C is the set of charging stations; D is the set of depots; E_v is the battery capacity of vehicle v [kWh]; R_v is the range of the vehicle v [km]; RE_{iv} is the residual energy of vehicle v when it reaches node i [kWh]; LE_{iv} is the energy of vehicle v when leaves from node i [kWh]; P_s is the power of the charging station s [kW]; t_{ijv} is the travel time from i to j [min]; t_j is the operation time at j [min]; τ_{vs} is the recharging time at the charging station s [min]; d_{ij} is the distance between two elements of set A [km]; w_v is the vehicle load capacity [kg]; TT_{max} is the maximum allowed value for the travel time [min], x_{ijv} and y_{sv} are the problem variables.

A client/customer can be reached only once by a vehicle (starting from a depot or another client), this is ensured by constraint 2. Constraint 3 ensures flow conservation, while constraint 4 ensures that the travel distance between two points in A is less than the vehicle range. Constraint 5 ensures that the quantity to be delivered does not exceed the vehicle load capacity, and Constraint 6 sets a limit on the maximum duration of working time of a vehicle. Constraint 7 ensures that when a vehicle leaves a depot or a charging station, it is fully charged. Finally, constraint 8 defines the domains of the variables.

4. Application Settings

In order to test the problem formulated in the previous section, a test case with a real dimension problem is proposed, having the inner ring of Rome (Italy) as the study area. In detail, a set of 100 clients has to be served by 3 operators (that is, 3 different depots). The position and characteristics of the clients are randomly generated. Since clients and depots are identified by geographical coordinates, it is possible to calculate the shortest paths (in terms of travel time and distance) between them. This is part of the input needed to solve the problem. The scenarios considered are the following:

- *Scenario 0* (Fig. 2), vehicle charging is allowed only at their own depot, the vehicles from one depot cannot recharge at another depot;
- *Scenario 1* (Fig. 3), charging stations are placed barycentrically with respect to the users to be served; this represents the case where the operators plan the position of the charging infrastructure;
- *Scenario 2* (Fig. 4), charging stations are randomly scattered in the area, similar to public charging stations.

In all scenarios, it is assumed that the vehicles are homogeneous with respect to vehicle range and load capacity, and that they start from the depot fully charged. A further assumption is that vehicles are recharged when the energy level is less than 20% of the battery capacity (the same thing is generally done for cars, see [22]). The characteristics of the charging stations are the same in each scenario.

The scenarios are simulated by formulating the problem as in equation (1), and the results are compared to evaluate the pros and cons of each one.

A genetic algorithm is used to solve the problem; the parameters remain the same across the three scenarios, with the only change being the location of the charging stations.

5. Discussion

Urban freight distribution, although fundamental for economic development, generates some issues that should be solved to improve the livability of the city [23,24]. New technologies, such as vehicles that do not produce local pollution emissions during service, represent a factor for developing new sustainable strategies for urban freight distribution. This implies that this sector is under transformation, with a transition from vehicles with internal combustion engines (traditional vehicles) to electric vehicles. However, one of the challenges for their real implementation is the reduced range of these vehicles, which may need to be recharged while in service. In addition, charging takes longer than refueling a traditional vehicle. As a consequence, the vehicle route needs to be optimized, also considering the position and management of the charging stations/hubs, to make the best use of battery energy.

From these premises, this research investigated the use of shared charging hubs by different logistics operators. In particular, three scenarios have been considered assuming different positions for the charging hubs, and the routes are optimized by providing charging even during service. In the base scenario (scenario *0*), it is assumed that the charging hub is located inside the depot of the logistic operator, and then, in this scenario, the hubs are not shared. In Scenarios 1 and 2, the hubs are shared among different operators, what changes is the position of the hubs with respect to the depots: in particular, they are barycentric in scenario 1 and randomly positioned in scenario 2. For each scenario, the routes are optimized obtaining the results summarized in Table 1, considering some key performance indicators for each scenario. Note that monetary costs (e.g., for charging or vehicle maintenance [25]) are not considered at this stage of the research.

Scenario 0, with charging infrastructures located within the private depot, is the scenario that requires the highest number of routes (Fig. 2). The other two scenarios (Fig. 3 and Fig. 4), although having a longer charging time, have a shorter total service time than Scenario 0 (since the location of the charging stations close to the customers/clients guarantees a shorter average time to reach the charging hub).

More in detail, the best result, in terms of total time, comes from Scenario 1, in fact, a reduction of 2.32% with respect to Scenario 0 and of 1.20% with respect to Scenario 2 is remarked. In terms of travel distance, the best performances are those of Scenario 2 (a reduction of 5.67% with respect to Scenario 0 and a reduction of 2.09% with respect to Scenario 1).

Table 1 Some key performance indicators that resume the scenarios studied. Source: authors.

Scenario	Depot id	Number of routes	Charging time [min]	Total time [min]	Travelled distance [km]
0	5	4	70.13	635.64	268.27
	33	2	0.00	268.75	122.52
	98	3	30.10	543.02	254.85
		9	***100.23***	***1447.41***	***645.64***
1	5	3	71.00	639.76	268.50
	33	2	0.00	268.75	122.52
	98	3	43.62	505.37	230.96
		8	***114.62***	***1413.88***	***621.98***
2	5	3	71.63	603.93	247.22
	33	2	0.00	268.75	122.52
	98	3	62.87	558.39	239.26
		8	***134.50***	***1431.07***	***609.00***

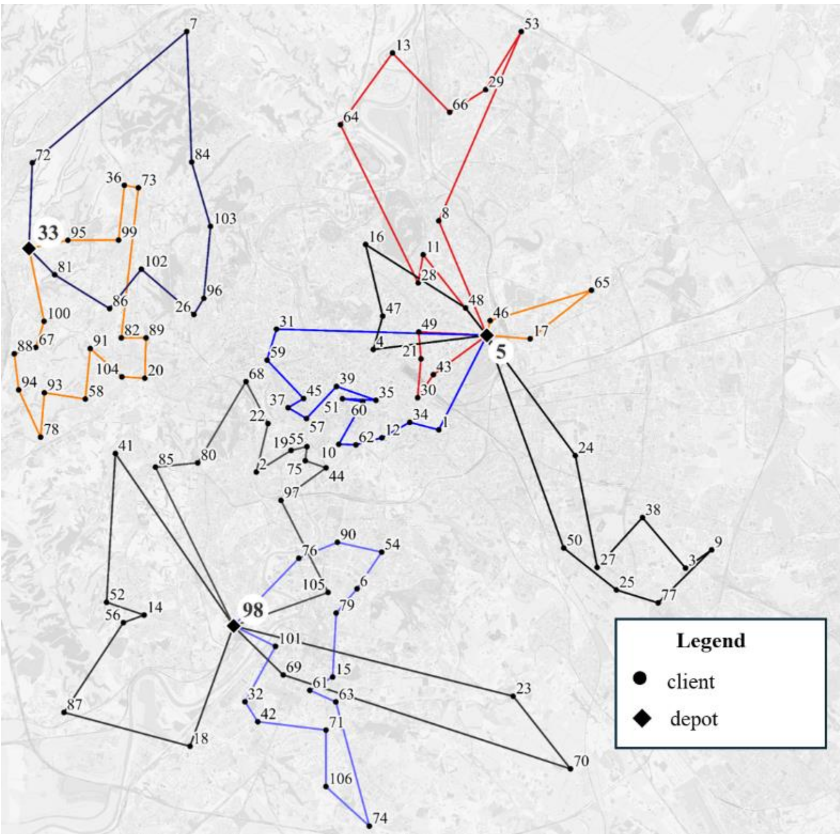

Fig. 2 Scenario 0 – Charging hub in the depot: a possible solution. Source: authors

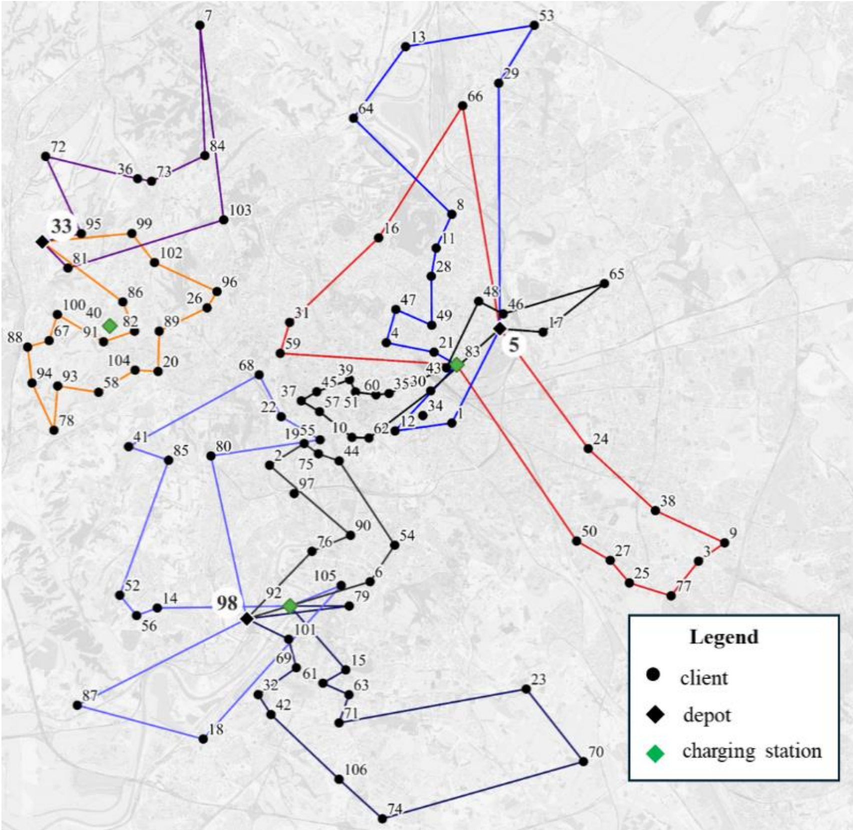

Fig. 3 Scenario 1 - Barycentric charging hub: a possible solution. Source: authors

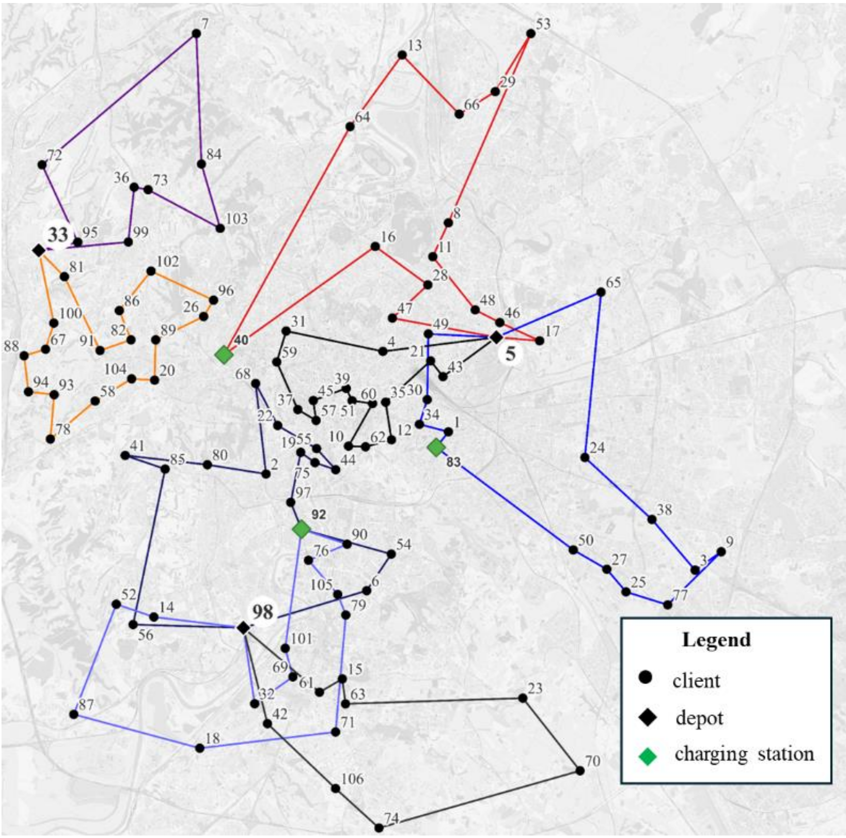

Fig. 4 Scenario 2 **-** Charging hub at random position: a possible solution. Source: authors

6. Conclusions

The transition to eco-friendly vehicles in urban logistics generates opportunities and challenges that were not encountered when only internal combustion engine vehicles were used. However, the reduction of pollutant emissions during freight distribution results in a reduced travel distance, leading to the need to swap or recharge the battery during the service. Battery swapping would require standard batteries and operators to perform the operation. However, recharging can be done independently, and many couriers are geared up to use this solution. This leads to a new approach to freight distribution planning, where operators must establish the strategy to use for the battery charging phase, particularly regarding the ownership and the location of the charging hubs. This paper aims to address this question by defining some hypothetical scenarios with different charging hub locations. The position of the charging stations serves as a proxy of the strategy adopted: (i) if they are inside the depot (Scenario 0), it is assumed that the operators prefer to own the hub, (ii) if they are located based on the user's position (Scenario 1), it is considered a shared strategy among operators, and (iii) if they are scattered randomly on the area (Scenario 2), it is assumed that they are owned by a third party.

From the specific case analyzed in this paper, it appears that the scenarios where charging hubs are managed by a third party (Scenario 1 and Scenario 2) offer the best performance in terms of travel time. In fact, when comparing Scenario 0 with Scenario 1 and 2, a reduction in travel time of 2.5% and 1.6%, respectively, was observed.

However, further analysis is needed regarding the willingness of operators to use charging hubs and the improvement of the proposed model by introducing monetary costs (e.g., electricity price, charging hub allocation costs), queue simulations at charging hubs (also considering the possibility of booking the service) and a more detailed simulation of the battery charging and discharging process. Furthermore, a combination of the proposed scenarios could be considered, also extending the study area to evaluate how to position the charging stations to allow optimal freight distribution throughout the city.

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