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A modelling framework to support the development of last-mile urban freight distribution systems based on the use of cargo bikes

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Abstract

Nowadays there is a growing interest in cargo bikes to mitigate the detrimental effects of urban freight transport, since the last-mile segment of freight delivery process is being challenged to reduce the number of vehicles, the distance travelled and the environmental impacts. This paper presents a modelling framework that, starting from the key reference units (freight demand, deliveries, and vehicles) and defining the relationship among stakeholders and choice dimensions, can support the implementation of freight distribution systems based on cargo bikes. In detail, the work follows a general approach and is focused on the estimation of the share of demand that can be satisfied by cargo bikes, freight flows in terms of number of deliveries and trips, obtained by assigning freight demand to the transport network. The model has been applied to the test case of the city of Ravenna by implementing several scenarios.

Keywords: Cargo Bikes, Last-Mile Freight Distribution, Urban Freight Transport.

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1. Introduction

Nowadays, more than half of the population lives in urban areas and this percentage is going to increase in the next years - 66% by 2050 as estimated by the (United Nations, Department of economic and social affairs, 2018) - which in turn is expected to lead to a growing freight demand in urban areas. In EU, a 42% increase in passenger transport and a 60% increase in freight transport by the year 2050 has been estimated (EC - European Commission, 2021). In addition to population growth, the rise of e-commerce and the demand for reduced delivery times are strongly affecting urban logistics.

While the distribution of goods is of paramount importance for a country and its citizens, it also generates negative consequences such as traffic congestion, accidents, climate change effects, local air pollution, and safety concerns (Ranieri, et al., 2018). The ratio

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emissions/ton/km is remarkably high for road transport, which is responsible for more than 60% of freight transport emissions (International Transport Forum, 2019) although it moves only a quarter of total volumes. Empirical studies show that urban freight transport represents 6–18% of the total urban transport, 14% of all the kilometres covered by vehicles in urban area, 19% of energy and 21% of CO_2 emissions of all urban transport (Russo & Comi, 2016). Efficient solutions to address this issue should achieve a balance between urban logistics systems and sustainable levels of externalities.

Urban freight distribution processes can be represented by the functional scheme below (Fig. 1). The flow of freight, originating from the producer, is delivered to the final receivers using different modes and travelling through several logistic nodes where transhipment and handling operations are carried out. The last leg of the chain is delivery to the final recipient, carried out in most cases from an urban consolidation centre (UCC) and using smaller and more environmentally efficient transport modes, by applying and implementing city logistics measures aimed at reducing the environmental impacts of freight transport, especially in vulnerable urban areas.

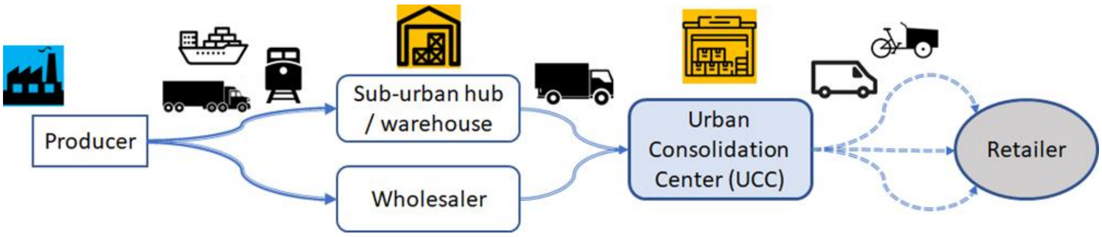

Figure 1: Urban freight distribution structure.

As showed in Fig. 1 and deepened in the next sections, the use of Urban Consolidation Centres, located in proximity to the areas to be served, can improve the efficiency of freight distribution by optimizing the load factor of vehicles, and by shortening the kilometres travelled, supporting the use of low/zero-impact vehicles such as cargo bikes or electric vans. Within this context, the aim of this paper is to present a methodological framework that, starting from the characteristics of the urban areas to be served, the types and quantities of goods to be delivered, and the adopted restocking services, can support the design and implementation of urban freight delivery systems based on the use of cargo bikes. More in detail, since the implementation of city logistics measures could be based on planning and design tools able to simulate the relevant effects of a specified scenario (*what-if* approach) and transport systems models are relevant part of such tools, the proposed framework is based on a sequential demand modelling system able to represent the actions undertaken by the stakeholders involved in urban freight transport, considering all the relevant dimensions (quantity and type of freight, frequency of deliveries, type of restocking service and transport mode). The output of the model represents an estimation of the amount of demand that can be delivered in the urban area using cargo bikes, taking into account the constraints introduced on the capacities and autonomies of such vehicles. The estimated demand is then used to design the service in terms of number of deliveries and resources needed to perform them.

The paper is organized as follows. After a literature review (section 2), in section 3 the methodological framework is presented and described and its application to the case study of the city of Ravenna (Italy) is shown in section 4. The results are finally discussed in section 5.

2. Literature review

Last-mile delivery is the final part of the logistic chain usually carried out on road, involved in delivering freight to final recipients, like private citizens or commercial activities. It is the most impacting and the least efficient stage of the logistic chain since it is usually characterized by low average speeds, low load factors of vehicles, and frequent start and stops, typical of congested road network environment, leading to a high cost/km ratio – up to 28% of total delivery cost (Allen, et al., 2018) – and to remarkable emission of pollutants. These issues lead not only to significant environmental impacts, but also to a contribution to worsening quality of life in urban areas and increased congestion. Several empirical investigations have pointed out that last mile logistics account up to 20% of energy consumption and up to more than 25% of emissions (Figliozzi & Tipagornwong, 2017), therefore, to improve urban liveability and lower negative externalities, city logistics measures have been studied and implemented (Taniguchi, et al., 2001). Among these: infrastructural measures (i.e., urban consolidation centres) (Narayanan & Antoniou, 2022), vehicle technology improvements (electric and connected/autonomous vehicles) (Asghari & Mirzapour, 2021), and regulations (i.e., limited traffic zones, LTZ; low emission zones, LEZ; pedestrian zones). Limited traffic zones (LTZ) or restricted traffic zones - areas in city centres where access for motorized vehicles is restricted to limited time slots - are widely applied measures. For example, limitations can be imposed during some hours of the day, during some days/weeks/months of the year or on working days or holydays (Holman, et al., 2015). Among the infrastructural measures, UCCs act as warehouses, since goods are delivered to them by trucks or motorized duty vehicles and then smaller vehicles with zero or low local emission (such as cargo bikes) are used to perform the last-mile delivery (Ehmke & Mattfeld, 2011).

Some studies suggest the potential of cargo bikes to improve the environmental efficiency of transportation systems (Llorca & Moeckel, 2021) for urban freight delivery, by focusing on operational, environmental, and potential road congestion reduction (Verlinde, et al., 2014). There are different types of cargo bikes depending on the number of wheels, their size, their loading capacity, whether they're electrical-powered or not, the position of their cargo box etc (Becker & Rudolf, 2018). Among the two-wheeled cargo bikes we can find the longtails, with the cargo placed behind the rider, and the frontlanders, which have a box placed between the front wheel and the driver. Both of them can carry up to 80/100 kg of goods, while the most advanced electric pedal-assisted quadricycles can transport weights up to 500kg (Vasiutina, et al., 2021). In the literature the results of some case studies are reported, for example Browne et al. found out that in the city of London the use of e-cargo cycles together with UCCs could lead to a reduction of 20% total distance travelled and 54% decrease in CO_2 equivalent emissions in comparison with traditional motorized vehicles (Browne, et al., 2011). However, it is necessary to point out that, despite the potential benefits, there are some limitations and critical issues in the use of cargo bikes. As first, riders performing deliveries using cargo bikes are exposed to accident risks, poor weather conditions and pollutants, as some studies in the literature have explored (Zhang & Wu, 2013). Moreover, cargo bikes may run through pedestrian areas, meaning that vulnerable road users can be exposed to additional risks (Hess & Schubert, 2019). In addition, one of the most relevant issues of electrical-powered vehicles, and in particular cargo bikes, is the low range in terms of kilometres travelled with a single battery-charge (Wang, et al., 2017). This issue is partially overcome by implementing distribution schemes aimed at reducing the distance travelled (Allen, et al., 2012); however, the load capacity constraints and low autonomy of these vehicles are a limitation to their deployment.

3. Methodological approach

Freight flows in urban areas are the result of interacting behaviours of commodity consumers and commodity suppliers/shippers/retailers (Russo & Comi, 2011). This study focuses on the segment of freight restocking (see Fig. 1).

The proposed modelling framework (Fig. 2), given a study area divided into zones within which are located the commercial activities, recipients of goods shipments, consists of three steps, to estimate:

1) the quantity of freight attracted by each zone "*d*" located in the study area, for freight category "*f*", and type of restocking service "*s*", expressed by:

   $$Q_d^f[s] = Q_d \cdot p[s/d] \tag{1}$$

   where Q_d is the total amount freight attracted by zone "*d*" and $p[s/d]$ is the probability of using transport restocking service s. The restocking service type "*s*" can be on own account or operated by a third-party logistic service provider.
2) the quantity of freight attracted by each zone and delivered by using the transport mode "*m*" (in this work "*m*" is the cargo bike transport mode) is calculated as follows:

   $$Q_d^{fm}[s,\tau] = Q_d^f[s] \cdot p[\tau/sd] \cdot p[m/\tau sd] \tag{2}$$

   where $p[\tau/sd]$ is the probability of performing the deliveries in the period "τ", and $p[m/\tau sd]$ is the probability of using the transport mode "*m*".

   The quantity of freight $Q_d^{fm}[s,\tau]$ is then stored in one or more Urban Consolidation Centres (UCCs) (acting as the origin node "*o*" of the last leg of urban logistic chain) and finally is delivered to the retailers located in each zone "*d*" of the study area during the reference period of analysis by using cargo bikes.
3) the number of deliveries $ND_{od}^{fm}[s,\tau]$ to every zone "*d*" within the study area from UCC "*o*", performed with restocking service "*s*", for freight type "*f*", during the period "τ", by using transport mode "*m*" (in this case cargo bikes) with load capacity "*v*" (in terms of volume and/or load) and average shipment size $q(m|v)$:

   $$ND_{od}^{fm}[s,\tau] = \frac{Q_{od}^{fm}[s,\tau]}{q(m|v)} \tag{3}$$

The outputs of sub-models 1 and 2 (quantity and modal dimensions) can be estimated either by adopting a descriptive approach, which establish empirical relations between freight demand and several economic and transportation system variables obtained with direct estimation through surveys and data collection campaigns (Ibeas, et al., 2012) or by adopting behavioural models, which are developed considering explicit assumptions regarding decision-makers involved in the choice processes (Nuzzolo & Comi, 2014).

Moreover, the amount of freight Q_d^{fm} that can realistically be shipped using vehicles that have peculiar characteristics such as cargo bikes has to be carefully evaluated. Indeed, the shipment size depends on the capacity and load factor of vehicles in terms of deliverable volumes and maximum allowed weight: as an example, freight consolidated in pallets (or packaging too bulky to be loaded onto cargo bikes) and fragile items or perishable goods should be excluded.

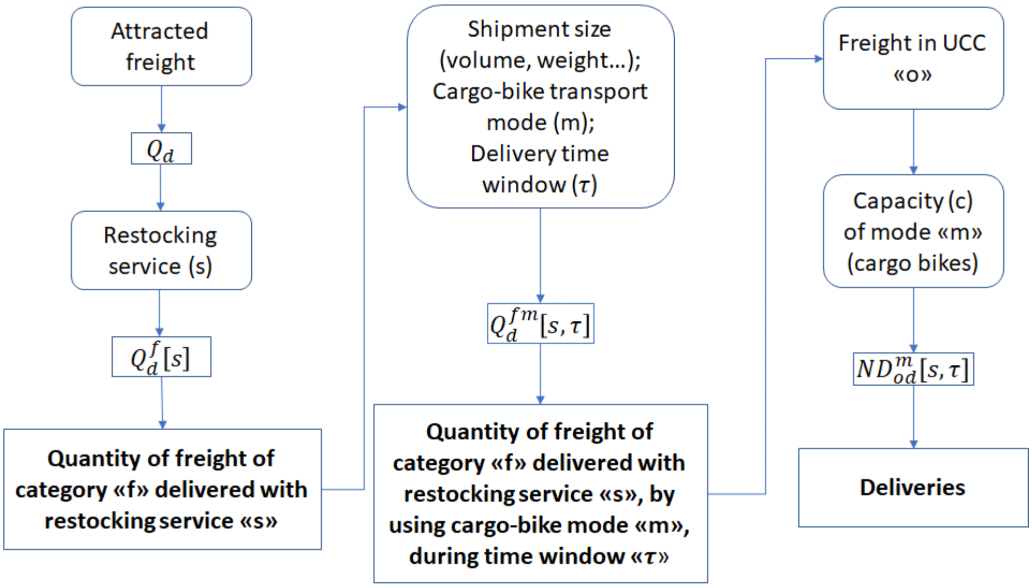

Figure 2: Methodological framework

In the third step, the number of delivery trips ND_{od}^{fm} necessary to distribute in the reference area the freight demand previously estimated is determined given the load capacity of the cargo bikes. Then, the generalized minimum cost paths connecting UCC to every destination zone d are evaluated from the network model and the cost/performance functions of the arcs, considering the specific features of different elements of the network such as road arcs and pedestrian arcs, which can be travelled by cargo bikes within the relevant speed limits. Once the times necessary to perform the service (by considering the minimum cost paths previously determined) and the distances to be covered on the network have been obtained, it is possible to calculate the number of delivery tours and the vehicles needed to perform the service by delivering all the expected goods in the time horizon of analysis, given the constraints of bike battery range and load capacity. It is also important to mention that in the calculation of service time, in addition to the time spent traveling through the network, the average time required to physically make deliveries to recipients (which in turn is dependent on the average number of recipients served during a delivery tour) and the time required to load the cargo bike at the UCC are also included.

4. Case study and results

The proposed methodological framework has been applied to the case study of the city of Ravenna, a mid-sized city in Northern Italy. The study area is the historical centre of the city, which is characterized by narrow streets and with a wide extension of limited traffic zones and pedestrian areas (Fig. 3) that make it difficult to access the city centre by motorized vehicles and forces them to comply with the time windows provided by the municipality. One single UCC to serve the demand requirements of the whole area has been considered, given the small size of the historical centre, and the elements necessary to implement the proposed sequential model are shown in the following paragraphs.

4.1. Transport supply

The LTZ in Ravenna has an extension of 520,000 m^2, of which 37,704 m^2 are pedestrian zones (Fig. 3).

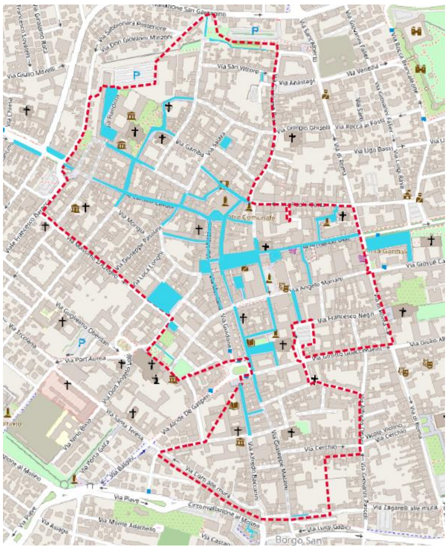

Figure 3: Study area, consisting of LTZ limits (red line) with pedestrian zone (highlighted in blue) in the city centre of Ravenna

The time windows for accessing the city centre by traditionally motorized vehicles are limited: the pedestrian zone access time is from 3:00 to 10:00 in the morning, while in LTZ the access is extended from 14:00 to 16:00 in the afternoon.

The study area has been divided into homogeneous traffic analysis zones, virtually represented by centroids, and within each zone the relevant commercial activities have been positioned and highlighted (Figure 4 (b)). The road network graph is composed of road/pedestrian/bike links (Figure 4 (a)) representing all possible access alternatives to the city centre by e-cargo bikes, as they can run through pedestrian zones as well as on road links.

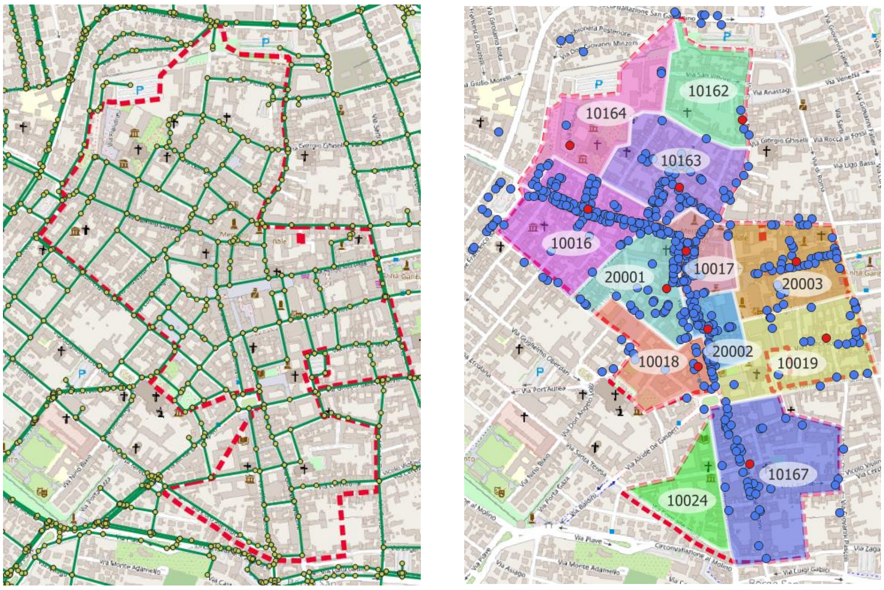

Figure 4: Road network graph (a) and traffic zones (b) of the studied area (red dots are centroids, blue dots are commercial activities).

4.2. Freight demand

To apply the proposed methodological framework (Fig. 2), the first step is to evaluate the total freight demand Q_d attracted from the study area. To this end, the activities in the area have been censused and divided into different categories, as reported in Fig. 5. A total of 480 commercial activities have been categorized and located in the study area (Figure 5: Number of activities located in the study area and surveyed, for each freight category.

Since in this framework only the segment of freight restocking to commercial activities is taken into account, the amount of goods currently delivered to the recipients located within the study area is the total demand Q_d in the considered period of analysis. The quantities, the characteristics and the time schedules of the deliveries have been obtained through a direct survey to the involved stakeholders (direct estimation). The activities have been sampled with a sampling rate of 26%, meaning 126 activities surveyed. These activities have been included in the sample taking into consideration both the category they have been assigned to (Figure 5) and their location (Figure 6).

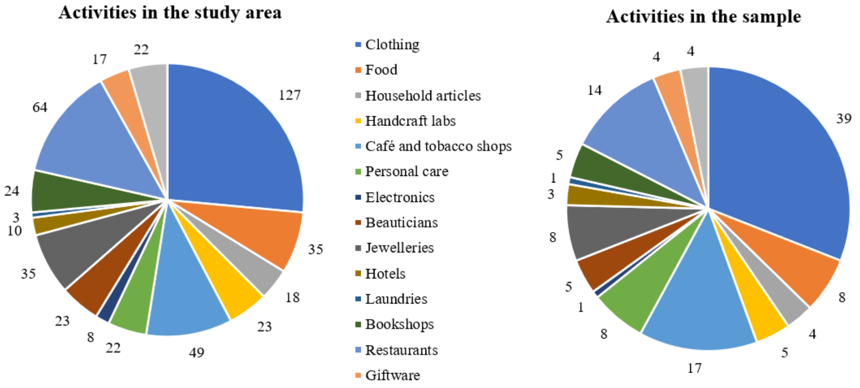

Figure 5: Number of activities located in the study area and surveyed, for each freight category.

Stakeholders have been surveyed about the characteristics of goods they receive, the restocking service used (own account or third-party logistics provider), the delivery frequency, and the quantity of freight received in terms of volume, weight, and type of packaging.

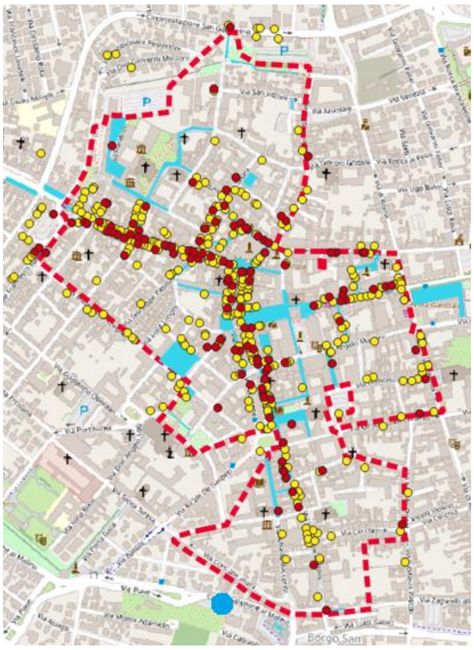

Figure 6: Activities in the city centre (red dots – surveyed, yellow dots – not surveyed) and the hypothesized location of the UCC (blue dot). Pedestrian areas are highlighted in light blue.

4.3. Deliveries

As seen in section 2, the allocation of the UCC is fundamental to improve the efficiency of the delivery process by reducing the generalized cost of the paths followed by cargo bikes while performing their service. For this reason, in the case study the UCC has been located close to the city centre (blue dot in Fig. 6), in a position that is well served by existing road network, making it easily accessible by trucks coming from sub-urban warehouses or directly from wholesalers through the highway, and it is furthermore connected to the city centre by road and cycling arcs.

Data obtained from the direct survey have been processed to determine the quantity of freight $Q_d^f[s]$ of every category f entering the city centre every day delivered by third-party logistic providers to any destination d within the study area. Considering the limits of cargo bikes in terms of capacity and range, for each category f the quantity of freight $Q_d^{fm}[s,\tau]$ potentially delivered by this mode in a selected time window τ has been evaluated.

Figure 7: e-quadricycle considered to perform the deliveries in the test case.

In particular, a quadricycle cargo bike has been considered for the test case (Fig. 7), whose main characteristics are: i) battery range: 55 km (on flat route); ii) load capacity: 150 kg; iii) average load factor: 0.8; iv) average delivery time: 3.5 minutes.

As introduced in section 3, to evaluate the freight share actually deliverable by cargo-bikes, firstly freight load consolidated in pallets have been excluded since additional freight operations are necessary to de-consolidate and re-consolidate the shipment in smaller packages, with consequent load break. Afterwards, fragile and perishable goods have been excluded from the volumes of freight delivered with the new mode. In detail, after excluding the beforementioned goods, the estimated amount of freight that can be potentially delivered in the study area is about 5 tons a day (Tab. 1).

Table 1: Quantity of freight potentially suitable for cargo bike delivery in the study area in one day.

Category	*Third-party deliveries without pallets (%)*	*Quantity of freight potentially suitable for cargo-bikes delivery (%)*	*Quantity of freight potentially suitable for cargo-bikes delivery (kg/day)*
Clothing shops	51%	30%	906.5
Food	62%	0%	
Household shops	46%	30%	1504.1
Handcraft labs	100%	20%	17.1
Café and tobacco shops	100%	40%	402.5
Personal care activities	46%	40%	137.6
Electronic shops	100%	0%	
Beauticians	100%	50%	9.2
Jewelleries	22%	10%	21.9
Hotels	100%	20%	1.3
Laundries	100%	40%	7.2
Book shops	33%	30%	331.8
Restaurants	67%	20%	1680.9
Various item shops	100%	50%	47.6
Other	50%	0%	

To determine the freight flows and the number of deliveries, the transport system model has been implemented in PTV Visum simulation environment, evaluating for each centroid-UCC pair the optimal path, namely the minimum generalized cost path. This evaluation has been done by considering the least time-consuming paths (the fastest ones), taking into account the effects of congestion on cargo-bikes while running on road arcs and limiting the speed on pedestrian (5 km/h) and cycling arcs (15 km/h). The average delivery time has been assumed based on several sources: a literature review (Llorca & Moeckel, 2021) (Verlinde, et al., 2014), a survey to cargo bike operators, and by performing an on-field test in the city centre of Ravenna. Finally, a delivery time window τ of 8 hours has been chosen, divided into two time slots: 4 hours in the morning (AM) and 4 hours in the afternoon (PM). Three different distributions of the deliveries throughout the day have been considered and the same number of scenarios has been modelled and simulated. In the first scenario the deliveries have been distributed between morning and afternoon exactly as emerged from the direct survey: 76% in the morning and 24% in the afternoon. In the second scenario, following the interest expressed by some interviewed operators in changing the delivery scheduling, the assumed distribution is 57% of deliveries in the morning and 43% in the afternoon. Finally, the third scenario considers 65% in the morning, 35% in the afternoon.

With the hypothesis introduced in the previous paragraph, the travel time and the distances necessary to perform the deliveries in each scenario have been computed. The number of delivery tours and the number of cargo bikes necessary to deliver all the estimated amount of freight in the considered time window τ have then been calculated (Tab. 2).

Table 2: Results of simulated scenarios for the distribution in the study area

	Scenario A		*Scenario B*		*Scenario C*	
	AM	*PM*	*AM*	*PM*	*AM*	*PM*
Delivery share [%]	76	24	57	43	65	35
Time of utilization of every cargo-bike [h]	3.6	3.8	3.8	3.4	3.5	3.8
Utilization rate [h/bike]	1.06		1.44		1.22	
Number of cargo-bikes in use simultaneously	7	2	5	4	6	3
Tot km travelled	77.5	22.3	60.2	38.3	62.2	33
Average commercial speed [km/h]	3.1	2.93	3.16	2.81	2.96	2.89

As can be seen in Tab. 2, the average resource time utilization and the total kilometres travelled does not vary remarkably among the considered scenarios. The number of cargo bikes simultaneously in use is the parameter that affects mostly the efficiency of a scenario, since it implies an increase in initial resource investment. To summarize, scenario B is the best one in terms total number of cargo bikes needed (5 cargo bikes, 4 of them re-employed in the afternoon, since the total kilometres travelled fall within the battery range) and higher vehicle utilization rate, which implies a service performed with higher efficiency.

5. Discussion and conclusions

The importance of implementing city logistics measures with the aim of reducing the detrimental effects of last-mile logistics has been pointed out by several authors, as showed in section 2. Among the highlighted measures, cargo bikes are even more employed and deeply studied as alternative to traditional motorized vehicles to perform last-mile deliveries in urban areas. This paper aims to develop a methodological framework to support the estimation of the amount of freight that can be actually delivered by using cargo bikes in an urban area, taking into account capacity and battery range limitations that are a constraint to their employment.

The proposed methodological framework has been applied to the case study of the city of Ravenna, in Italy. The total freight demand Q_d daily attracted from the study area has been directly estimated through a survey administered to a sample of commercial activities located within the study area. The application of the developed methodological framework has shown its usefulness to support the design and planning of an urban freight delivery system envisaging the use of cargo bikes, allowing not only to determine the amount of demand that can be carried by such transport mode starting from general attributes of the recipients to be served, but also to define the optimal service configuration in terms of the number of vehicles used in relation to their performance and usage limits. The application is performed with a view to the optimal integration of cargo bikes with other traditional motorized vehicles and, more generally, with other logistic measures, e.g., trucks heading to the UCC before the reconsolidation of freight. In fact, as seen before, cargo bikes have operational constraints such as limited capacity (in terms of weight and volume) and battery range, that do not make them suitable to perform all deliveries of goods within an urban area and to substitute totally current delivering vehicles. Therefore, the optimal location of the UCCs is fundamental to implement such a system.

The results obtained are useful to support the design of the operational characteristics of the system and the results of the simulation are comparable to the ones reported in the literature; in particular, the average commercial speeds obtained in the case study scenarios are similar to the ones reported by Leonardi et al. (Leonardi, et al., 2012) and Navarro et al. (Navarro, et al., 2016). Moreover, as shown in the application, the estimation of the quantity of freight deliverable by cargo bikes is fundamental to support the design of the system, estimating the number of resources needed to set-up a cargo bikes distribution service. Furthermore, the application shows that the use of a single UCC next to a small city centre can potentially be sufficient to satisfy the demand deliverable by employing cargo bikes. In fact, according to the literature, a distribution system based on e-vehicles is suitable in small/medium sized cities (Melo & Baptista, 2017), since the UCCs can be placed closer to the served areas thus requiring less vehicles to perform last-mile deliveries in compliance with their low battery range.

Finally, as highlighted in the literature, specific attention should be paid on the safety of cargo bike riders because these vehicles increase their exposure risk to accidents, atmospheric pollution, and adverse meteorological conditions. In addition, since cargo bikes also travel in pedestrian areas, it is even important to consider the additional potential risks for other road vulnerable users.

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