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Assessing the viability of parking slot utilization as transhipment points for parcel carriers: a case study in Barcelona

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Abstract

The measures proposed in the sustainable and smart mobility strategy developed by the European commission are crucial for achieving the environmental objectives for 2030. This strategy includes measures specifically aimed at reducing the impact of e-commerce distribution. One widely adopted strategy for mitigating the impact of e-commerce distribution is the establishment of urban consolidation centres (UCCs). While this infrastructure quickly demonstrates its environmental success in urban areas, achieving long-term economic sustainability proves challenging. In this paper, we introduce a methodology aimed at incentivizing parcel carriers to shift towards an economically feasible and environmentally sustainable distribution mode within urban areas by leveraging their own transhipment space. This methodology includes a mathematical program for determining the quantity and locations of parking slots, taking into account the number of parcels and transportation vehicles used. It also utilizes the Continuous Approximation technique to assess the transportation and environmental costs of the proposed solutions. The proposed methodology is implemented for the city of Barcelona, considering three different sizes of parcel carriers: the carrier handling the largest volume of parcels, the carrier handling the lowest volume of parcels, and an intermediate case. The vehicles considered for delivery from the transhipment points include vans, cargo bikes, and trolleys for distribution on foot. The results indicate that a significant reduction in both transport and environmental costs is achieved when using zero-emissions vehicles for delivery from transhipment points for any of the parcel carriers considered.

Keywords Transhipment points · Urban consolidation centres · B2C · Barcelona · City logistics

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1 Introduction

The European Commission has clearly defined environmental objectives for 2030. Specifically, in terms of both people and freight mobility, a strategy for Sustainable and Smart Mobility has been developed to achieve these goals. This strategy places significant emphasis on promoting eco-friendly freight transport, it includes measures such as reducing empty and unnecessary freight transport, and implementing sustainable urban logistics plans (European Commission 2020). In these urban logistic plans, cities like Stockholm (Stockholms stad 2014) and London (Transport for London 2019) have incorporated provisions for mitigating the impact of freight distribution, particularly in the realm of e-commerce distribution.

E-commerce distribution, also known as business-to-consumer (B2C) distribution, is a concern for municipalities due to its fragmented deliveries, intense competition resulting in precarious job conditions, and its broader impact on the city. Therefore, in order to establish a sustainable, intelligent, and resilient freight distribution system, and to work towards the goal of becoming the first climate-neutral continent by 2050 (European Commission 2020), it is imperative to initiate an exploration of strategies to mitigate this impact.

Since the 1940s, a widely adopted measure or strategy to mitigate distribution impact has been the establishment of urban consolidation centres (UCCs), although this term wasn't coined until the 90 s. Urban consolidation centres are designated as strategically located spaces where different companies deposit their goods for consolidation with those of other companies. Following this, the consolidated goods are distributed using zero-emission vehicles (Browne et al. 2005). While the name and definition of this infrastructure are comprehensive, they fundamentally emphasize that these centres are located in urban areas, serving as hubs for transhipping freight and playing a role in consolidating shipments from various companies.

The initial implementations of UCCs quickly demonstrated their success in urban areas. Over the years, several positive outcomes have been observed, including a substantial reduction in pollution (for instance, Concorde UCC reduced CO_2 emissions by 74% (Chronopost 2016)), a notable decrease in traffic congestion (reduced by 38% in Monaco (Campbell et al. 2010)), a significant reduction in the space required for distribution vehicles (42% in Monaco (Campbell et al. 2010)), and a decrease in the distance travelled by freight vehicles (a 20% reduction is expected in Chonocity, Paris (Chronopost 2020)).

With these positive environmental outcomes and increased distribution efficiency, it appeared that this infrastructure held the key to achieving sustainable urban distribution. Consequently, numerous grants have been allocated towards the development of such centres, including the Green Link in Paris (subsidized with project LaMilo (The Green Link, 2014)), Vanapedal in Barcelona (subsidized with project SMILE (Estrada and Magín, 2017)) or Komodo in Berlin (founded by the National Climate Initiative of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Komodo 2018)).

Some of the earliest consolidation centres are still in operation today, such as the UCC in Monaco (operating since 1989) (Catapult Transport Systems 2018), as well as cases like the UCC in Bristol and Bath (operating since 2002) (Paddeu 2017) and CityPorto in Padua (operating since 2004) (Cityporto Padova 2021). However, this is not the norm for the majority. The ones that remain operational are primarily sustained by ongoing subsidies in various forms. These may come in the form of direct subsidies or indirect support (i.e. money to acquire environmentally friendly vehicles or to cover rent expenses for the space utilized) (Lebeau et al. 2017).

The environmental benefits of urban consolidation centres, as previously mentioned, have consistently proven to be positive. Their discontinuation has primarily been attributed to economic factors (Ciardiello et al. 2021). When the profit margin for parcel distribution is already minimal, the addition of costs such as renting an expensive space of significant size makes it nearly impossible (Van Rooijen and Quak 2010). Furthermore, concerns about potential loss of parcel tracking or brand visibility, stemming from the consolidation of goods from multiple companies and the utilization of a neutral carrier shared with others (Van Heeswijk et al. 2019), have exacerbated this challenge.

As a result, the original concept and definition of an urban consolidation centre have become somewhat outdated, giving rise to various alternative approaches—essentially modifications of the original idea. For instance, Janjevic and Ndiaye (2017) differentiate between types of UCCs based on size and the volume of distributed parcels. This implies that the infrastructure could be classified as either a UCC or a micro-UCC. Rosenberg et al. (2021) define micro-depots and shared micro-depots, which may not necessarily involve consolidation activity and can be utilized by different logistics service providers. Another example can be found in Verlinde et al. (2014), where mobile depots are introduced. These are trailers equipped with loading docks, warehousing facilities, and offices, capable of relocating to different locations during distribution hours.

Learnings from both successful and unsuccessful examples of UCCs highlight that their operational advantages stem from their proximity to demand, allowing for supply during peak hours, and facilitating the shift towards zero-emission vehicles (Giampoldaki et al. 2023). Consequently, numerous businesses to consumer (B2C) companies are redefining the concept of UCCs, repurposing cost-effective spaces like parking areas for this purpose, as observed in Prague (EIT Urban Mobility, 2021), Madrid (Ayuntamiento de Madrid, 2023), and Paris (Hasse, 2021). Nevertheless, despite the potential cost savings from consolidation, companies remain reluctant to mix their goods with those of others. This results in these spaces primarily functioning as hubs for sorting cargo, particularly parcels, with each company having its designated area.

The utilization of transhipment points situated in close proximity to the demand, facilitates delivery to consumers' homes via zero-emissions vehicles. However, in many cities, available space for logistics activities is limited. Therefore, repurposing parking slots as transhipment points can be a viable solution, benefiting not only parcel carriers but also parking facilities looking for new opportunities. Additionally, this approach can contribute to reduced congestion and pollution, making it a valuable option for cities.

Given this innovative proposal to repurpose parking slots for logistics activities, this paper develops a methodology to analyse the economic sustainability of using single-company parking slots or other low-rent spaces for transhipping parcels for last-mile delivery. This methodology includes a mathematical program for determining the quantity and locations of parking slots, taking into account the number of parcels and transportation vehicles used. Considering the reluctance of different companies to share UCCs, the objective of this paper is to encourage parcel carriers to transition towards an economically viable and more sustainable distribution mode within urban areas by utilizing their own transhipment space. Therefore, the methodology developed in this paper equips parcel carriers with a tool for designing a sustainable distribution model and empowers them to evaluate the economic feasibility of utilizing their own low-rent spaces as transhipment points for parcels. In light of the regulatory changes being implemented by Barcelona City Council, to allow this activity in underground parking facilities, a thorough assessment of the methodology's application is carried out in the city of Barcelona.

The rest of the paper is structured as follows. Section 2 offers a literature review. Section 3 outlines the problem addressed in this paper. Section 4 presents the methodology approach. Section 5 details the implementation for the city of Barcelona. Conclusions and future work are presented in Sect. 6.

2 Literature review

The location of UCC as well as transhipment points plays a crucial role. There is a consensus regarding the significance of strategically siting infrastructures for multimodal transfers to ensure its effectiveness (Allen et al. 2007; Browne et al. 2005; Simoni et al. 2018; Van Duin et al. 2010). As demonstrated by Mepparambath et al., (2021) through analytical results and simulations, the location of a UCC can lead to a reduction in the number of freight trips. Nevertheless, there is no standardized approach to determine an appropriate location, as criteria and constraints are entirely case-dependent.

The location and costs of the UCC have been thoroughly examined due to their significant positive environmental impact on urban freight distribution. In (Dupas et al. 2023), a generic evaluation method is proposed based on a Mixed Integer Programming (MIP) model to compare scenarios implementing UCCs with the classical distribution approach. They assess the differences in cost and CO_2 emissions resulting from implementing their model in the city of Bordeaux. The study concludes that the mandatory use of UCCs leads to increased transportation costs, making the scenario challenging to implement without subsidies. Furthermore, the optimal scenario involves a hybrid delivery approach (combining direct delivery from the distribution centre with distribution through the UCC), along with balanced UCC capacity (where the UCC's capacity matches the demand) and high-speed operations. This combination provides the most significant overall cost reduction compared to direct delivery.

Challenges in achieving UCC long-term economic sustainability have prompted the evolution of this infrastructure into various forms, including depots, transhipment points, mini-hubs, and satellite locations, among others. While they share the common feature of facilitating freight transfers between vehicles, they employ distinct strategies to enhance last-mile delivery (Leyerer et al. 2019).

Regarding satellite locations, which refer to public spaces used for transhipping freight, different options exist depending on the available public space. Alewijnse and Hübl (2021) develop a Mixed Integer Linear Problems (MILP) formulation of a Two-Echelon, Multi-Depot, Capacitated Vehicle Routing Problem (2E-MD-CVRP) to deliver parcels using cargo bikes from satellite locations, in this case, ships traveling through the Canal Network in Amsterdam city. Their approach reveals that the combination of ships and cargo bikes presents promising economic, social, and environmental outcomes compared to van distribution. Bayliss et al. (2023) propose a scalable two-phase heuristic algorithm to solve the problem of a multi-modal and a variable-echelon delivery system for the last mile. They suggest transferring parcels between different types of vehicles at kerbside locations. The study concludes that using alternative vehicle types and changing the freight at mobile satellites decreases costs and van movements inside the city. Enthoven et al. (2020) analyse how to effectively integrate the use of satellite and covering locations considering the two-echelon vehicle routing problem with covering options (2E-VRP-CO), where goods are transhipped from a central depot to intermediate locations in the first echelon. They conclude that when delivery occurs via two types of locations (the covering locations where customers go to collect the parcels and the satellite location from where cargo bikes distribute the parcels to the consumers' homes), the ALNS heuristic they developed yields high-quality and optimal results when solving the case of 2E-VRP-CO, the 2E-VRP (two-echelon location routing problem), and SFL-VRP (the simultaneous facility location and vehicle routing problem without duration constraints). Faugère et al. (2020) propose a mathematical modelling framework and an integer program to assess the usage of mobile access hubs combined with cargo bikes for parcel distribution within the city. They conclude that this type of infrastructure can lead to significant potential savings in terms of cost, time efficiency, and environmental sustainability.

Leyerer et al. (2019) also considering mobile hubs, provide a decision support system for CEP service providers and city authorities that optimize mobile hub location and fleet composition to distribute from the hub by estimating driving distances and considering an adjustable CO_2-emission ceiling and external costs. The decision support system proposed is implemented for the city of Hannover. They concluded that using only cargo bikes is useful for short distances and small parcels, but it is necessary to complement them with electric vans for distribution in larger areas.

Additionally, Kania et al. (2022) introduce a toolbox for planning and implementing transhipment hubs, specifically nano-hubs as a modular infrastructure that uses three parking spaces in-line on the street with cargo bikes as vehicles for distribution. Additionally, they applied a simulation-based case study to quantify the economic and environmental impact of introducing the nano-hubs with cargo-bike distribution in the city of Magdeburg in Germany, comparing it to deploying a conventional micro-hub approach.

There are also more theoretical approaches that do not specify the infrastructure for transhipment. In their study, Cortes and Suzuki (2022) propose shipment transloading using a Vehicle Routing Problem within route Transloading and Time Windows (VRPTTW). They suggest that transloading parcels (transferring parcels from one vehicle to another) can enhance the speed and reduce the costs of parcel deliveries by increasing vehicle capacity. They concluded that this solution could be beneficial in specific cases, such as urgent deliveries that were not received at the distribution centre in time, and that it works for a limited number of transloading points.

Numerous studies have examined and endorsed the strategy of utilizing various types of infrastructure to consolidate freight and/or transfer it to other, more sustainable vehicles. Upon reviewing the literature, it becomes evident that different methodologies are employed. For example in (Alewijnse and Hübl 2021; Dupas et al. 2023; Faugère et al. 2020), exact methodologies such as linear programming are utilized. Alternatively, in (Bayliss et al. 2023; Cortes and Suzuki 2022; Enthoven et al. 2020), heuristic methodologies such as the ALNS heuristic are employed. Furthermore, simulation is utilized in certain cases (Kania et al. 2022; Mepparambath et al. 2021). However, the literature lacks a comprehensive study that not only addresses the problem of locating and analysing costs associated with using transhipment spaces and zero-emission vehicles but also considers the current operational features of parcel carriers.

In Mepparambath et al., (2021) is analysed the distribution to fixed location points (such as distribution to shops). However, this model may not be applicable to e-commerce, where distribution is often non-uniform and directed towards individual end consumers. In (Dupas et al. 2023), despite examining various distribution models, the study does not address the specific location of transhipment spaces, as these infrastructures are already predetermined in this analysis. In the case of Faugère et al. (2020), the location of the hub is not predetermined; however, areas are defined based on a maximum distribution radius. Furthermore, while the study concludes that hubs are more profitable when handling higher volumes, it fails to establish a minimum demand for each hub to ensure the economic feasibility of these infrastructures.

Additionally, in other studies such as those addressing the Capacitated Vehicle Routing Problem (CVPR), the 2E-VRP-CO, or the 2E-MD-CVRP, critical attributes of last-mile distribution for parcel carriers are overlooked. In Kania et al. (2022) and Enthoven et al. (2020), the maximum distance a vehicle can cover is not considered. They also exclusively employ a single type of vehicle for distribution from nano-hubs or satellites and fail to account for a minimum volume of parcels required to be handled from each of these infrastructures. In Alewijnse and Hübl (2021), solutions are proposed considering a minimum volume of parcels handled, but they did not address the economic feasibility necessary to render this scenario economically viable. On the other hand, Bayliss et al. (2023) face a challenge of distributing a low volume of parcels due to high computation costs. In the case of Leyerer et al. (2019), neither the maximum distance that a vehicle can cover nor a minimum demand for each hub is considered to ensure their economic sustainability. In Cortes and Suzuki (2022), a solution to the Vehicle Routing Problem with Split Deliveries (VRPSD) is presented, which includes mid-route shipment consolidation. However, it is not convenient for parcel carriers due to their reluctance to participate in such distribution schemes.

Each study provides insights and drives towards the use of environmentally friendly vehicles for intra-city distribution, leveraging various types of transhipment spaces. Nevertheless, none of these studies offer a comprehensive solution applicable across various parcel carriers, considering their diverse volumes of handled parcels. Such a solution should ensure the economic viability of transhipment spaces by stipulating a minimum quantity of goods distributed from these points. Moreover, it should accommodate the possibility of using different types of vehicles, taking into account their respective characteristics, such as maximum delivery radius or capacity.

Furthermore, the existing distribution infrastructure operates on a zip code basis. Therefore, it is imperative to consider this operational condition when proposing a new distribution model through transhipment spaces. Notably, this operational feature remains unaddressed in the analysed papers.

To address these challenges, we propose a methodology comprising a mathematical model and a Continuous Approximation model. The mathematical model integrates a minimum demand threshold to ensure the economic sustainability of transhipment spaces. It allows for the consideration of distribution areas based on their zip codes and can be easily applied regardless of whether the parcel carrier deals with low or high freight distribution volumes.

Additionally, the Continuous Approximation model approach we propose advocates for the use of aggregated data over detailed inputs. This is because data aggregation offers the advantage of simplifying the handling of large-scale problems, thereby enhancing operational awareness (Nourinejad and Rooda 2022). Moreover, precise consumer location data is only feasible when customers opt for parcel pickup or collection points, lockers, or if the final recipient is a local business (such as a shoe shop or restaurant). However, the behaviour of e-commerce consumers varies daily, resulting in a solution derived from precise data representing only one example of a given day. Determining the location of a UCC, or in this case, a transhipment space, is a strategic decision that cannot solely rely on assuming the exact locations of e-commerce consumers. This task is challenging to predict and requires highly accurate routing data. The Continuous Approximation model serves to address these challenges effectively.

Given the reluctance of companies to share urban consolidation centres, this paper aims to incentivize parcel carriers to embrace a financially viable and environmentally sustainable distribution approach within urban areas by utilizing their individual transhipment spaces. Consequently, the methodology outlined in this paper provides parcel carriers with a framework for devising a sustainable distribution model that accommodates the operational peculiarities specific to parcel carriers.

3 Problem description

A two-tier distribution network is considered with potential use of parking lots as transhipment points of parcels for home delivery. The type of vehicle used from this transhipment points affects the number of trips required for distribution but also determines the maximum area that can be covered. Consequently, it influences the necessary number of transhipment centres and the associated transportation costs.

Additionally, the number of trips is contingent upon the vehicle's capacity. Vehicles with larger capacities can handle more parcels in a single distribution route, resulting in fewer return trips to the transhipment point for reloading compared to vehicles with low parcel capacities. While it's possible to return to the parking slot to refill the vehicle, doing so may reduce vehicle efficiency due to trips with minimal or no cargo. This suggests that as the number of parcels to be delivered in a distribution route increases, the distribution cost per parcel decreases due to economies of scale. Conversely, vehicles with lower capacities may require more resources, including personnel, additional vehicles, or extra time. For example, since vans have greater capacity than cargo bikes, multiple cargo bikes and drivers, or additional time, would be needed to transport the same number of parcels as a van. Therefore, opting for low-capacity vehicles could be a viable option when the resources utilized by these vehicles (and the vehicles themselves) are not expensive and can be compared with the cost of a single vehicle with higher capacity.

The area to cover will vary depending on the type of vehicle used. The velocity of the vehicle affects the maximum distance it can travel. For instance, using a van allows for covering a larger area compared to making deliveries on foot. Consequently, the maximum radius the vehicle can cover becomes a crucial factor in determining the size of the distribution areas.

Another important factor to consider is ensuring a minimum distribution volume of parcels from a transhipment point. This aspect, as demonstrated in the case of the UCCs, is crucial for achieving long-term economic sustainability (Aljohani and Thompson 2021; Björklund et al. 2017; Browne et al. 2005).

In the case study presented in this paper, we have taken into account a minimum distribution volume for each transhipment point, and explored on-foot distribution using trolleys, cargo bikes, and vans as potential delivery vehicles for these spaces.

4 Methodology

In order to assess the economic feasibility of utilizing parking slots as transhipment points for home parcel delivery with different last-mile vehicles, we employ a mathematical program to determine the optimal number and locations of the parking slots. Subsequently, the cost evaluation is computed using the Continuous Approximation technique.

Three scenarios, each considering a different vehicle as the primary option for delivery from the parking slot are considered and compared with the current case (base scenario), where parcel carriers deliver their parcels from a distribution centre to the customer home with vans.

4.1 Mathematical model for quantifying and locating transhipment points

Once the distributing vehicle is chosen, the maximum radius of the distribution area and the number of trips, contingent on the vehicle's capacity, become known. Consequently, the number of transhipment points, their optimal locations, and the areas they encompass can be determined.

The mathematical program proposed for determining the transhipment points and distribution areas is based on the model introduced by Dantrakul et al. (2014). Unlike this approach, which relies exclusively on transportation costs for decision-making, we propose assessing transportation costs while factoring in distance and the capacity of the distributing vehicle. In place of setting a maximum demand for centre assignment, a minimum demand constraint is imposed to ensure the rental cost can be met, in order to achieve economic sustainability. Consequently, the determination of the number and placement of parking slots is achieved by minimizing the overall cost, which encompasses both the daily rental cost of a parking slot and the transportation cost from these spaces to each demand node. It is considered that each demand node *i* aggregates customer demands within zone *i*.

We denote f_j as the daily renting cost of transhipment space *j*, d_{ij} as the distance between demand node *i* and transhipment point *j*, cd_{v} as the cost per kilometre driven (in €/km) of the zero-emission vehicle *v*, and the number of trips the fleet makes to customer demand zone *i*, which is estimated by dividing the demand of a customer *i* (h_i) by the capacity of the fleet vehicle *v* (C_v). The decision variables are y_j, which takes a value of 1 if the transhipment space is used, and x_{ij}, which is set to 1 if demand zone *i* is served from transhipment space *j*.

Using this notation, the mathematical program can be formalized as follows:

$$\text{Minimize Z} = \sum_{j=1}^{k} f_j y_j + \sum_{i=1}^{k}\sum_{j=1}^{k} d_{ij}\frac{h_i}{C_v}\mathrm{cd}_{\mathrm{v}} x_{ij} \tag{1}$$

Subject to:

$$\sum_{j=1}^{k} x_{ij} = 1, \forall i = 1 \dots k \tag{2}$$

$$\sum_{i}^{k} h_i x_{ij} \geq h y_j, \forall j = 1 \dots k \tag{3}$$

$$d_{ij} x_{ij} \leq r, \forall i, j = 1 \dots k \tag{4}$$

$$\sum_{i=1}^{k} x_{ij} \leq k y_j, \forall j = 1 \dots k \tag{5}$$

$$x_{ij} \in \{0, 1\}, \forall i, j = 1 \ldots k \tag{6}$$

$$y_j \in \{0, 1\}, \forall j = 1 \ldots k \tag{7}$$

The objective function is defined in Eq. (1). The first term represents the opening cost, i.e., the daily renting cost of a transhipment space (f_j), if the transhipment point y_j is in use. The second term accounts for the cost of transporting parcels from the transhipment point j to the customer demand zone i. This is calculated by multiplying the distance (d_{ij}) between transhipment space j and demand node i by the cost per kilometre driven by vehicle v (cd_v) and the number of trips required to transport parcels from transhipment point j to customer demand zone i ($\frac{h_i}{C_v}$). Constraint (2) ensures that each demand zone i is only assigned to one transhipment space. Constraint (3) imposes that a minimum demand (h) must be allocated to a transhipment space to ensure its long-term economic sustainability. Constraint (4) imposes a maximum delivery radius (r) from the transhipment point. Constraint (5) stipulates that if transhipment space j is closed, no customer i can be assigned to that facility. Constraints (6) and (7) define the binary condition of the decision variables. A summary of the parameters is presented in Table 1.

However, this mathematical program can determine that there is no optimal solution for covering all the areas if either the minimum demand or the maximum radius constraints are not met by the chosen vehicle. In such a scenario, the procedure outlined in Fig. 1 is applied. For the areas that cannot be covered with the established vehicle, if the radius constraint is not met, vehicles with a higher distribution radius are tested. When the maximum radius is constrained but not the minimum demand, the remaining areas are distributed from the distribution centre by van, as the company does not have enough volume to use a transhipment space. Once all the areas have the scheme for distribution, the transportation costs for distributing each area with the corresponding distribution vehicle are estimated.

4.2 Continuous approach model for quantifying transportation and environmental costs

Once the number and location of transhipment spaces, as well as the areas they cover, are set, we proceed to calculate the transportation cost associated with the respective type of vehicle. This is done by evaluating the distance travelled from the distribution centre (located outside the city) to the consumer's home, whether it be a direct route or via a transhipment point. This estimation is carried out using an extended version of the method employed in (Estrada and Roca-Riu 2017). The distance travelled comprises the line-haul distance per vehicle (Dlh_j), which is the distance from the distribution centre to the centre of distribution area j, and the local distance per vehicle (Dl_j), which is the distance from the centre of distribution area j to the end consumer. Here, j denotes each distribution area ($j = 1 \ldots k$). They are calculated as in Eqs. (8) and (9), respectively. In these equations, ρ_j represents the distance from the distribution centre to the centre of distribution area j, $\Delta\rho$ represents the average additional line-haul distance from the centre of area j to the transhipping

Table 1 Summary of parameters

Parameters	Definition
A_j	Area of the distribution zone *j*
β_v	Detour distance
C_v	Vehicle capacity
C^T	Transportation costs
C^E	Environmental costs
C_{Total}	Total costs
cd_v	Distribution distance cost
ct_v	Distribution time cost
d_{ij}	Distance between transhipment point *j* and demand node *i*
Dl_j	Local distance from transhipment point *j*
Dlh_j	Line-haul distance for transhipment point *j*
f_j	Cost of renting a transhipment space *j*
H	Time slot in which parcel distribution is allowed
h	Minimum demand required to open a transhipment space *j*
h_i	Parcels distributed at demand node *i*
h_j	Parcels distributed from transhipment space *j*
κ	Routing factor
l_{xi}	Horizontal dimension of the distribution area
l_{yi}	Vertical dimension of the distribution area
ρ_i	Distance from the centre of the distribution area to the distribution centre
$\Delta\rho$	Average additional line-haul distance from the centre of area to the transhipping space's location
ψ_j	Number of parcels delivered in one vehicle tour
r	Maximum radius for distributing
T_j	Routing time for distributing in a transhipment space *j*
τ_L	Time required for loading a vehicle
τ_U	Time required for unloading a vehicle
τ_v	Time spent for delivering a parcel
vlh_v	Line-haul distance speed
vl_v	Local distance speed
y_{exp}	Expected volume of parcels

space's location *j*, κ is the routing factor, h_j is the number of customers in distribution area *j*, β_v is the detour distance (the additional distance travelled due to the unidirectional nature of the roads), ψ_j is the maximum number of parcels that a vehicle can deliver in a single vehicle tour, and A_j is the rectangle representing the distribution area. Specifically, l_{yj} represents the vertical side of the rectangle for distribution area *j* and l_{xj} represents the horizontal side ($A_j = l_{yj} \cdot l_{xj}$) (as depicted in Fig. 2).

The number of parcels delivered in one vehicle tour (ψ_j) is calculated according to Eq. (10) and is restricted by the vehicle's capacity (C_v) and the expected parcel volume (y_{exp}), or by the designated time slot for parcel distribution (H), the detour

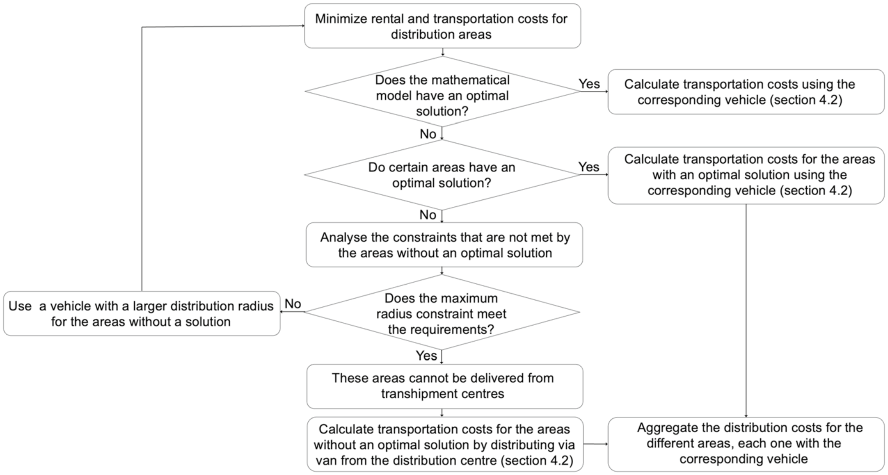

Fig. 1 Algorithm for covering each distribution area with various types of vehicles while minimizing rental and transportation costs

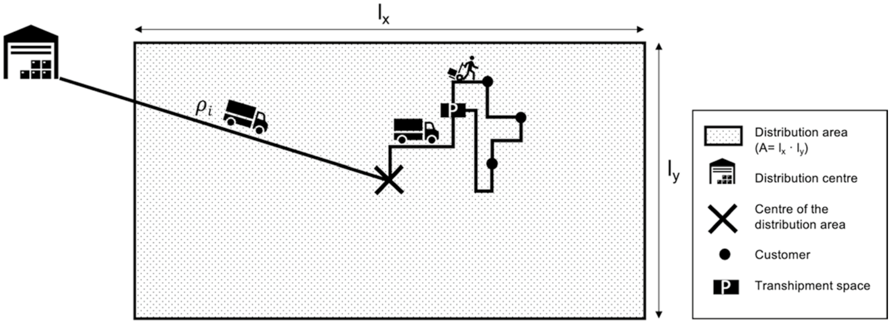

Fig. 2 Distribution area framework

distance (β_v), the vehicle's cruising speed over local distances ($\mathrm{vl_v}$), the routing factor (κ), the number of customers in distribution area j (h_j), the distribution area (A_j) and the time spent unloading and delivering parcels to the receiver (τ_v).

Following the calculation of the distance travelled, the routing time for distribution per vehicle in distribution area j (T_j) can be estimated as in Eq. (11). Here, $\mathrm{vlh_v}$ denotes the cruising speed of vehicle v in the line-haul distance, $\mathrm{vl_v}$ represents the cruising speed of vehicle v in the local distance. τ_v refers to the time spent unloading the parcel and delivering it to the end consumer, τ_U is the time needed to unload a van at the transhipment point and τ_L is the time required to load a van, a cargo bike or a trolley.

Once the line-haul and local distances, as well as the routing time per vehicle, have been estimated, the daily transport cost for each parcel carrier (C^T) is calculated using Eq. (12). In this equation, cd_v and ct_v denote the distance and time cost of vehicle v, and f_j represents the daily rent of the parking space for each distribution area j for conducting the transhipment (which will be 0 if no parking spaces are used). The environmental cost is calculated using Eq. (13). Here, lh_{CO2} denotes the environmental cost associated with the line-haul distance, while l_{CO2} represents the environmental cost linked to the local distance. The environmental cost assessed for both the line-haul distance (lh_{CO2}) and the local distance (l_{CO2}) may involve monetizing the emissions of CO_2, NO_x, and/or $PM_{2.5}$ from the vehicle handling freight distribution. These values can be estimated utilizing the Tier 3 approach method outlined by the European Environment Agency (European Environment Agency 2014). The overall cost (C_{Total}) is computed by adding together the transport and environmental costs, as shown in Eq. (14).

$$\mathrm{Dlh}_j = 2\left(\rho_j + \triangle\,\rho\right)\left[h_j/\psi_j\right]^+. \tag{8}$$

$$\mathrm{Dl}_j = \kappa\left(\mathrm{A}_j h_j\right)^{1/2} + \beta_v \tag{9}$$

$$\psi_j = \min\left\{\frac{\mathrm{C}_v}{\mathrm{y}_{\exp}};\frac{\mathrm{H} - \beta_v/\mathrm{vl_v}}{\kappa/\mathrm{vl_v}\left(\mathrm{A}_j/h_j\right)^{1/2} + \tau_v}\right\} \tag{10}$$

$$\mathrm{T}_j = \left(\frac{\mathrm{Dlh}_j}{\mathrm{vlh_v}} + \frac{\mathrm{Dl}_j}{\mathrm{vl_v}}\right) + h_j\tau_v + \left[h_j/\mathrm{C}_{van}/\mathrm{y}_{\exp}\right]^+\tau_U + \left[h_j/\mathrm{C}_v/\mathrm{y}_{\exp}\right]^+\tau_L \tag{11}$$

$$C^T = \sum_{\mathrm{j}=1}^{k}\left(\mathrm{Dlh}_j + \mathrm{Dl}_j\right)\cdot \mathrm{cd_v} + \sum_{\mathrm{j}=1}^{k}\mathrm{T}_j\cdot \mathrm{ct_v} + \sum_{\mathrm{j}=1}^{k} f_j \tag{12}$$

$$C^E = \sum_{j=1}^{k}\left(Dlh_j\cdot lh_{CO2} + Dl_j\cdot l_{CO2}\right) \tag{13}$$

$$C_{Total} = C^T + C^E \tag{14}$$

The parameters utilized in this methodology are outlined in Table 1. To calculate transportation and environmental costs, it is imperative to define the attributes of each distribution area. This encompasses not only knowing the number of parcels distributed within it, but also calculating its dimensions, determining its centre, and ascertaining the distance between distribution area centres. Additionally, it is essential to specify the type of vehicles that will be employed for distribution from the transhipment points. The vehicle attributes include capacity, maximum distribution radius, speed (both in line-haul and local distances, as applicable), loading and unloading time, and associated costs. Other necessary data include the routing factor, detour distance, distance to the distribution centre, costs associated with renting a transhipment space, and the time required to deliver a parcel.

5 Case study in Barcelona City

The methodology proposed in the previous section is applied to the case of Barcelona City. In Barcelona, the City Council recognizes the importance of minimizing the impact of last-mile distribution. They are actively pursuing this goal, as outlined in their urban freight distribution strategy for 2030 (Ajuntament de Barcelona 2023a). Additionally, they are committed to the responsible use of public spaces, such as loading and unloading areas, and are working to reduce private car usage within the city. Consequently, the decrease in private car usage has led to a significant reduction in the utilization of underground parking slots.

This shift towards utilizing underground parking has prompted the municipality to implement regulations aimed at relocating certain activities from public spaces to parking areas, thereby optimizing the use of this space. As mentioned in the introduction, these regulations will facilitate economic activities, including parcel transhipment (Ajuntament de Barcelona 2023b).

With this regulatory shift in Barcelona, this section aims to analyse the economic sustainability for parcel carriers of using transhipment spaces in underground parking areas.

In this study, we have used zip code areas to define distinct distribution zones in Barcelona. This is exemplified by Nacex, which operates several offices within Barcelona, each tasked with managing the freight for specific zip codes (Nacex, 2023). In the analysis presented here, the zip codes used range from 08001 to 08042, excluding 08040, which is an industrial zone and has been omitted from consideration. Consequently, in scenarios 1, 2 and 3, the distinct areas are defined by their respective zip codes.

5.1 Data set

In this section, we present the primary input data utilized for the case study: the demand estimation, parameters for locating the parking slots for rent, and the estimation of transportation costs.

5.1.1 Demand

To estimate the demand, we draw on a survey conducted in Catalonia in 2021, which offers insights into customers' purchasing behaviour correlated with their annual income (Institut d'Estadística de Catalunya 2021). By combining this survey data with income-specific information for each zip code area in Barcelona (Epdata, 2023) and factoring in the population of each respective area (Cybo, 2023) we can project the daily purchases made in Barcelona.

Additionally, only 74.6% of these purchases are considered, as this represents the percentage of parcels delivered directly to homes (Barcelona Oberta, 2019). We also take into account a 17.5% increase in daily parcel volume, accounting for cases where the recipient is not at home during delivery (Barcelona Oberta, 2019). In such instances, the delivery person needs to return to these addresses. The estimated demand refers to the number of orders distributed to homes in the city of Barcelona on any given day, sourced from various parcel carriers. By considering carriers operating in Barcelona that contribute to over 0.1% of the profit generated by postal operators, based on data from SABI (Sistema de Análisis de Balances Ibéricos), we establish the number of parcels delivered by each parcel carrier (PC) in proportion to their annual profits. Consequently, we analyse three distinct parcel carriers: the one with the highest volume (PC_H), the one with the lowest volume (PC_L), and an intermediate case (PC_I). This corresponds to 27,013 parcels for PC_H, 13,968 for PC_I, and 923 for PC_L.

5.1.2 Parameters for locating the parking slots to rent

The parameters used to quantify the number of transhipping points include the cost of renting a transhipment space (f_j), which is 10€ per day (equivalent to 200€ per month, based on 20 working days (Saba, 2023). The distance (d_{ij}) between transhipment space j and demand node i is measured as the distance between the centres of zip codes, given that both the demand node and the transhipment space are centrally located within each zip code. For example, the distance between zip code 08001 and the demand node in zip code 08002 is 720 m according to Google maps. h_i represents the parcels distributed in a zip code by a parcel carrier. For instance, in zip code 08001, h_i for PC_H is 454 parcels, for PC_I is 235 parcels and PC_L is 16 parcels. The minimum demand (h) assigned to a transhipment point is 35 parcels as it is the minimum parcels delivered per day during the months of April, May, June, and July 2023 by a profitable company in Barcelona. As mentioned in Sect. 4.1, the inclusion of the minimum demand constraint ensures that the cost of rent is covered, and that long-term economic sustainability can be achieved.

C_v corresponds to 66 parcels for a van (assuming a 9.8m^3 van (Nationwide 2020) and taking into account the maximum allowable parcel volume of 0.3m^3 (Correos, 2022) we set the expected parcel volume, y_{exp}, at 0.15m^3, assuming it to be half of the maximum allowable volume. Additionally, 21 parcels can be accommodated in a cargo bike (Zhang et al. 2018), and 15 parcels in a trolley (as explained in the most restrictive case (Amazon Staff 2023)). The maximum radius for distribution by cargo bike or on foot are 3 km (Gruber et al. 2023) and 1 km (information sourced from an operational company in Barcelona), respectively.

Attributes of the distribution areas, l_{xi} and l_{yi}, are obtained for each area using Google Maps. For the base scenario, they correspond to 10.8 km and 6.4 km, respectively. Additional attributes of the distribution areas include the longitude and latitude of their respective centres. These coordinates are essential for calculating the distances between areas and determining the feasibility of distributing from one transhipment point to another. For instance, the distance between zip code area 08001 and zip code area 08001 is 0.72 kms. Additionally, since the transhipment points are assumed to be located at the centre of the area, the radius to cover for each area is calculated as the maximum between half of the vertical side and half of the horizontal side of the area. For example, the maximum radius for zip code area 08001 is 0.70 kms.

5.1.3 Parameters for calculating transportation and environmental costs

To estimate transportation costs, insights gathered from carrier interviews indicate that distribution centres in Barcelona are typically located in the north (about 20 kms from Barcelona) and in the south (about 13 kms from Barcelona). Therefore, it is assumed that the average distance from each distribution centre to the distribution area in Barcelona (ρ_i) is approximately 16.5 km. The routing factor (κ) is set at $\frac{2}{\sqrt{3}}$ based on research by (Daganzo 1984; Robusté et al. 1990) which has demonstrated the suitability of these equations for estimating both local and line-haul distances, especially when the number of parcels delivered by each company greatly exceeds the vehicle's capacity ($h \gg C_v$). In our specific case, the carrier handling the lowest number of parcels in the base scenario delivers 923 parcels, whereas the van's capacity is 66 parcels. The lowest number of parcels allocated to a transhipment space is 35 parcels, and the capacity of the cargo bike or the trolley is 21 or 15 parcels, respectively.

The detour distance (β_v) is considered to be 0.1 km for a van and negligible for a cargo bike or pedestrian delivery. In Barcelona, generally, the time slot during which parcel distribution is allowed (H) covers 12 h (from 8 am to 8 pm) for vans, while cargo bikes and trolleys for distribution do not have any restrictions on distribution hours. The time spent unloading and delivering the parcel to the end consumer (τ_v) is set at 0.05 h per stop for a van, and 0.03 h per stop for a cargo bike or trolley delivery. τ_U and τ_L are both set at 0.25 h. These values are derived from the average loading and unloading times for parcels using various vehicles, observed from Monday to Friday, throughout the months of April, May, June, and July 2023, as reported by operational companies in Barcelona.

Regarding line-haul speed (vlh_v)as the line-haul distance will be in every scenario done using vans, the line-haul speed for base scenario is 36.37 km/h (mean speed in the metropolitan area of Barcelona from 8 am to 8 pm from Monday to Friday) and for scenario 1, 2 and 3 is 42.72 km/h (mean speed in the metropolitan area of Barcelona from 8 pm to 8am from Monday to Friday) (TomTom Traffic Index 2023). For a van during daytime hours, the local speed (vl_v) is 31.20 km/h (mean speed in the centre of Barcelona from 8 am to 8 pm, Monday to Friday, according to (TomTom Traffic Index 2023)). The speed of a cargo bike is 20 km/h, and the speed of distribution on foot is the average walking speed of a person, which is 5 km/h.

Distance and time costs are 0.289€ per kilometre and 30.15€ per hour for a van (Generalitat de Catalunya 2023), 0.015€ per kilometre and 15.54€ per hour for a cargo bike (Estrada and Roca-Riu 2017). For a person delivering by trolley, the distance cost is negligible, and the time cost is 8.81€ per hour (Talent 2023). As per the regulation in Catalonia, there is a 25% increase in price for hours worked during the night (Ramells Ramoneda, 2023).

The environmental cost produced by a van involves the monetization of CO_2, NO_x, and $PM_{2.5}$ from a EURO V Light commercial vehicle weighing less than 3.5 tonnes. These values were calculated using the Tier 3 approach method provided by the European Environment Agency (European Environment Agency 2014). The kilograms of pollutant or gas per kilometre for the line-haul distance are 0.193026 for CO_2, 0.000626 for NO_x, and 0.00000089 for $PM_{2.5}$. In the case of the local distance, the values are 0.29332 kg/km for CO_2, 0.000724 kg/km for NO_x, and 0.00000188 kg/km for $PM_{2.5}$. The monetization rates for these emissions are 0.00768€/kg for CO_2, 6.3€/kg for NO_x, and 48€/kg for $PM_{2.5}$ (European Commission 2019). With these numbers, environmental cost in the line-haul distance (lh_{CO2}) and in the local distance (l_{CO2}) is 0.00546896€/(vehicle-km) and 0.00690414€/vehicle-km, respectively. When instead of vans are used cargo bikes or the distribution is done using trolleys, the environmental costs are zero.

5.2 Results

The transportation costs for parcel carriers handling the highest volume of parcels (PC_H), the intermediate condition (PC_I), and the parcel carrier handling the lowest volume of parcels (PC_L) are analysed. The proposed methodology has been implemented using MATLAB.

To grasp the cost implications of this shift in the distribution model, four distinct scenarios are presented. The base scenario follows the conventional distribution model, involving the delivery of parcels by van from the distribution centre to consumers' homes. In scenarios 1, 2, and 3, we explore the feasibility of utilizing parking spaces as transhipment centres. These spaces are stocked during the night. In scenario 1, vans are employed; in scenario 2, cargo bikes; and in scenario 3, distribution is conducted on foot with the aid of trolleys.

5.2.1 Base scenario

This scenario is the most commonly used by parcel carriers delivering in the city of Barcelona. The parcel distribution is carried out with vans directly from the distribution centre located outside the city (Fig. 3).

Transportation costs have been calculated for three parcel carriers: the one delivering the highest number of parcels (PC_H), the one delivering the lowest number (PC_L), and an intermediate case (PC_I). According to the explanation provided in

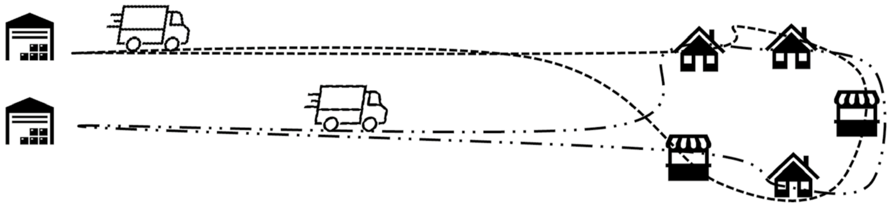

Fig. 3 Base scenario

Table 2 Transhipment spaces open and areas covered using cargo bikes for PC_L

		PC_H	PC_I	PC_L
Number of transhipment spaces	j	0	0	0
Line-haul distance (km)	Dlh	13,662	7,062	495
Local distance (km)	Dl	1,613	1,151	292
Time (h)	T	1,778	929	69
Transportation costs (€/daily)	C^T	58,020	30,397	2,312
Environmental costs (€/daily)	C^E	86	47	5
Total costs (€/daily)	C_{Total}	58,106	30,444	2,317
Cost per parcel (€)	C^P	2.15	2.18	2.51

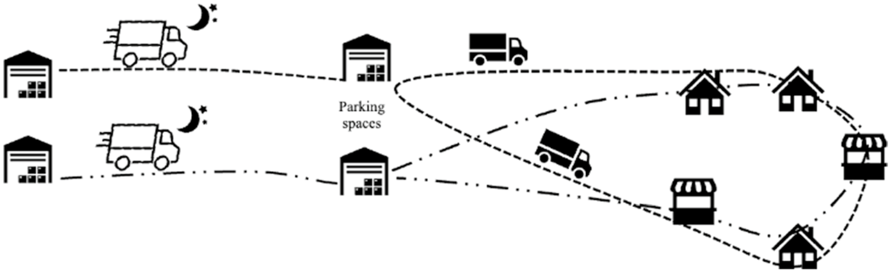

Fig. 4 Scenario 1- Distribution using vans from the transhipment spaces

Sect. 5.1.1, the parcels daily distributed by PC_H are 27,013, by PC_I are 13,968 and by PC_L are 923.

The daily transportation costs are computed using Eqs. (8) to (12), resulting in 58,020€ for PC_H, 30,397€ for PC_I, and 2,312€ for PC_L. Using Eq. (13) it is estimated the daily environmental costs: 86€, 47€ and 5€ for PC_H, PC_I, and PC_L, respectively. By dividing the total cost (Eq. (14)) by the volume of parcels delivered, we obtain the cost per parcel. Specifically, the cost per parcel for PC_H is 2.15€, for PC_I is 2.18€, and 2.51€ for PC_L.

The line haul and local distances, the required distribution time, as well as the transportation and parcel costs obtained using equations in Sect. 4.2 are detailed in Table 2.

5.2.2 Scenario 1: delivery by van from transhipment spaces

In the first scenario, parcel carriers use vans as the distribution vehicle from the transhipment spaces (Fig. 4).

Upon implementing the mathematical model for the PC_H and PC_I using vans, it is indicated that each zip code area should be equipped with a transhipment space to minimize rent and transportation costs. As a result, these two parcel carriers will require 41 transhipment points, with each one situated in a designated zip code area.

Table 3 Transhipment spaces open for $\mathrm{PC_L}$ and areas covered by them using vans

Transhipment location	Areas covered	Transhipment location	Areas covered
08002	08001, 08002, 08003	08026	08018, 08026
08004	08004, 08039	08028	08028
08005	08005	08029	08014, 08029,08036
08006	08006, 08012, 08021	08030	08030
08009	08009, 08010, 08013, 08037	08032	08031, 08032
08011	08007, 08008, 08011, 08015	08034	08034
08017	08017	08035	08035
08019	08019, 08020	08038	08038
08022	08022, 08023	08041	08027,08041
08024	08024, 08025	08042	08016, 08033, 08042

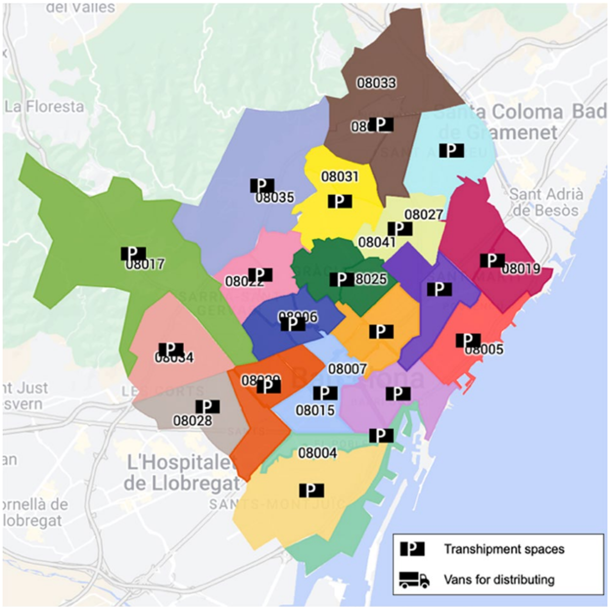

Fig. 5 Distribution areas for PC_L using transhipment points and vans

Using Eqs. (8) to (12), the daily transport costs for the PC_H and PC_I are calculated. This leads to daily costs of 68,110€ and 36,767€ for the PC_H and PC_I, respectively. Using Eq. (13) daily environmental costs are estimated, this results in for 160€ and 60€ for the PC_H and PC_I, respectively. Taking into account the total costs and the parcels distributed by each company, the parcel costs amount to 2.53€ and 2.64€, respectively.

For the PC_L, the mathematical model proposes to open 20 parking slots for servicing the 41 designated zip code areas. The location of the 20 parking slots and its

Table 4 Main performance indicators for scenario 1

		PC_H	PC_I	PC_L
Number of transhipment spaces	j	41	41	20
Line-haul distance (km)	Dlh	17,133	9,488	825
Local distance (km)	Dl	1,752	1,253	417
Time (h)	T	2,023	1,080	89
Transportation costs (€/daily)	C^T	68,110	36,767	3,312
Environmental costs (€/daily)	C^E	106	60	8
Total costs (€/daily)	C_{Total}	68,216	36,827	3,320
Cost per parcel (€)	C^P	2.53	2.64	3.60

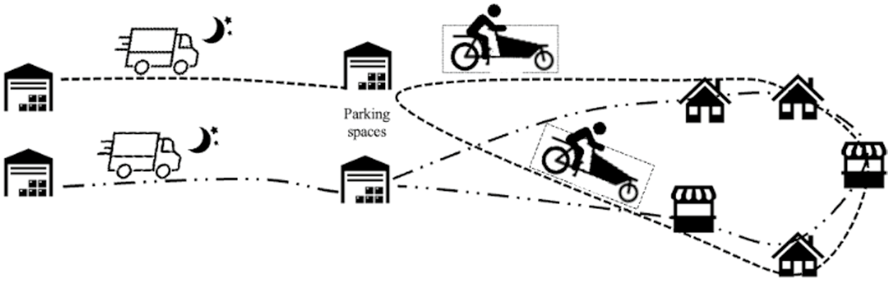

Fig. 6 Scenario 2- Distribution using cargo bikes from the transhipment spaces

distribution areas are presented in Table 3 and visually represented in Fig. 5, where each colour represents the area covered by the transhipment space drawn in the centre. Consequently, in this scenario, utilizing Eqs. (8) to (12) results in a daily transport cost of 3,312€, a daily transport cost of 8€ and a parcel cost of 3.60€. Table 4 summarises the main performance indicators of this scenario.

5.2.3 Scenario 2: delivery by cargo bike from transhipment spaces

In the second scenario, parcel carriers use cargo bikes for home deliveries from the transhipment spaces. As presented in Fig. 6, this transhipment points are supplied during night hours.

The maximum distribution radius is set to 3 kms with a vehicle capacity of 21 parcels, matching the specifications of a cargo bike.

The mathematical model located the 41 transhipment points, illustrated in Fig. 7, for both companies, PC_H and PC_I, each corresponding to a zip code, that are serviced by cargo bike. Conversely, for PC_L, the model suggests utilizing only 21 transhipment spaces to cover all the distribution area. In Fig. 8, the 21 areas allocated for PC_L are visually represented in different colours. In this case, for instance, zip code area 08008 covers the areas of the zip code areas 08007, 08008, 08011, 08036 and 08037. The areas covered by each transhipment space are detailed in Table 5.

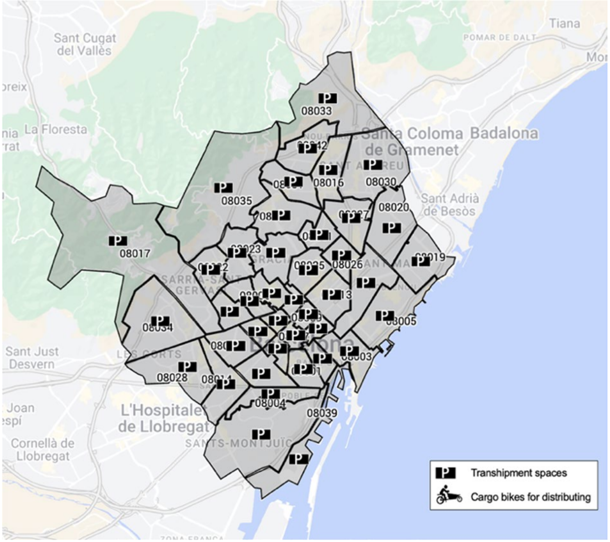

Fig. 7 Transhipment location for PC_H and PC_I by distributing using cargo bikes

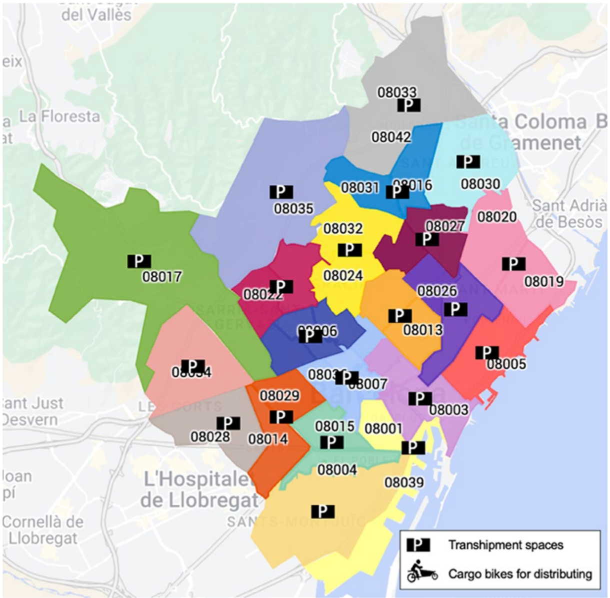

Fig. 8 Distribution areas for PC_L in scenario 2

Notice that for parcel carrier, PC_H and PC_I, it is obtained to allocate one parking slot per zip code area. In the case of PC_L, the mathematical model suggests using a single parking slot to service multiple zip code areas. These results indicate that the lowest costs, if the minimum demand and maximum radius are met,

Table 5 Transhipment spaces open and areas covered by them using cargo bikes for PC_L

Transhipment location	Areas covered	Transhipment location	Areas covered
08005	08005	08022	08022, 08023
08006	08006, 08012, 08021	08027	08027, 08041
08008	08007, 08008, 08011, 08036, 08037	08028	08028
08010	08002, 08003, 08009, 08010	08030	08030
08013	08013, 08025	08032	08024, 08032
08014	08014, 08029	08034	08034
08015	08004, 08015	08035	08035
08016	08016, 08031	08038	08038
08017	08017	08039	08001, 08039
08018	08018, 08026	08042	08033, 08042
08019	08019, 08020		

are achieved when distribution is conducted from transhipment points located in close proximity to the demand. However, in the case of PC_L, the company does not handle a sufficient volume to justify deploying a parking slot in each zip code area.

The transportation costs are calculated assuming that the transhipment points are replenished by van during the night. Hence, the velocity and the daily cost in Eq. (12), are 42.72 km/h and 37.69€/h respectively, which incorporates a 25% cost increase attributed to night time operations.

The line haul and local distances and the time required for the distribution are calculated with Eqs. (8) to (11). The resulting daily transport costs estimated using Eq. (12) are 41,972€, 22,726€, and 2,145 for PC_H, PC_I, and PC_L, respectively. The daily environmental cost calculated using Eq. (13) result in 94€, 52€ and 3€ for PC_H, PC_I, and PC_L, respectively. This translates to a cost per parcel of 1.56€, 1.63€, and 2.33€. Table 6 summarises the main indicators obtained for this scenario.

Table 6 Main performance indicators for scenario 2

		PC_H	PC_I	PC_L
Number of transhipment spaces	j	41	41	21
Line-haul distance (km)	Dlh	17,133	9,488	831
Local distance (km)	Dl	1,766	1,270	409
Time (h)	T	2,275	1,214	105
Transportation costs (€/daily)	C^T	41,972	22,726	2,145
Environmental costs (€/daily)	C^E	94	52	3
Total costs (€/daily)	C_{Total}	42,066	22,778	2,149
Cost per parcel (€)	C^P	1.56	1.63	2.33

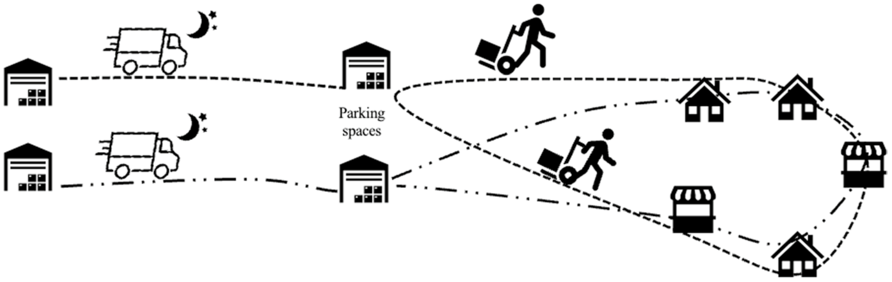

Fig. 9 Scenario 3- Distribution on foot from the transhipment spaces

5.2.4 Scenario 3: delivery on foot from transhipment spaces

In the third scenario, the parking spaces are also supplied at night, but the parcel delivery is done by foot with trolleys (Fig. 9).

The maximum radius is set to 1 km and a trolley has a capacity of 15 parcels. Additionally, as mentioned earlier, we consider a minimum demand of 35 parcels per parking lot to ensure long-term economic sustainability.

For PC_H and PC_I, the mathematical program indicates that there is no optimal solution for delivering to every zip code of Barcelona exclusively on foot. Instead, it suggests that 32 zip code areas meet the maximum radius and minimum demand constraints, allowing them to have their own transhipment point and be serviced using trolleys. However, nine areas do not meet the maximum radius constraint for having their own transhipment point. Hence, the algorithm (Fig. 1) proposes using cargo bikes as the distribution vehicle in these nine areas, which leads to the allocation of one transhipment space for each of them. Therefore, 41 transhipment spaces are utilized, 32 serviced by trolleys and 9 by cargo bikes.

Applying Eqs. (8) to (13) yields the transportation and environmental costs for PC_H. This includes both on-foot distribution for 32 zip code areas and cargo bike distribution for nine zip code areas, all originating from their respective transhipment points. The total costs (Eq. (14)) amounts to 34,439€ per day, being 34,403€ per day transport cost, 36€ environmental cost per day, and resulting in 1.28€ cost per parcel.

For PC_I, transportation and environmental costs are also calculated using Eqs. (8) to (13). If distribution is executed using both trolleys and cargo bikes, the daily transport, environmental and parcel costs for PC_I are 18,925€, 19€ and 1.35€, respectively.

It's worth noting that for $\mathrm{PC_H}$ and $\mathrm{PC_I}$, the parking slots correspond to one per zip code area whether distributing by trolley and cargo bike. Thus, the distribution areas for $\mathrm{PC_H}$ and $\mathrm{PC_I}$ for on-foot distribution are all the zip code except 08005, 08014, 08017, 08018, 08033, 08034, 08035, 08038 and 08039. These zip code areas are serviced by cargo bike, each having a designated transhipment point.

Regarding PC_L, the mathematical model indicates that there is no optimal solution for exclusive on-foot delivery to all zip code areas. It suggests that only three zip code areas meet the criteria of minimum demand and maximum radius for foot

Table 7 Transhipment spaces open and areas covered using cargo bikes for PC_L

Transhipment location	Areas covered	Transhipment location	Areas covered
08004	08004, 08015	08019	08019, 08026
08006	08006, 08012, 08021	08023	08022, 08023
08008	08007, 08008, 08011, 08036, 08037	08024	08024, 08032
08010	08002, 08003, 08009, 08010	08027	08027, 08041
08013	08013, 08025	08034	08034
08014	08014, 08029	08035	08035
08016	08016, 08031	08038	08038
08017	08017	08039	08001, 08039
08018	08005, 08018	08042	08033, 08042

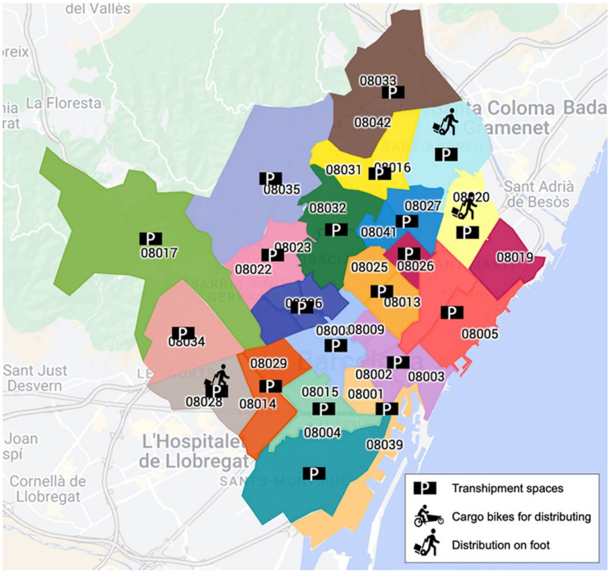

Fig. 10 Distribution areas for PC_L in scenario 3

distribution (08020, 08028 and 08030). As presented in the algorithm in Fig. 1, it is employed a vehicle with a larger maximum radius to cover areas that cannot be reached through foot distribution.

When using cargo bikes for the remaining 39 zip code areas, as per the implementation of the mathematical model to minimize rent and transportation costs, it is advised to utilize 18 transhipment points for covering these areas. The distribution areas for distributing by cargo bike to complement the transhipment spaces delivered on foot are presented in Table 7 and visually shown in Fig. 10.

The daily transport and environmental and parcel costs for PC_L are computed using Eqs. (8)–(13). In the case of using cargo bikes to complement the 39 zip code

Table 8 Main performance indicators for scenario 3

		PC_H	PC_I	PC_L
		Foot + cargo	Foot + cargo	Foot + cargo
Number of transhipment spaces	j	32 + 9	32 + 9	3 + 18
Line-haul distance (km)	Dlh	17,133	9,488	833
Local distance (km)	Dl	1,766	1,270	404
Time (h)	T	2,508	1,366	111
Transportation costs (€/daily)	C^T	34,403	18,906	2,106
Environmental costs (€/daily)	C^E	36	19	3
Total costs (€/daily)	C_{Total}	34,439	18,925	2,109
Cost per parcel (€)	C^P	1.28	1.35	2.28

areas that cannot be reached on foot, the daily transportation, daily environmental and parcel costs are 2,106€, 3€ and 2.28€, respectively. Table 8 shows the results obtained for this scenario.

5.3 Discussion

This section discusses the changes in transportation and environmental costs, and consequently, the cost per parcel, for the various scenarios and alternatives studied, based on the results presented in Tables 2, 4, 6 and 8.

When comparing the base scenario with the use of transhipment spaces for distributing by cargo bikes or trolleys, the results indicate that regardless of the volume distributed by the parcel carrier, both environmental and transportation costs are reduced. Although more line-haul and local distance are covered when using transhipment points, the cost difference between distributing by van (30.15€ per hour) and by cargo bike (15.54€ per hour) or trolley (8.81€ per hour) makes the option of delivering with a zero-emissions vehicle more profitable. While more distance is covered when distributing by cargo bike and trolley, more time is needed for distribution. Therefore, for longer distribution times using a cargo bike and trolley, more resources (including personnel and vehicles for distribution) will be required to ensure timely delivery.

Considering the use of transhipment spaces in scenario 3, along with trolleys and cargo bikes (to cover areas not accessible by trolleys), proves to be the most profitable scenario for any company. It reduces the total costs by 41% for PC_H, 38% for PC_I, and 9% for PC_L compared to the base model. Although delivering from transhipment points only by cargo bikes is not the optimal choice, it still yields more profitable results than the base scenario by reducing transportation costs by 28% for PC_H, 25% for PC_I, and 8% for PC_L. The reduction in parcel cost due to the utilization of transshipment centers is less significant for parcel carriers handling fewer packages. However, its feasibility could be enhanced if integrated with additional operations, including value-added activities like labeling or product storage, aimed at increasing economic profitability (Aljohani and Thompson 2021; Janjevic 2015).

The scenario where distribution is conducted using transhipment spaces and vans proves to be the most expensive option, being 18%, 21%, and 43% more costly than the base scenario for PC_H, PC_I and PC_L, respectively.

It is worth mentioning that the minimum demand to open a transhipment space has been set at 35 parcels per day. This constraint does not affect parcel carriers that handle a large volume of parcels, as is the case for PC_H and PC_I. However, it does affect PC_L, which must cover different zip code areas from only one transshipment point. This threshold of 35 parcels has been derived from a real case that achieved economic sustainability by paying a rent of 20€ per day for a parking slot. However, if this rent cost increases, the minimum daily demand will also need to be higher to adapt to the new rental costs. This scenario may not affect the result obtained for transshipment spaces PC_H and PC_I, but for PC_L, as their volume falls within the same range, the trashipment spaces to use should be recalculated.

Concerning the constraint of the maximum delivery radius for distributing by trolley and cargo bikes, the distances of 1 and 3 kms have been derived from real-world cases. If a higher radius for cargo bikes is used, for PC_H and PC_I, it is not necessary to recalculate the transhipment spaces to open, as it does not affect these cases. However, for the case of PC_L, it is necessary to reevaluate it. On the contrary, if a smaller radius for cargo bikes is utilized, a revaluation of the scenarios for each parcel carrier becomes necessary. Similarly, for the maximum delivery radius of distributing on foot, regardless of the scenario, the results should be reassessed, as this constraint significantly influences the obtained outcomes.

Through the proposed methodology in this paper, we have demonstrated that in the case of Barcelona, employing transhipment points in parking slots allows parcel carriers to significantly reduce their transportation and environmental costs. In Scenario 3, where transhipment points are utilized with trolleys and cargo bikes: for PC_H total costs are reduced from 58,106€ daily to 34,439€, for PC_I total costs are reduced from 30,444€ daily to 18,925€ and for PC_L, total costs are reduced from 2,317€ daily to 2,109€. These findings demonstrate a substantial opportunity for various parcel carriers to enhance their distribution models by adopting the proposed methodology.

It is important to emphasize that this analysis does not take into consideration the topography of the city. While the lower part of Barcelona is mostly flat, the upper part features a significant slope. This factor could impact the speed of foot or bicycle distribution. Furthermore, in sparsely populated areas with limited public transport and higher car usage, it is worthwhile to compare the costs of establishing transhipment centres equipped with lockers. These facilities may prove to be highly practical given these particular characteristics.

6 Conclusions

In this paper, we introduce a methodology aimed at incentivizing parcel carriers to shift towards an economically feasible and environmentally sustainable distribution mode within urban areas by leveraging their own transhipment space. Our methodology evaluates the profitability of utilizing parking spaces for transhipping parcels, taking into account the transportation vehicle used for the last mile delivery. This approach enables parcel carriers to ascertain the optimal number and locations of transhipment points. By employing this methodology, companies handling varying parcel volumes can investigate the feasibility of utilizing their own parking spaces to mitigate transportation and environmental expenses.

We implemented this proposal in the city of Barcelona for parcel carriers handling various parcel volumes: high, low, and intermediate. The results for this case in Barcelona indicate that, regardless of the volume handled by each parcel carrier, the scenario that effectively reduces transportation costs involves a combination of transhipment centres along with distribution by cargo bike and on foot. The total transportation cost reduction for the parcel carrier distributing the highest number of parcels in Barcelona is 41%. For the parcel carrier distributing an intermediate volume of parcels, the reduction in transport costs amounts to 38%. Additionally, for the company distributing the lowest number of parcels using this distribution model, the cost reduction is 9%. The results also highlight the time advantages of distributing solely by van without utilizing a transhipment point. However, the lower cost of resources used for distribution by cargo bike and on foot allows for the deployment of more resources, resulting in a significant cost reduction.

The comprehension of transport costs for B2C parcel carriers, depending on the vehicle used for the last mile delivery, can assist them in cost reduction. Furthermore, adopting zero-emission vehicles, as proposed in this paper, can alleviate congestion and mitigate environmental impacts. Consequently, these findings should motivate public administrations to reconsider their regulations concerning the use of parking spaces for logistic activities, and to promote their utilization.

Future research will focus on integrating the potential use of lockers or collection points into the methodology.

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Declarations

Conflict of interest The author declares no conflict of interest.

References

Ajuntament de Barcelona (2023a) Estratègia municipal de la distribució urbana de mercaderies (EDUM). Horitzó 2030

Ajuntament de Barcelona (2023b) Pla especial urbanístic de noves activitats en els aparcaments de la ciutat de Barcelona. https://ajuntament.barcelona.cat

Alewijnse B, Hübl A (2021) Minimising total costs of a two-echelon multi-depot capacitated vehicle routing problem (2E-MD-CVRP) that describes the utilisation of the Amsterdam city canal network for last mile parcel delivery. In: IFIP advances in information and communication technology 633 IFIP. Springer International Publishing. https://doi.org/10.1007/978-3-030-85910-7_64

Aljohani K, Thompson RG (2021) Profitability of freight consolidation facilities: a detailed cost analysis based on theoretical modelling. Res Transp Econ. https://doi.org/10.1016/j.retrec.2021.101122

Allen J, Thorne G, Browne M (2007) Good practice guide on urban freight transport. In: BESTUFS. http://www.bestufs.net

Amazon Staff (2023) A delivery driver for Amazon gives us a tour of his van—see what it's like inside. https://www.aboutamazon.com

Ayuntamiento de Madrid (2023) Abre sus puertas el `hub´ Canalejas 360 con la electrolinera urbana más potente de España. Retrieved October 20, 2023, from https://www.madrid.es

Barcelona Oberta (2019) L'anàlisi del comerç a Barcelona: físic i online Recomanacions per a guanyar competitivitat.

Bayliss C, Bektaş T, Tjon-Soei-Len V, Rohner R (2023) Designing a multi-modal and variable-echelon delivery system for last-mile logistics. Eur J Oper Res 307(2):645–662. https://doi.org/10.1016/j.ejor.2022.08.041

Björklund M, Abrahamsson M, Johansson H (2017) Critical factors for viable business models for urban consolidation centres. Res Transp Econ 64:36–47. https://doi.org/10.1016/j.retrec.2017.09.009

Browne M, Sweet M, Woodburn A, Allen J (2005) Urban freight consolidation centres final report. In: University of Westminster

Campbell J, Macphail L, Cornelis G (2010) Freight consolidation centre study final report prepared by final report transport planner. pp 1–46

Catapult Transport Systems (2018) Consolidating public sector logistics operations. Final report. https://s3-eu-west-1.amazonaws.com

Chronopost (2016) CP ELU Paris- Concorde. https://www.chronopost.fr

Chronopost (2020) Notre engagement responsable. https://www.chronopost.fr

Ciardiello F, Genovese A, Luo S, Sgalambro A (2021) A game-theoretic multi-stakeholder model for cost allocation in urban consolidation centres. Ann Oper Res. https://doi.org/10.1007/s10479-021-04013-3

Cityporto Padova (2021) Cityporto Padova Freight mobility in urban areas A successful model of citylogistics. www.cityporto.it

Correos (2022) Parcel delivery at the best price. Retrieved April 27, 2022, from https://www.correos.es

Cortes JD, Suzuki Y (2022) Last-mile delivery efficiency: en route transloading in the parcel delivery industry. Int J Prod Res 60(9):2983–3000. https://doi.org/10.1080/00207543.2021.1907628

Cybo (2023) Barcelona, Catalonia Postal Code List. Retrieved October 16, 2023, from https://postal-codes.cybo.com

Daganzo CF (1984) Distance traveled to visit N points with a maximum of C stops per vehicle: an analytical model and an application. Transp Sci 18(4):331–350. https://doi.org/10.1287/trsc.18.4.331

Dantrakul S, Likasiri C, Pongvuthithum R (2014) Applied p-median and p-center algorithms for facility location problems. Expert Syst Appl 41(8):3596–3604. https://doi.org/10.1016/j.eswa.2013.11.046

Dupas R, Deschamps JC, Taniguchi E, Qureshi AG, Hsu T (2023) Optimizing the location selection of urban consolidation centers with sustainability considerations in the city of Bordeaux. Res Transp Bus Manag. https://doi.org/10.1016/j.rtbm.2022.100943

EIT Urban Mobility (2021) Prague successfully implements cargo bicycle hubs to reduce freight congestion in the inner city. Retrieved March 8, 2022, from https://marketplace.eiturbanmobility.eu

Enthoven DLJU, Jargalsaikhan B, Roodbergen KJ, Uit Het Broek MAJ, Schrotenboer AH (2020) The two-echelon vehicle routing problem with covering options: city logistics with cargo bikes and parcel lockers. Comput Op Res. https://doi.org/10.1016/j.cor.2020.104919

Epdata (2023) Buscador de renta media por códigos postales en España. Retrieved October 16, 2023, from https://www.epdata.es

Estrada M, Roca-Riu M (2017) Stakeholder's profitability of carrier-led consolidation strategies in urban goods distribution. Transp Res Part E: Logistics Transp Rev 104:165–188. https://doi.org/10.1016/j.tre.2017.06.009

Estrada M, Magín J (2017) Estratègies de distribució de mercaderies per fomentar una mobilitat més sostenible.

European Commission (2019) Handbook on the external costs of transport. In: European Commission

European Commission (2020) Sustainable and Smart Mobility Strategy–putting European transport on track for the future. https://ec.europa.eu

European Environment Agency (2014) EMEP/EEA emission inventory guidebook 2013 update Sept 2014 1.

Faugère L, White C, Montreuil B (2020) Mobile access hub deployment for urban parcel logistics. Sustainability (Switzerland). https://doi.org/10.3390/su12177213

Generalitat de Catalunya. (2023). Observatori de costos del transport de mercaderies per carretera a Catalunya. Número 91–abril 2023

Giampoldaki E, Madas M, Zeimpekis V, Vlachopoulou M (2023) A state-of-practice review of urban consolidation centres: practical insights and future challenges. Int J Log Res Appl 26(6):732–763. https://doi.org/10.1080/13675567.2021.1972950

Gruber J, Heldt B, Seidel S (2023) New neighborhood, old habits? Delivery preferences of residents in new development areas and their assessment of alternative parcel logistics concepts: a case study of Berlin. J Shipp Trade. https://doi.org/10.1186/s41072-023-00138-9

Hasse B (2021) Grand Paris: des dépôts-bus RATP prêts à accueillir des livraisons d'Amazon et Chronopost. Le Parisien, 2021. Retrieved October 20, 2023, from https://www.leparisien.fr

Institut d'Estadística de Catalunya. (2021) Nombre de compres a través d'Internet. https://www.idescat.cat

Janjevic M, Ndiaye A (2017) Investigating the theoretical cost-relationships of urban consolidation centres for their users. Transp Res Part A: Policy Practice 102:98–118. https://doi.org/10.1016/j.tra.2016.10.027

Janjevic M (2015) Urban freight consolidation centers–trends, challenges, solutions. European cycle logistics conference, san Sebastian.

Kania M, Rolf B, Assmann T, Zadek H (2022) The smaller, the better? Nano-hubs for cycle logistics as an urban-friendly alternative to micro-hubs. Logist J 2022(11):9–14. https://doi.org/10.2195/lj_Proc_kania_en_202211_01

Komodo (2018) KoMoDo: Projektpartner. https://www.komodo.berlin/projektpartner/

Lebeau P, Verlinde S, Macharis C, Van Mierlo J (2017) How can authorities support urban consolidation centres? A review of the accompanying measures. J Urban 10(4):468–486. https://doi.org/10.1080/17549175.2017.1310747

Leyerer M, Sonneberg MO, Heumann M, Breitner MH (2019) Decision support for sustainable and resilience-oriented urban parcel delivery. EURO J Decision Process 7(3–4):267–300. https://doi.org/10.1007/s40070-019-00105-5

Mepparambath RM, Cheah L, Courcoubetis L (2021) A theoretical framework to evaluate the traffic impact of urban freight consolidation centres. Transp Res Part E 145(January 2020):102134. https://doi.org/10.1016/j.tre.2020.102134

Nacex (2023) Localitzador de punts Nacex. Retrieved October 23, 2023, from https://www.nacex.es

Nationwide (2020) Understanding Van Size and Dimensions. https://www.nationwidevehiclecontracts.co.uk

Nourinejad M, Rooda MJ (2022) Locating urban consolidation centers under shipper rationality. J Adv Transp. https://doi.org/10.1155/2022/5078042

Paddeu D (2017) The Bristol-bath urban freight consolidation centre from the perspective of its users. Case Stud Transp Policy 5(3):483–491. https://doi.org/10.1016/j.cstp.2017.06.001

Ramells Ramoneda (2023) Retribució del treball nocturn: el plus de nocturnitat. Retrieved October 20, 2023, from https://www.ramells.com

Robusté F, Daganzo CF, Souleyrette RR (1990) Implementing vehicle routing models. Transp Res Part B 24(4):263–286. https://doi.org/10.1016/0191-2615(90)90002-G

Rosenberg LN, Balouka N, Herer YT, Dani E, Gasparin P, Dobers K, Rüdiger D, Pättiniemi P, Portheine P, van Uden S (2021) Introducing the shared micro-depot network for last-mile logistics. Sustainability (switzerland) 13(4):1–21. https://doi.org/10.3390/su13042067

Saba (2023) Cercador de Parkings - Localitza pàrquing a prop teu. Retrieved October 18, 2023, from https://www.saba.es

Simoni MD, Bujanovic P, Boyles SD, Kutanoglu E (2018) Urban consolidation solutions for parcel delivery considering location, fleet and route choice. Case Stud Transp Policy 6(1):112–124. https://doi.org/10.1016/j.cstp.2017.11.002

Stockholms stad (2014) The Stockholm Freight Plan. https://frevue.eu

Talent (2023) Salario para Repartidor en España, 2023. https://es.talent.com/salary?job=repartidor

The Green Link (2014) LAMILO. Sustainable city logistics. https://www.urbantransportgroup.org/system/files/general-docs/Michael Darchambeau.pdf

TomTom Traffic Index. (2023). *Barcelona traffic report*. https://www.tomtom.com/traffic-index/barcelona-traffic/

Transport for London (2019) Freight and servicing action plan. pp 1–150.

Van Duin R, Quak H, Muñuzuri J (2010) New challenges for urban consolidation centres: a case study in The Hague. Proc Soc Behav Sci 2(3):6177–6188. https://doi.org/10.1016/j.sbspro.2010.04.029

van Rooijen T, Quak H (2010) Local impacts of a new urban consolidation centre – the case of Binnenstadservice.nl. Proc - Soc Behav Sci 2(3):5967–5979. https://doi.org/10.1016/j.sbspro.2010.04.011

Van Heeswijk W, Larsen R, Larsen A (2019) An urban consolidation center in the city of Copenhagen: a simulation study. Int J Sustain Transp. https://doi.org/10.1080/15568318.2018.1503380

Verlinde S, Macharis C, Milan L, Kin B (2014) Does a mobile depot make urban deliveries faster, more sustainable and more economically viable: results of a pilot test in Brussels. Transp Res Proc 4:361–373. https://doi.org/10.1016/j.trpro.2014.11.027

Zhang L, Matteis T, Thaller C, Liedtke G (2018) Simulation-based assessment of cargo bicycle and pick-up point in urban parcel delivery. Proc Comput Sci 130:18–25. https://doi.org/10.1016/j.procs.2018.04.007

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