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RESEARCH ARTICLE

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Assessing the potential impacts of public transport-based crowdshipping: A case study in a central district of Copenhagen

Abstract The expansion of e-commerce and the sharing economy has paved the way for crowdshipping as an innovative approach to addressing last-mile delivery challenges. Previous studies and implementations have predominantly concentrated on private vehicle-based crowdshipping, which may lead to increased traffic congestion and emissions due to additional trips made specifically for deliveries. To circumvent these possible adverse effects, this paper explores a public transport (PT)-based crowdshipping concept as a complementary solution to the traditional parcel delivery systems. In this model, PT users leverage their routine journeys to perform delivery tasks. We propose a methodology that includes a parcel locker location model and a vehicle routing model to analyze the effect of PT-based crowdshipping. Notably, the parcel locker location model aids in planning a PT-based crowdshipping network and identifying obstacles to its development. A case study conducted in the central district of Copenhagen utilizing real-world data assesses the effects of PT-based crowdshipping. The findings suggest that PT-based crowdshipping can decrease the total kilometers traveled by vehicles, the overall working hours of drivers, and the number of vans required for last-mile deliveries, thereby alleviating urban traffic congestion and environmental pollution. Nevertheless, the growth of PT-based crowdshipping may be limited by the availability of crowdshippers, indicating that initiatives to increase the number of crowdshippers are essential.

Keywords last-mile delivery, crowdshipping, public transport-based crowdshipping, integrated passenger and freight transportation, impact assessment

1 Introduction

E-commerce has experienced substantial growth in the past decade. Global e-commerce sales reached \$5.311 trillion in 2022, a significant increase from \$1.336 trillion in 2014, and are projected to reach \$8.034 trillion by 2027 (Statista, 2024). This growth presents not only business opportunities but also significant challenges for retailers and logistics service providers. On the one hand, companies stand to generate increased revenues due to higher demand. On the other hand, the final step of delivery, known as last-mile delivery, has become crucial for securing a competitive edge in the market. Consumers now place high importance on delivery speed and flexibility (Gevaers et al., 2011; Lim et al., 2018; Boysen et al., 2021). Additionally, the escalating demand for transportation has led to a surge of delivery vans in urban areas, leading to worsening traffic congestion and environmental concerns. As a result, both industry professionals and researchers are actively seeking efficient and sustainable solutions for last-mile delivery.

One emerging solution to last-mile delivery is the implementation of parcel lockers, which offer numerous advantages. By utilizing centralized facilities, logistics companies can take advantage of economies of scale and reduce the costs associated with "not-at-home" delivery. Parcel lockers also provide recipients with the convenience of retrieving their parcels at their own convenience, without the need to wait for a delivery person or worry about

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missed attempts. Furthermore, parcel lockers facilitate contactless delivery, making them particularly valuable in situations where minimal interaction is preferred, such as during a pandemic. According to a report by the European Regulators Group for Postal Services (2022), the number of parcel lockers has seen significant growth in various countries, notably, Denmark (from 465 in 2017 to 1740 in 2021), Finland (from 487 in 2017 to 2288 in 2021), and Norway (from 191 in 2020 to 2800 in 2021).

In recent years, the concept of crowdshipping, inspired by successful business models in the sharing economy (e.g., Uber and Airbnb), has emerged as another innovative solution for last-mile delivery. In a crowdshipping system, individuals leverage their spare time and/or available space to deliver parcels in exchange for monetary compensation. Both logistics service providers and E-retailers have tested crowdshipping through various experiments (Alnaggar et al., 2021). For instance, in 2013, DHL launched a project called "Myways" in Stockholm, which allowed individuals to deliver parcels while en route to their destinations. In 2015, Amazon proposed "Amazon Flex", a service where ordinary people use their own vehicles to deliver Amazon orders to customers. This service is now operational in more than 50 cities.

There are different approaches to implementing crowdshipping. The majority of previous research and practical applications have focused on using personal vehicles, leading to dedicated trips or detours that often cannot be avoided (Punel and Stathopoulos, 2017; Allahviranloo and Baghestani, 2019). These personal vehicle-based models could result in rebound effects, where emissions increase rather than decrease (Buldeo Rai et al., 2018). Moreover, sharing economy concepts have frequently faced criticism for jeopardizing workers' rights and contributing to a precarious "gig economy" (Paus, 2018). To leverage the advantages of parcel lockers and crowdshipping while mitigating the disadvantages of crowdshipping with personal vehicles, this paper focuses on public transport (PT)-based crowdshipping. This concept is considered a method of integrating the transportation of people and goods (Cheng et al., 2023a), which aligns with the European Commission's call for the integration of passenger and freight transportation (European Commission, 2007). Figure 1 provides a schematic overview of PT-based crowdshipping. Before investigating the specifics of our PT-based crowdshipping approach, we will first clarify the terminology used in this context. It is important to note that in our PT-based crowdshipping concept, all parcel lockers are installed at PT stations.

Recipients: Customers who purchase a PT-based crowdshipping service. They are also the owners of the parcels.

Pickup Parcel Lockers (P-PL): Parcel lockers that crowdshippers use to collect parcels. In this study, these lockers are positioned at PT stations near the distribution center, and their locations are predetermined.

Delivery Parcel Lockers (D-PL): Parcel lockers that crowdshippers use to drop off parcels. These lockers are where the final recipients collect their parcels. The locations of D-PLs are determined by the model presented in Section 3.3.

In the traditional distribution model, all parcels are delivered by vans owned and operated by logistics companies. In our PT-based crowdshipping, parcel lockers are installed in selected PT stations to accommodate small parcels. Portions of parcels, referred to as crowdshipped parcels, transition from vans to crowdshippers. The journey of these crowdshipped parcels from the distribution center to their final destinations consists of three legs. In the first leg, crowdshipped parcels are transported by trucks from the distribution center to P-PLs located at PT stations near the distribution center. In the second leg, crowdshippers, who are users of the PT

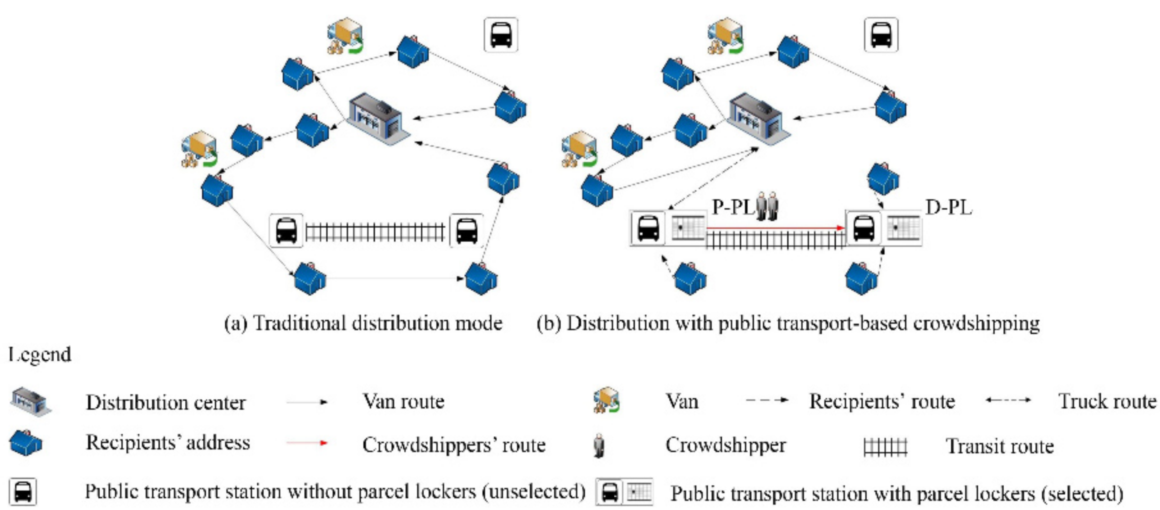

Fig. 1 An illustration of PT-based crowdshipping.

system, transport parcels between different PT stations. They retrieve crowdshipped parcels from P-PLs at their initial PT stations, undertake PT trips, and deliver the parcels to D-PLs at their destination PT stations. The final leg is completed by recipients who retrieve their parcels from D-PLs located at PT stations near their residences. It should be noted that crowdshippers are compensated with credit from transit systems. This ensures that only trips that would have been made anyway are utilized, thus preventing crowdshipping from creating a new precarious job market lacking workers' rights.

It is anticipated that PT-based crowdshipping will have a positive impact on traffic congestion and environmental pollution by reducing the number of vans entering the city center and the total distance traveled by vehicles. Prior to implementing a PT-based crowdshipping service, operators should investigate the attitudes and preferences of their target customers and evaluate the potential benefits of this service. This would allow operators to customize the service to meet customer needs and increase its adoption rate. Fessler et al. (2022) conducted a study in this field analyzing passengers' preferences for PT-based crowdshipping in the Greater Copenhagen Area. In contrast, this study focuses on assessing the impacts of this service to explore its potential benefits.

The contributions of this paper can be summarized as follows. First, we provide additional insights into the limited studies on PT-based crowdshipping. Second, we develop an approach to estimate the impacts of PT-based crowdshipping, which includes a parcel locker location model and a vehicle routing model. The parcel locker location model not only assists in the strategic planning of a PT-based crowdshipping network but also provides guidance on the efforts required to achieve various development objectives for PT-based crowdshipping. Third, we quantify the potential benefits of PT-based crowdshipping in terms of reducing the number of vehicle kilometers traveled, easing drivers' workloads, and addressing driver shortages based on a case study that utilizes real-world data. Furthermore, our analysis demonstrates that PT-based crowdshipping outperforms the parcel locker solution, especially in terms of reducing the number of vans (drivers) used.

The rest of the paper is organized as follows. Section 2 reviews the literature on PT-based crowdshipping. Section 3 presents the methodology used to assess the impacts of PT-based crowdshipping. Section 4 presents the results of a case study. Finally, Section 5 concludes the paper and outlines future research directions.

2 Related works

Although PT-based crowdshipping is not a completely new concept, there is still relatively limited research on this topic compared to personal vehicle-based crowdshipping. This section provides an overview of related studies in this field.

As mentioned in Section 1, PT-based crowdshipping involves three legs: the first leg delivery (from the parcel's origin to the PT system), the PT trip, and the last leg delivery (from the PT system to the parcel's destination). We categorize three ways of organizing PT-based crowdshipping based on which legs involve the participation of crowdshippers.

- **Crowdshippers involved in the first and last legs (P1)**

Kızıl and Yıldız (2023) proposed a system in which crowdshippers are responsible for the first and last legs of transportation, which typically involve short distances. In cases where crowdshippers are unable to handle parcels, backup delivery vehicles are utilized. Their study presented an optimization model to determine the optimal locations for parcel lockers and routes for backup delivery vehicles. The objective of this system is to minimize the overall transportation cost of the backup vehicles. The results of a case study conducted in Istanbul demonstrated that integrating public transport into the crowdshipping system could help mitigate the negative externalities associated with last-mile delivery operations.

- **Crowdshippers involved in the PT trip and the last leg (P2)**

Zhang et al. (2023) and Zhang and Cheah (2024) investigated a PT-based crowdshipping system in which crowdshippers are involved in the PT trip and the final leg of delivery. Under this system, logistics companies transport crowdshipped parcels from the distribution center to parcel lockers located at PT stations. Crowdshippers then pick up parcels, utilize public transport and deliver parcels to their final destinations. The researchers developed a parcel allocation model and a vehicle routing model to evaluate the impact of this PT-based crowdshipping system. The findings from a case study conducted in Singapore demonstrated that this approach can reduce the number of vehicle kilometers traveled and the associated air emissions.

- **Crowdshippers involved only in the PT trip (P3)**

In contrast to the previous two PT-based crowdshipping systems, where customers wait for parcel delivery at home, in this system, customers pick up their parcels from designated parcel lockers at PT stations. Logistics companies and crowdshippers are responsible for the initial leg and PT trips, respectively. Several studies have been conducted on this concept from different perspectives. Gatta et al. (2019) estimated people's willingness to participate as crowdshippers and utilize a PT-based crowdshipping service through a survey conducted in Rome. The results emphasized the importance of flexible delivery times for customers and the need to provide compensation for passengers involved in PT-based crowdshipping. This finding aligns with the observations

Table 1 Ways of implementing PT-based crowdshipping

	First leg	PT trip	Last leg	References
P1	Crowdshipper and backup delivery vans	PT lines	Crowdshipper and backup delivery vans	Kızıl and Yıldız (2023)
P2	Logistics company	Crowdshipper	Crowdshipper	Zhang et al. (2023); Zhang and Cheah (2024)
P3	Logistics company	Crowdshipper	Recipient	Gatta et al. (2019); Fessler et al. (2022); Karakikes and Nathanail (2022); This study

of Fessler et al. (2022), who analyzed passengers' willingness to act as crowdshippers based on a survey conducted in Copenhagen. Assuming that the locations of the pickup and delivery parcel lockers are predetermined, Karakikes and Nathanail (2022) estimated the impact of PT-based crowdshipping by developing a city-scale traffic freight microsimulation model using PTV Vissim. They used a mid-sized Greek city as an example. The simulation results demonstrated the positive effects of PT-based crowdshipping on reducing traffic congestion and air pollution.

Each PT-based crowdshipping system has its own set of advantages and challenges. P1 has the potential to have the most significant impact on reducing delivery vehicle miles traveled by utilizing PT lines, but it also presents several practical challenges. For instance, passenger vehicles and PT stations need to be retrofitted to facilitate the safe movement of parcels. Additionally, dedicated operators might be needed to handle parcels at PT stations. P2 and P3 are easier to implement in practice than P1. Analyzing P2 and P3, it is more likely that P3 will attract a larger number of passengers to act as crowdshippers. This is because P3 does not require crowdshippers to make the final delivery to customers, the direction of which might be opposite to the crowdshippers' intended destinations. This requirement in P2 reduces passengers' willingness to act as crowdshippers. However, P3 may have lower crowdshipping demand since it requires customers to collect parcels from D-PLs at PT stations near their homes instead of having the parcels delivered to their homes. Nevertheless, this drawback could be mitigated by optimizing the locations of D-PLs, as a case study in Rome (Iannaccone et al., 2021) has shown that over 72% of customers would like to opt for picking up parcels from nearby parcel lockers if the lockers are within a short distance (less than 500 m) and accessible 24/7, and they are offered a small incentive (€ 1). Even without a small incentive, the probability of a customer being willing to collect parcels from parcel lockers exceeds 60%. Given that PT stations accessible around the clock and parcel lockers are cost-effective and that many countries have plans to expand their parcel locker networks, we believe that P3 is a promising and sustainable solution for last-mile delivery, provided that the locations of parcel lockers are well designed.

It is important to note that compared to the literature on P1 and P2, which focuses on mathematical modeling techniques to optimize operations and analyze impacts, research on P3 offers a broader perspective, including the analysis of commuters' willingness to participate as crowdshippers on the supply side, evaluating customers' readiness to adopt a PT-based crowdshipping service on the demand side, and assessing associated impacts using simulation methodology. However, there is still a research gap in terms of optimizing the layout of P3 and exploring alternative methods for impact assessment beyond simulation.

This study aims to fill this research gap by utilizing mathematical models, which provide a clear and analytical framework for understanding the system. These models can offer insights that may not be readily apparent through simulation alone. Furthermore, this study utilizes real-world public transport data, which sets it apart from the literature on P3.

3 Methodology

3.1 Overview of the methodology

Figure 2 shows an overview of the modeling framework used to evaluate the impacts of PT-based crowdshipping. The framework categorizes parcels into van delivery parcels and crowdshipped parcels (Arrows 1 and 2 in Fig. 2). Various factors from both the demand and supply sides influence the number of crowdshipped parcels.

On the demand side, the primary influencing factors include the following:

DF1) Parcels' attributes such as weight, size, and type;

DF2) Customers' willingness to collect their parcels from parcel lockers instead of from home. This is mainly influenced by the distance between parcel lockers and homes and the accessibility of parcel lockers.

From the supply side, the primary influencing factors include the following:

SF1) The number of passengers traveling between specific PT stations;

SF2) Passengers' willingness to act as crowdshippers. This is mainly influenced by passengers' sociodemographic characteristics and compensation;

SF3) The deployment of parcel lockers.

It is important to note that this study focuses on assessing the impacts of PT-based crowdshipping rather than investigating customers' and passengers' preferences for this

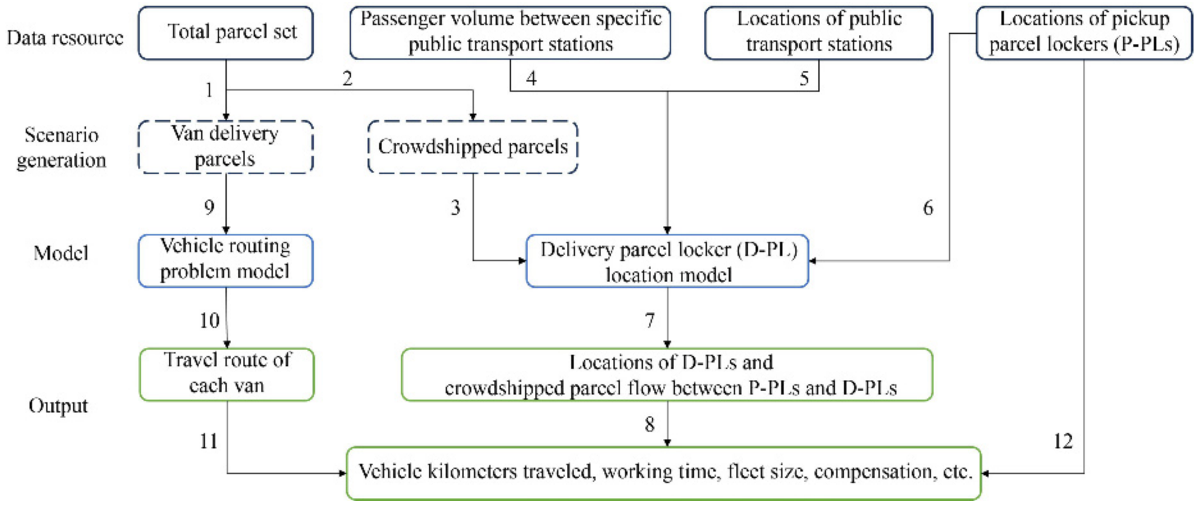

Fig. 2 Overview of the modeling framework.

service. Thus, crowdshippers and deliveries are predetermined to be “matched” based on given levels of demand and passenger volumes between specific PT stations. To ensure that the number of crowdshipped parcels is not limited by the availability of D-PLs, a D-PL location model is developed (Section 3.3). This model determines the locations of D-PLs, ensuring that each customer can be served by at least one D-PL within a short distance from their homes. The inputs of this model include crowdshipped parcels, passenger volume between specific PT stations, the locations of PT stations, and the locations of P-PLs (Arrows 3, 4, 5, and 6 in Fig. 2). The outputs of this model are the selected PT stations for installing D-PLs and the flow of crowdshipped parcels between P-PLs and D-PLs (Arrow 7 in Fig. 2). Depending on the compensation scheme, such as fixed compensation per crowdshipper or per parcel, the flow of crowdshipped parcels affects the total compensation cost (Arrow 8 in Fig. 2). This is because crowdshippers might carry multiple parcels per trip. By conducting sensitivity analysis on certain parameters within this model, we can gain insights into potential actions and strategies that can be implemented to achieve the objective of shifting a certain percentage of parcels from vans to crowdshippers (Section 4.2).

For van delivery parcels, a vehicle routing model is developed (Section 3.4) to determine the routes of the vans (Arrows 9 and 10 in Fig. 2). Based on the solutions provided by the vehicle routing model, various indicators related to vans can be calculated, such as the number of vehicle kilometers traveled, the working time of van drivers, and the number of vans used (Arrow 11 in Fig. 2). Since the initial transportation of crowdshipped parcels from the distribution center to P-PLs is performed by trucks, the assessment of the impacts of PT-based crowdshipping also takes into account indicators related to trucks that are associated with the locations of P-PLs (Arrow 12 in Fig. 2).

3.2 Notations and assumptions

The specifications used in the delivery parcel locker location model and vehicle routing model are listed in Table 2.

The following assumptions are made.

- All parcels are delivered on the same day.
- Only one parcel locker is installed at each selected PT station, but the capacity of parcel lockers is sufficient to meet the demand. In reality, the required capacity can be estimated according to the results of the D-PL location model.
- Given a specific compensation level, passengers' willingness to act as crowdshippers $Pr_{\text{csshipper}}$ is uniformly distributed. The value of $Pr_{\text{csshipper}}$ is influenced by many factors such as compensation, crowdshippers' age. We cautiously set the value of $Pr_{\text{csshipper}}$ as the smallest value provided in Fessler et al. (2022).
- The speed of the vans is constant.
- The distance matrix is obtained by finding the shortest path between two nodes using the Julia package (OpenStreetMapX.jl).

3.3 Delivery parcel locker location model

The D-PL location model is formulated as follows:

$$\min \sum_{i \in S^d} y_i, \tag{1}$$

s.t.

$$\sum_{a \in S^o} \sum_{i \in S^d} w_{aij} = Q_j^{cs}, \quad \forall j \in V_{cs}, \tag{2}$$

$$\sum_{j \in V_{cs}} w_{aij} \leqslant y_i L_{ai} \eta Pr_{\text{csshipper}}, \quad \forall a \in S^o, \ i \in S^d, \tag{3}$$

Table 2 Notations

Sets	
K	Set of homogeneous delivery vans, $K=\{1,2,\ldots,\lvert K\rvert\}$, where $\lvert K\rvert$ is the number of vans
S^o	Set of PT stations to install P-PLs, $S^o=\{1,2,\ldots,\lvert S^o\rvert\}$, where $\lvert S^o\rvert$ is the number of candidate PT stations to install P-PLs
S^d	Set of candidate PT stations to install D-PLs, $S^d=\{1,2,\ldots,\lvert S^d\rvert\}$, where $\lvert S^d\rvert$ is the number of candidate PT stations to install D-PLs
V_{cs}	Set of crowdshipping customers, $V_{cs}=\{1,2,\ldots,\lvert V_{cs}\rvert\}$, where $\lvert V_{cs}\rvert$ is the number of crowdshipping customers
V_h	Set of van delivery customers, $V_h=\{1,2,\ldots,\lvert V_h\rvert\}$, where $\lvert V_h\rvert$ is the number of home delivery customers
N	$N=V_h\cup\{0,\lvert V_h\rvert+1\}$, where 0 and $\lvert V_h\rvert+1$ are the distribution center nodes indicating the start and end nodes of a van route
Parameters	
Cap	Capacity of a van
T_{ij}	Travel time between nodes $i\in N$ and $j\in N$
ST_j	Service time at node $j\in V_h$
$T_{\max}$	Maximum travel time of a van route
Q_j^{cs}	Demand value at crowdshipping customer node $j\in V_{cs}$
Q_j^h	Demand value at van delivery customer node $j\in V_h$
D_{ij}	Distance between nodes $i\in S^d$ and $j\in V_{cs}$
$D_{\max}$	Service range of a D-PL. It also represents the maximum walking distance customers are willing to travel to pick up their parcels
L_{ij}	The number of passengers traveling between $i\in S^o$ and $j\in S^d$
η	The average number of parcels a crowdshipper takes per trip
$Pr_{\text{csshipper}}$	The probability of a passenger acting as a crowdshipper
Variables	
w_{aij}	Amount of crowdshipped parcels traveling from $a\in S^o$ to $i\in S^d$ and finally picked up by customer $j\in V_{cs}$
y_i	$y_i=1$, if a D-PL is installed D-PLs at $i\in S^d$; otherwise $y_i=0$
x_{ijk}	$x_{ijk}=1$, if van k travels from nodes $i\in N$ to $j\in N$; otherwise, $x_{ijk}=0$
t_{jk}	The arrival time of van k at node $j\in N$

$$w_{aij}\geqslant 0,\ \ \forall a\in S^o,\ \ i\in S^d,\ \ j\in V_{cs}, \tag{4}$$

$$w_{aij}=0,\ \ \forall a\in S^o,\ \ i\in S^d,\ \ j\in V_{cs},\ \text{ if }\ D_{ij}>D_{\max}, \tag{5}$$

$$y_i\in\{0,1\},\ \ \forall i\in S^d. \tag{6}$$

The objective function (1) minimizes the number of D-PLs. Constraint (2) ensures that the total crowdshipped parcel flow to node $j\in V_{cs}$ satisfies all demands. Constraint (3) ensures that if there is no D-PL at PT station $i\in S^d$, the crowdshipped parcel flow through $i\in S^d$ is zero; otherwise, the crowdshipped parcel flow between $a\in S^o$ and $i\in S^d$ does not exceed the product of the number of crowdshippers traveling between nodes $a\in S^o$ and $i\in S_d$ and the average number of parcels carried per crowdshipper. Constraints (4)–(6) define the domains of decision variables. Constraint (5) states that if the distance between nodes $i\in S^d$ and $j\in V_{cs}$ is greater than $D_{\max}$, the crowdshipper parcel flow routed between nodes $i\in S^d$ and $j\in V_{cs}$ is zero. The developed model is an integer linear programming model that can be solved by existing commercial solvers such as CPLEX.

3.4 Vehicle routing model

Similar to Zhang et al. (2023), we develop a vehicle routing model to determine the routes of vans. The model is formulated as follows:

$$\min\sum_{(i,j)\in N}\sum_{k\in K}T_{ij}x_{ijk}, \tag{7}$$

s.t.

$$\sum_{k\in K}\sum_{i\in N,i\neq j}x_{ijk}=1,\ \ \forall j\in V_h, \tag{8}$$

$$\sum_{j\in N\setminus\{0\}}x_{0jk}\leqslant 1,\ \ \forall k\in K, \tag{9}$$

$$\sum_{i\in N\setminus\{\lvert V_h\rvert+1\}}x_{i,\lvert V_h\rvert+1,k}\leqslant 1,\ \ \forall k\in K, \tag{10}$$

$$\sum_{i\in V_h,i\neq j}x_{ijk}-\sum_{i\in V_h,i\neq j}x_{jik}=0,\ \ \forall j\in V_h,\ \ k\in K, \tag{11}$$

$$\sum_{i\in N\setminus\{\lvert V_h\rvert+1\}}\sum_{j\in V_h,i\neq j}Q_j^h x_{ijk}\leqslant Cap,\ \ \forall k\in K, \tag{12}$$

$$t_{0k} = 0, \ \forall k \in K, \tag{13}$$

$$t_{ik} + ST_i + T_{ij} - T_{\max}(1 - x_{ijk}) \leqslant t_{jk}, \ \forall i \in N \setminus \{|V_h| + 1\}, \ j \in N \setminus \{0\}, \ j \neq i, \ k \in K, \tag{14}$$

$$t_{|V_h|+1,k} \leqslant T_{\max}, \ \forall k \in K, \tag{15}$$

$$x_{ijk} \in \{0,1\}, \ \forall k \in K, \ (i,j) \in N. \tag{16}$$

The objective Function (7) minimizes the total travel time of vans. It should be noted that this objective function also results in the minimization of distance-based cost, given our assumption of the constant speed of vans. Constraint (8) ensures that each home delivery customer is visited exactly once. Constraint (9) ensures that all vans depart from the depot at most once. Constraint (10) ensures that all vans return to the depot at most once. Constraint (11) ensures flow conservation. Constraint (12) ensures that the sum of demand at customers served by van k does not exceed the capacity of that van. Constraints (13) state that all vans are ready at time 0. Constraint (14) calculates the arrival time of van k at node $j \in N \setminus \{0\}$. They also eliminate subtours. Constraint (15) ensures that all vans should return to the depot before exceeding the maximum travel time of a route. Constraint (16) defines the domains of the decision variables.

The vehicle routing problem is known to be NP-hard, making it challenging to obtain optimum solutions for large instances using exact methods within an acceptable timeframe. In this study, we have developed an adaptive large neighborhood search (ALNS) metaheuristic to address the routing problem. The ALNS has proven to be highly effective in solving various vehicle routing problem variants (Ropke and Pisinger, 2006; Li et al., 2016; Cheng et al., 2023b). The ALNS algorithm was implemented in C++. The termination criterion for the ALNS is either reaching 25,000 iterations or no improvement in the best solution for 7,000 consecutive iterations.

4 Case study

4.1 Study area and data sources

For this study, we have selected a central district in north-western Copenhagen as our study area. This district has a high population density of 18,820 persons per square kilometer. Additionally, the district benefits from extensive PT coverage, including 3 S-train[1)] stations, 5 metro stations, and 56 bus stops. The choice of this district as our study area is justified by the following factors: 1) the district's dense urban environment results in significant traffic congestion; 2) the availability of good PT coverage makes it suitable for PT-based crowdshipping; and 3) a dedicated team in an anonymous logistics services provider in Denmark, responsible for last-mile delivery in this district, has validated our simulation results.

The total parcel data utilized in this study were obtained from a prominent logistics service provider in Denmark. This comprehensive data set contains the coordinates and demand values for each customer within specified central district, which is serviced by last-mile delivery vans. The data were extracted between October 11th and October 17th, 2021, representing a typical operating week unaffected by pandemic restrictions, Black Fridays, public holidays, and similar factors. On an average weekday, around 900 parcels with 500 delivery points are successfully delivered, while on weekends, about 500 parcels with 150 delivery points are handled.

Additionally, we retrieved smart card data (Rejsekort) from Rejsekort & Rejseplanen A/S for the same time period. Rejsekort & Rejseplanen A/S operates an electronic ticketing system facilitating bus, train, and metro travel across Denmark on behalf of transport operators. The retrieved data provide insights into the chosen trips and routes taken within Copenhagen's public transport network. It includes approximately 40% of all public transport journeys, excluding monthly pass holders whose specific travel patterns remain unknown. OpenStreetMap serves as the source for our geospatial data, including the road map and public transport stations.

The parcels distributed by the anonymous logistics service provider to the study area underwent sorting at a distribution center located in a south-western suburb of Copenhagen. Subsequently, vans with smaller capacities depart from this distribution center, visit their designated areas for last-mile delivery, and ultimately return to the distribution center. There are two S-train stations in close proximity to this distribution center, where we assume the presence of P-PLs (pickup parcel lockers). The precise locations of D-PLs (delivery parcel lockers) within the selected central district are determined using the D-PL location model.

4.2 Scenario development and analysis

To evaluate the effects of PT-based crowdshipping, we developed seven scenarios. The base scenario (S0) mirrors the current delivery system, where vans are responsible for all parcel deliveries. The remaining six scenarios are divided into two sets, each consisting of three scenarios. The first set (S1, S2, and S3) represents PT-based crowdshipping as a solution for last-mile delivery, incorporating crowdshippers and parcel lockers.

[1)] S-train serves the Copenhagen metropolitan area. It has 86 stations that connect the suburban and urban areas. The S-train system carries more than 357, 000 passengers a day.

Scenarios S1, S2, and S3 involve the transition of 10%, 20%, and 30% of parcels, respectively, from vans to crowdshippers. To address the randomness in the selection of crowdshipped parcels, we generated 15 samples for each scenario to obtain a comprehensive understanding of the crowdshipping scenarios. The compensation for crowdshippers is set at 10 DKK per parcel, which aligns with the field test conducted in Denmark (Fessler et al., 2023).

The second set of scenarios (S4, S5, and S6) represents the use of parcel lockers as a last-mile delivery solution without the involvement of crowdshippers. In scenarios S4, S5, and S6, the parcels that would have been delivered to designated parcel lockers by crowdshippers in scenarios S1, S2, and S3 are instead delivered by vans. In scenarios S4, S5, and S6, we refer to these crowdshipped parcels from scenarios S1, S2, and S3 as "van-visited locker parcels".

As discussed in Section 3, the volume of crowdshipped parcels is influenced by various factors from both the demand and supply sides. While our data sets lack information on specific demand-side factors (DF1 and DF2), we have gathered insights from relevant studies. For DF1, a case study conducted in Singapore suggested that approximately 74.9% of parcels are suitable for crowdshipping (Zhang et al., 2022). For DF2, although the idea of incentives seems promising, a stated preference experiment conducted in the Netherlands found that only a minority of car-sharing users would be willing to exchange average compensation for even minor inconveniences (Curtale and Liao, 2023; Wang and Liao, 2023). However, a study conducted in Rome on PT-based crowdshipping revealed that more than 60% of customers would choose to collect their parcels from parcel lockers without any incentives if the lockers were installed within 500 m of their residences and accessible 24 h a day (Iannaccone et al., 2021). Based on these studies, we believe that achieving a 30% share of crowdshipped parcels is feasible from a demand perspective, provided that the deployment of parcel lockers is well designed.

Turning to influencing factors on the supply side (SF1, SF2, and SF3), we have access to SF1 information through the Rejsekort data. For SF2, we set $Pr_{\text{csshipper}}$ = 30% in this study. As reported by Fessler et al. (2022), when the compensation to the crowdshipper is 10 DKK per parcel, the probability of a passenger bringing a parcel during his/her trip is approximately 30%. To prevent SF3 from limiting the supply of PT-based crowdshipping, we do not impose a maximum limit on the number of D-PLs that could be installed. By inputting these data into the D-PL location model, we could gain valuable insights into the feasibility of achieving scenarios S1, S2, and S3 and evaluate the ease or difficulty associated with each of them.

Ideally, the values of $D_{\max}$ and η should be set to 500 m and 1, respectively. However, these ideal values could lead to infeasible solutions under some scenarios. Hence, we conducted a sensitivity analysis on $D_{\max}$ and η to explore the challenges of achieving the corresponding scenarios. We consider three values of $D_{\max}$: 500, 600, and 700 m. Given a value of $D_{\max}$, we initially set $\eta = 1$ and solve the D-PL model. If there is no feasible solution, we increase the value of η by 0.1 and rerun the model until there is a feasible solution. By doing so, we determine the minimum number of parcels a passenger should take under a specific value of $D_{\max}$. The corresponding objective value indicates the minimum number of required D-PLs under the combination of ($D_{\max}$, η). Table 3 presents a view of the minimum number of parcels per crowdshipper and the corresponding number of delivery parcel lockers needed to achieve varying scenarios under different values of $D_{\max}$.

According to Table 3, S1 can be easily achieved given the current passenger volumes. This is supported by the acceptability of a 500-m distance to transit and the practice of a crowdshipper carrying just one parcel per trip. When $D_{\max}$ increases, the required number of D-PLs decreases.

In contrast, the realization of S2 and S3 presents more challenges than S1. When $D_{\max}$ = 500 m, each crowdshipper needs to carry 1.5 and 2.2 parcels per trip to achieve S2 and S3, respectively. Although increasing $D_{\max}$ leads to a reduction in the minimum number of parcels a crowdshipper needs to carry, it may cause inconvenience for customers and consequently affect the demand for PT-based crowdshipping. Certain measures should be implemented to cope with the challenges arising from higher $D_{\max}$ values. One such solution is to lower prices for PT-crowdshipping customers. Alternatively, if we keep $D_{\max}$ = 500 m and look at parameters on the supply side, there are two ideas to address the challenges of achieving S2 and S3. First, efforts could be made to increase passengers' willingness to participate as crowdshippers or to carry more than one parcel. This could be achieved by increasing the compensation level. As demonstrated

Table 3 The minimum number of parcels per crowdshipper should take and the corresponding number of delivery parcel lockers needed to achieve varying scenarios under different values of $D_{\max}$

Scenario	$D_{\max}$/m	The minimum number of parcels per crowdshipper should take	Number of delivery parcel lockers
S1	500	1.0	19
S1	600	1.0	16
S1	700	1.0	13
S2	500	1.5	30
S2	600	1.3	32
S2	700	1.0	30
S3	500	2.2	35
S3	600	1.9	37
S3	700	1.5	30

by Fessler et al. (2022), increasing the compensation level leads to a greater likelihood of passengers acting as crowdshippers. Additionally, a crowdshipper would be more willing to carry an additional parcel if the compensation is increased by 2.67 DKK. Second, if the compensation level remains unchanged and each crowdshipper continues to carry only one parcel per trip, actions could be taken to increase the number of PT users. This is beyond the capacity of logistics companies but is in line with the policies of many nations that encourage a shift from private car usage to public transport.

4.3 Impacts

Using the methodology described in Section 3, we simulated the delivery operation of an anonymous carrier under various scenarios. In this real-world case, we first report the computation time before presenting the results.

In our case study, the CPLEX solver can optimally solve the location model within 1 s. This is due to the limited size of the problem, which involves two P-PLs and 64 candidate D-PL locations. The number of delivery points per day ranges from 68 to 514. Additionally, the number of PT stops within a reasonable distance of D_{max} to the delivery point is limited. As a result, the problem remains relatively modest in scale. Regarding the vehicle routing problem, the computation time depends on the number of locations that vans need to visit. The longest computation time occurs in the base scenario, ranging from 3 to 1317 s throughout the week. The computation time for the parcel locker solution is longer than that for the PT-based crowdshipping solution, ranging from 1 to 1031 s and from 0.8 to 783 s, respectively. The computation time decreases when more home delivery parcels are shifted to van-visited locker parcels and crowdshipped parcels.

Three key performance indicators are used to evaluate the performance of each scenario: vehicle kilometers traveled per day (including the travel distance of trucks transporting crowdshipped parcels from the distribution center to P-PLs), the total working time of drivers, and the number of vans used to serve the selected central district. These indicators provide a comprehensive overview of each scenario's performance. The simulation results of the base scenario have been validated by an anonymous carrier, confirming that the three indicators obtained from our simulation closely align with their actual operations.

4.3.1 Impact on vehicle kilometers traveled

Figure 3 illustrates the percentage change in the number of vehicle kilometers traveled during the study period under the different crowdshipping scenarios compared to the traditional delivery method S0. Notably, all PT-based

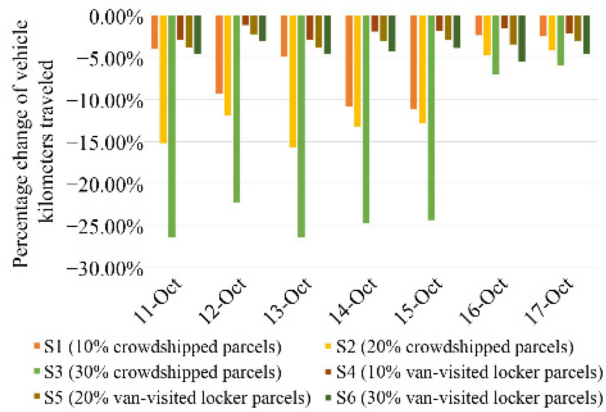

Fig. 3 Percentage change of vehicle kilometers traveled under different scenarios.

crowdshipping scenarios (S1, S2, and S3) show negative signs, indicating that using PT-based crowdshipping as a complementary solution to last-mile delivery effectively reduces the number of vehicle kilometers traveled, even considering the additional distance required to transport crowdshipped parcels from the distribution center to P-PLs. Additionally, there is a direct correlation between the number of crowdshipped parcels and the percentage reduction in the number of vehicle kilometers traveled. Specifically, scenarios S1, S2, and S3 achieve average percentage reductions of 6%, 11%, and 20%, respectively, in the number of vehicle kilometers traveled. Significantly, the reduction in vehicle kilometers traveled on weekdays (8%, 14%, and 25% for scenarios S1, S2, and S3, respectively) is more pronounced than that on weekends (2%, 4%, and 6% for scenarios S1, S2, and S3, respectively).

For parcel locker solutions, we observe similar negative signs for scenarios S4, S5, and S6. Again, the reduction in vehicle kilometers traveled increases as more home delivery parcels are shifted to parcel lockers. However, there is no significant difference between weekdays and weekends in this case. This lack of variation can be attributed to the fact that no vans were saved during the study period (as shown in Fig. 5). Since the distance from the distribution center to the study area accounts for the majority of the total vehicle kilometers traveled, the reduction in vehicle kilometers traveled does not vary significantly when no vans are saved.

Comparing scenarios S1, S2, and S3 with scenarios S4, S5, and S6, respectively, reveals that although clustering parcels to parcel lockers can reduce the number of vehicle kilometers traveled, the benefits are further enhanced by replacing vans with PT crowdshippers to deliver parcels to parcel lockers.

4.3.2 Impacts on the total working time of drivers

Figure 4 illustrates the percentage change in drivers'

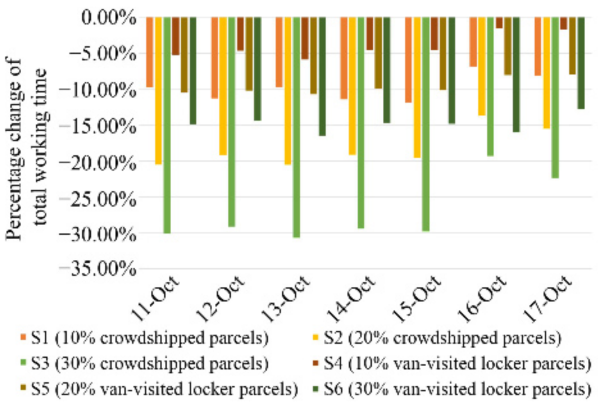

Fig. 4 Percentage change in total working time under different scenarios.

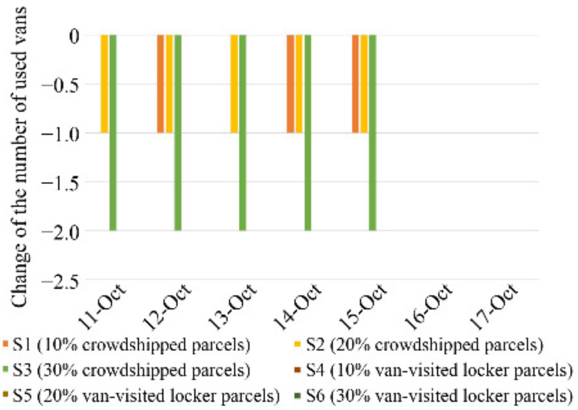

Fig. 5 Changes in the number of vans used under different scenarios.

overall working time across various scenarios. On average, there is a notable reduction in working time, with scenarios S1, S2, and S3 leading to decreases of 11%, 20%, and 30% on weekdays and 7%, 15%, and 21% on weekends, respectively. This highlights the potential of PT-based crowdshipping to mitigate the increasing workload on drivers. While there is also a decrease in drivers' working time when some home delivery parcels are diverted to parcel lockers (scenarios S4, S5, and S6 in Fig. 4), the reduction is comparatively less than that with PT-based crowdshipping scenarios.

4.3.3 Impact on the number of vans used

Figure 5 illustrates the variation in the number of vans utilized to serve the designated central district across different scenarios. The simulation results confirm our expectation that as parcels are progressively transferred from vans to crowdshippers, the number of vans in use should either decrease or remain the same as in the base scenario. Notably, the number of vans in use remains constant on weekends across all scenarios. Furthermore, in scenario S1, on October 11th and October 13th, the number of vans utilized remains unchanged. This phenomenon is intriguing and is attributed to the limited capacity of vans. In these instances, the number of vans utilized equals the minimum number required to serve the designated central district, determined by dividing the total district demand by the van's capacity. This observation underscores that achieving significant reductions in the required number of vans (and drivers) hinges on shifting a substantial parcel volume from vans to crowdshippers. Generally, if 20% of parcels can be delivered by crowdshippers, one van (driver) can be released, while a 30% crowdsourced parcel rate results in the release of two vans (drivers). In contrast, the number of vehicles utilized in scenarios S4, S5, and S6 remains identical to the number of vans used in the base scenario. This result is expected, as the number of vans utilized is primarily influenced by their capacity, whereas all parcels in the parcel locker solution still necessitate van delivery.

4.4 Cost analysis

Our cost analysis considers four distinct categories of costs: driving costs of vans and trucks, external costs related to traffic (such as the marginal costs of air pollution and traffic congestion), labor costs, and compensation paid to crowdshippers. In this section, we will outline the potential benefits of PT-based crowdshipping based on the transport economic unit prices (TEUP) of 2022, as-prepared by Transport DTU and COWI for the Ministry of Transport in Denmark (source: DTU website).

Driving costs. The driving costs of vans and trucks include expenses related to fuel, tires, repair and maintenance, and depreciation. These costs are split into fixed and variable costs per hour and per kilometer, respectively, in the TEUP. The fixed costs for vans and trucks are 529 DKK/hour and 542 DKK/hour, respectively. The variable costs for vans and trucks are 1.82 DKK/km and 4.19 DKK/km, respectively.

External costs. The negative externalities of transport include air pollution, climate change, noise, accidents, congestion, and wear on the infrastructure. The marginal external costs are used to estimate the cost per kilometer for the external effects. The marginal external costs for vans and trucks are 1.46 DKK/km and 6.01 DKK/km, respectively.

Labor cost. The average salary for a postal delivery worker is 24,274 DKK per month (Paylab website).

Compensation paid to crowdshippers. This stands at 10 DKK per parcel, the same as the field test in Fessler et al. (2023).

Table 4 provides an overview of the four cost categories under various scenarios. The distribution of these costs within a last-mile delivery solution demonstrates a consistent pattern. Figure 6 illustrates the percentage breakdown of each cost category. In the PT-based crowdshipping solution, labor costs account for the majority of total costs (70.80%), followed by driving

Table 4 Cost analysis of public transport-based crowdshipping and parcel locker solutions

		11-Oct	12-Oct	13-Oct	14-Oct	15-Oct	16-Oct	17-Oct
Driving costs (DKK)	S0	16,123	17,275	17,010	16,239	15,230	2,717	7,747
	S1	14,117	15,431	14,882	14,502	13,558	2,487	6,965
	S2	12,569	13,648	13,228	12,887	12,034	2,256	6,228
	S3	11,239	12,192	11,806	11,529	10,780	2,082	5,618
	S4	15,285	16,480	16,017	15,506	14,539	2,674	7,615
	S5	14,450	15,541	15,214	14,642	13,710	2,501	7,139
	S6	13,764	14,828	14,249	13,890	13,010	2,289	6,770
External costs (DKK)	S0	288	314	292	282	279	58	140
	S1	281	289	283	255	252	57	138
	S2	253	286	255	253	251	56	137
	S3	225	259	228	225	223	56	137
	S4	219	243	222	216	215	44	107
	S5	217	240	220	214	212	43	106
	S6	215	238	218	211	210	42	104
Labor costs (DKK)	S0	42,480	48,548	42,480	42,480	42,480	6,069	18,206
	S1	42,480	42,480	42,480	36,411	36,411	6,069	18,206
	S2	36,411	42,480	36,411	36,411	36,411	6,069	18,206
	S3	30,343	36,411	30,343	30,343	30,343	6,069	18,206
	S4	42,480	48,548	42,480	42,480	42,480	6,069	18,206
	S5	42,480	48,548	42,480	42,480	42,480	6,069	18,206
	S6	42,480	48,548	42,480	42,480	42,480	6,069	18,206
Compensation (DKK)	S0	0	0	0	0	0	0	0
	S1	870	970	870	830	800	120	360
	S2	1,730	1,930	1,740	1,650	1,600	240	720
	S3	2,600	2,900	2,610	2,480	2,390	360	1,080
	S4	0	0	0	0	0	0	0
	S5	0	0	0	0	0	0	0
	S6	0	0	0	0	0	0	0
Total costs (DKK)	S0	58,890	66,137	59,782	59,000	57,989	8,843	26,092
	S1	57,747	59,169	58,514	51,998	51,021	8,732	25,668
	S2	50,962	58,344	51,634	51,201	50,297	8,621	25,291
	S3	44,407	51,761	44,987	44,576	43,735	8,566	25,041
	S4	57,983	65,271	58,719	58,201	57,233	8,787	25,927
	S5	57,147	64,329	57,914	57,335	56,402	8,613	25,450
	S6	56,459	63,615	56,947	56,581	55,700	8,400	25,080
Percentage change in total costs	S1	−2%	−11%	−2%	−12%	−12%	−1%	−2%
	S2	−13%	−12%	−14%	−13%	−13%	−3%	−3%
	S3	−25%	−22%	−25%	−24%	−25%	−3%	−4%
	S4	−2%	−1%	−2%	−1%	−1%	−1%	−1%
	S5	−3%	−3%	−3%	−3%	−3%	−3%	−2%
	S6	−4%	−4%	−5%	−4%	−4%	−5%	−4%

costs (25.30%), compensation (3.30%), and external cost (0.50%). We observe a similar cost distribution in the parcel locker solution.

Since labor cost is the primary driver of total costs in both solutions, significant cost reductions occur only when at least one van is eliminated. On weekdays, the

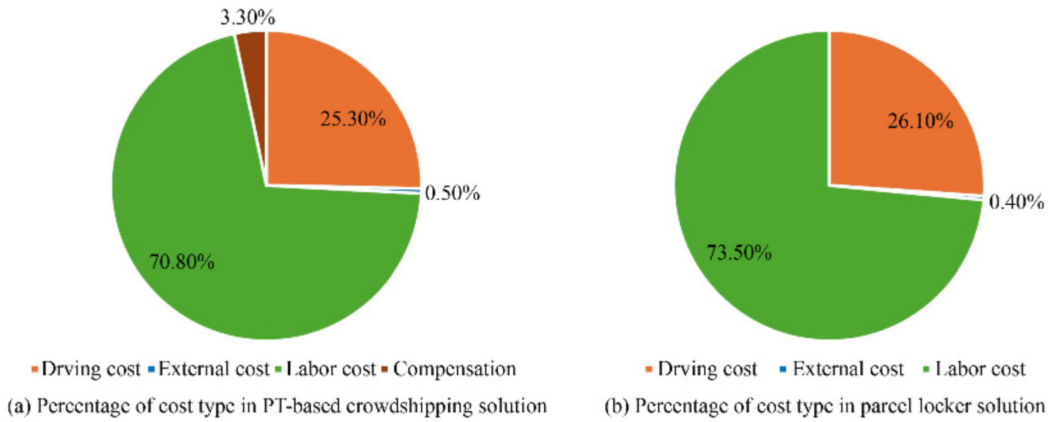

Fig. 6 Percentage of each cost type.

average total costs of S1, S2, and S3 are reduced by 8%, 13%, and 24%, respectively, compared to those of the base scenario. On weekends, the reductions are 1%, 3%, and 4%, respectively. In contrast, the total costs of S4, S5, and S6 are reduced by 1%, 3%, and 4%, respectively, with minimal differences between weekdays and weekends. Based on Table 4, we can conclude that while the parcel locker solution contributes to cost reduction in last-mile delivery, the PT-based crowdshipping solution has significantly greater potential for reducing costs, especially labor and driving expenses, due to modest compensation. This would undoubtedly benefit logistics companies by lowering operational costs, although its impact on employment opportunities may be negative in markets oversaturated with delivery workers or positive in markets with a shortage of delivery workers.

5 Conclusions

Both parcel locker networks and crowdshipping offer means to mitigate the negative effects of direct-to-customer deliveries. This paper investigates a PT-based crowdshipping solution for last-mile delivery that integrates parcel lockers and PT crowdshippers. A case study in Copenhagen's central district demonstrated that both parcel locker and PT-based crowdshipping solutions led to reductions in total vehicle kilometers traveled and driver working time, thereby reducing greenhouse gas emissions associated with freight trips and driver exertion. However, a notable advantage of PT-based crowdshipping, which is absent in the parcel locker solution, is the decrease in the number of vans required for last-mile delivery. This can help alleviate traffic congestion and driver shortages. This difference stems from the fact that in the parcel locker solution, all parcels are transported by vans, whereas in PT-based crowdshipping, a portion of parcels are transferred to crowdshippers.

Cost analysis reveals labor costs as the primary component of overall expenses. The implementation of PT-based crowdshipping has the potential to yield significant savings in labor and driving costs by offering modest compensation to crowdshippers. However, a key challenge lies in achieving a sufficient volume of parcels transferred from vans to crowdshippers to realize meaningful cost reductions. While customers are highly inclined to collect parcels from parcel lockers within a 500-m radius of their homes, we believe that the bottleneck impeding the development of PT-based crowdshipping stems from the supply side rather than the demand side. Efforts can be made to increase the supply of crowdshipping from various angles, such as promoting the use of public transportation over private vehicles, increasing compensation levels to attract more passengers as crowdshippers, or motivating crowdshippers to carry a greater number of parcels per trip.

This research contributes to the advancement of last-mile delivery solutions and supplements the literature on PT-based crowdshipping by introducing a mathematical model to quantify the impact of PT-based crowdshipping implementation. While our study offers valuable insights into the potential benefits and implications of PT-based crowdshipping, as well as strategies for its development based on a real-world case study, it does have certain limitations that warrant further investigation:

First, the study area should be expanded to include larger regions. Second, optimization models are developed to further refine the system deployment. For instance, instead of merely selecting PT stations near the distribution center for placing P-PLs, an optimization model could be devised to determine the optimal locations of P-PLs for maximizing the potential benefits of PT-based crowdshipping, particularly when expanding the service to a larger area. Third, additional features are integrated into the location and routing models. For example, a logit model could be incorporated into the traditional location model to account for customer preferences. Given that P-PLs can also be utilized for customers to send parcels and considering situations where recipients fail to collect their parcels, optimizing locker capacity and determining their locations represent interesting avenues for future research. On the topic of the routing problem, a promising research opportunity lies in considering the use of vans to collect parcels that remain unclaimed by recipients after a certain period or allowing people to send parcels while delivering home delivery parcels in the PT-based crowdshipping system. Finally, developing more accurate methodologies, employing advanced software to simulate actual city traffic, and employing a broader range of indicators to depict system performance may be necessary to scale the results at the regional/city level rather than solely at the district level.

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Competing Interests The authors declare that they have no competing interests.

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