

Research Article

A Multimodal Passenger-and-Package Sharing Network for Urban Logistics

Yuxiong Ji, Yujing Zheng, Jizhou Zhao, Yu Shen , and Yuchuan Du 

Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, Shanghai 201804, China

Correspondence should be addressed to Yu Shen; yshen@tongji.edu.cn

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This paper envisions a multimodal passenger-and-package sharing (PPS) network for urban logistics integrating metro, taxi, and truck. A hub-and-spoke structure is designed including hubs located at metro stations and service stores connected to the hubs. Packages are transported by metro on backbone links between the hubs and are carried by taxis or trucks between service stores and hubs, depending on the unit costs of these two modes and capacity constraint of the taxi. A mixed integer linear programming model for hub location problems—fusing the multiassignment p-hub median problem without capacity constraints and the capacitated multiassignment p-hub covering problem—is formulated to optimize the multimodal PPS network. The model is implemented based on the real-world data in Shanghai (China) under a series of scenarios to evaluate the network performance from two perspectives: the number of hubs and the proportion of taxi drivers who are willing to carry packages. The scenarios show that with increased number of hubs, the spatial distribution of hubs disperses from the city center to peripheral areas and more areas can be serviced by taxis. There is, however, a trade-off between the operation cost saved by taxis and the establishment cost of an extra hub. The analysis also presents that if the proportion of taxis willing to carry packages associates with the incentive payments to taxi drivers, an optimal value of incentives exists, by balancing the operation costs of taxis and trucks.

1. Introduction

The demand for urban parcel delivery booms with the prevalence of e-commerce in the recent years. Take China as an example. Over 40 billion packages were delivered in urban areas in 2017, with an increase of 28% comparing with the previous year [1]. The booming demand for urban parcel deliveries potentially leads to heavy urban freight traffic that inevitably brings negative impacts on traffic congestion and air pollution. To mitigate the negative effects and to improve urban mobility, the European Commission recommends a passenger-and-package sharing (PPS) system integrating passenger and freight transportation [2], and some typical services was overviewed and introduced by Sampaio et al. [3]. In general, three sharing options are proposed: share of space (e.g., multiuse lanes and night deliveries), share of public transport vehicles and networks, and share of urban delivery facilities such as delivery bays and goods lockers [4–7]. This study focuses on the PPS network design with passengers and packages sharing the same public transport vehicles and networks.

Current studies on the PPS system mainly focus on vehicle routing for package pickup and delivery, considering various scenarios like taxi sharing or self-owned vehicle routing between public transit stations and customers. For example, Li et al. [8] formulate a share-a-ride problem to optimize taxi routes and schedules to better match the supply of taxis and the demand from passengers and parcel deliveries. The model is evaluated in Tokyo city by Nguyen et al. [9] and extended by Li et al. [10] by integrating stochastic travel times and delivery locations. Masson et al. [11] propose a public transit-based PPS system that firstly uses buses to deliver the packages from a consolidation/distribution center to a set of bus stops and then dispatches a fleet of freighters to deliver packages to customers. Taking into account time windows, schedules, and stochastic demands, Ghilas et al. [12, 13] use the public transit as a part of freight journey and optimize the pickup-and-delivery routes of private vehicles between given transfers and demand nodes. Fatnassi et al. [14] assess the potential of integrating personal rapid transit and freight rapid transit vehicles into one

network with the objective of minimizing the movements of empty vehicles and the waiting times of passengers and packages. Yildiz and Savelsbergh [15] explore the service and capacity planning problem in store-to-door meal delivery, where the delivery service is provided by individual's willing to participate in such activity.

The contribution of this study—different from current studies on vehicle routing in a PPS system—is to design the multimodal PPS network with the hub-and-spoke structure. The idea of the hub-and-spoke network design for multimodal logistics networks is widely supported by past scholars [16]. By integrating multiple modes into one logistics network, the new system is able to achieve economies of scale more effectively, thus improving the transport efficiency [17, 18]. Current literatures mainly focus on the intercity multimodal logistics network. Qu et al. [19] design a logistics network integrating ocean and coastal routes, inland waterways, railways, roadways, and airways with nonlinear transfer costs between different modes. Taking into account demand uncertainties and network disruptions, Fotuhi and Huynh [20] identify the rail links to retrofit, existing intermodal hubs to expand, and locations of new hubs in the rail-road network. Similarly, Kim and Ryerson [21] identify a set of unaffected hubs during network disruption in the US ocean-inland freight network.

A conceptual design of the multimodal PPS network for urban parcel delivery is envisioned and drawn in Figure 1, integrating metro carriages, taxis, and trucks. The fusion of metro, taxi, and truck absorbs the advantages of the three modes: metro trains follow predetermined routes and schedules with high reliability, punctuality, and large carrying capacities; taxis and trucks are flexible and are able to provide door-to-door services. The carrying capacity of taxis is constrained by the willingness of drivers to help carrying packages. The capacity of trucks is unlimited since the freighters are fully controlled by the couriers. However, the delivery cost of trucks is higher than the cost of the shared taxis.

To explore the optimal design of a multimodal PPS network, we formulate the network design task into hub location problems (HLPs). The rest of the paper is organized as follows. Section 2 reviews current HLPs and states the novelty of the proposed multimodal PPS network. In Section 3, we propose a variant of the HLP model and develop a mixed integer linear programming model with a modified genetic algorithm to optimize the hub-and-spoke network. Section 4 presents an example of Shanghai for the case study and provides quantitative assessment of the network from the perspectives of the number of hubs and the proportion of taxi drivers who are willing to carry packages. Finally, we conclude the study and offer some discussions.

2. Literature Review: Hub Location Problems

Hub location problems are firstly proposed by O'Kelly in 1980s [22–24]. Typical HLPs can be classified based on their objectives: the p -hub median problems locate p hubs to minimize the total routing cost [25–31]; the p -hub center

problems locate p hubs so that the maximum cost between any OD pair can be minimized [25, 32]; and the p -hub covering problems aim to maximize the total flow between all OD pairs covered by p hub facilities [33]. In these studies, the number of hubs to be established, i.e., p , is prespecified. Instead of predetermining the number of hubs, some works assume a setup and operation cost for each hub with the objective of minimizing the sum of hub cost and routing cost [29, 34] or maximizing the system profit [35]. Comprehensive reviews can be found in Alumur and Kara [36], Campbell and O'Kelly [37], and Farahani et al. [38].

The network topology of HLPs depends on the structure of backbone links and spoke links. Typically, the hubs are completely connected. However, in some special cases, incomplete interhub network structures, e.g., ring [39], star [40], tree [41, 42], and line [43], are adopted. In terms of the design of spoke links for flow assignment, a demand node can be connected to one or multiple hubs, i.e., single or multiple assignment structures. Aykin [44] and Martins de Sá et al. [43] extend the topology of spoke links by considering that the flows between some OD pairs can be shipped directly without being routed through hubs. Besides direct links, Lin and Chen [45] integrate stopovers and feeders to the network. Klinecicz [46] introduce a spoke network in which a demand node is allowed to be linked to a hub through other demand nodes. In addition to the backbone-and-spoke bilevel networks, some researches consider the trilevel network connecting hierarchical hubs and demand nodes [40, 47].

The capacity of links is another essential feature of the HLPs. Capacity constraints on flows are usually applied on hubs [25, 48–52], links [53, 54], or both [55], as exogenous constraints. Some studies also treat hub capacities as decision variables to select the optimal hub capacity from a list set of predefined capacity levels, each of which is associated with a fixed setup cost [56–58]. Consider that the capacity limits make the model more realistic, though it increases the computation time in most cases.

The hub location-routing problem, introduced by Nagy and Salhi [59], combines the HLPs with the vehicle routing problems (VRPs), where the vehicle routes are optimized with respect to hub locations and flow assignments simultaneously. The combination of HLPs and VRPs, both of which are NP-hard problems, leads to a great growth in the solution cost. Thus, the hub location-routing problems are normally formulated with a hierarchical structure, in which the upper and lower levels deal with the HLPs and VRPs, respectively [59–62]. In this study, the vehicle route planning is not considered for simplification.

This study applies a complete interhub structure. A demand node is allowed to be connected to multiple hubs to improve the flexibility and capacity of the network, as metro stations are completely connected by metro lines and transfer stations. The spoke links are served by taxis and trucks. The features of the two modes—e.g., the costs to deliver a package and the capacity constraints—vary largely. The study also takes into account the exogenous constraints on spoke links served by taxi due to the drivers'

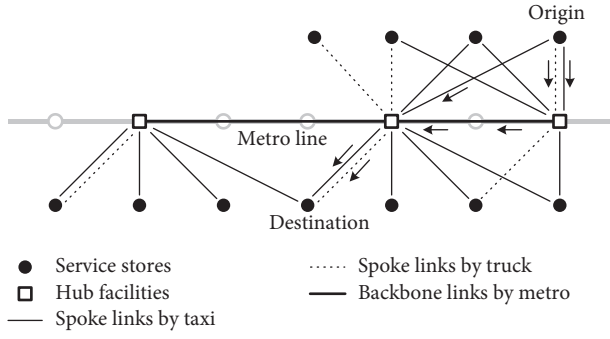


FIGURE 1: A conceptual multimodal passenger-and-package sharing network.

willingness to help carrying packages. The spoke links served by truck and the backbone links served by metro are uncapacitated. The fusion of these modes enriches the formulation of HLPs.

3. Methodology

3.1. Model Settings and Assumptions. Figure 1 illustrates all potential routes of an origin-destination (OD) pair. The service stores spread out in the city for first-mile package collection and last-mile delivery. The hub facilities are located at metro stations for package storage and transfer, fully connected by the metro network. Between service stores and hubs, packages are transported by taxi with limited carrying capacities and by truck without capacity limits, according to the costs of these two modes. In the hub-and-spoke network, the backbone links and the spoke links are served by metro and taxi/truck, respectively.

The envisioned multimodal PPS network also includes the following characteristics. Standardized delivery boxes—fitting into the trunks of taxi and truck—and containers, designed for metro carriages, are used for parcel transfer. The boxes and containers are (un) packed and reassembled at stores and hubs. The requests for package delivery to taxis can be automatically matched by a central operation platform, guiding the taxi drivers if they need to transport packages besides passengers. The platform is also responsible to rent trucks from cooperative on-demand logistic companies to deliver the packages that cannot be covered by taxis and to arrange the transportation of package in the metro network.

The following assumptions are made for modeling:

- (i) The service stores are the O/D nodes of the model.
- (ii) Packages have to be routed via at least one hub.
- (iii) Packages of an OD pair can be routed through multiple hubs.
- (iv) On spoke links, the package flows served by taxi are constrained by taxi flows, the proportion of drivers who are willing to carry packages, and the trunk capacity of each taxi. The package flows served by truck are unlimited.

- (v) The capacities on hub facilities and backbone links served by metros are unlimited.

Finally, we focus on the low-cost urban courier service without the constraints of the same-day delivery. Therefore, the system is evaluated in the dimension of cost rather than time.

3.2. Model Formulation. Table 1 summarizes the inputs, parameters, and variables used in this study. The package flows in this model are treated as multicommodity flows [63]. Each commodity i represents the packages originating from node i . For commodity i , denote z_{ik} and u_{ik} as the flows routed from the origin service store i to hub k by taxi and truck, respectively, y_{ikl} as the flows routed between hubs k and l , and x_{ilj} and v_{ilj} as the flows routed from hub l to destination service store j by taxi and truck, respectively.

The multimodal PPS network design problem is formulated as the mixed integer linear programming (MILP) problem, expressed as follows:

$$\begin{aligned} \min \quad TC = & \sum_{i \in \Omega} \sum_{k \in \Theta} c_{ik} \times z_{ik} + \sum_{j \in \Omega} \sum_{l \in \Theta} c_{lj} \times \sum_{i \in \Omega} x_{ilj} + \sum_{i \in \Omega} \sum_{k \in \Theta} t_{ik} \\ & \times u_{ik} + \sum_{j \in \Omega} \sum_{l \in \Theta} t_{lj} \times \sum_{i \in \Omega} v_{ilj} + \sum_{k \in \Theta} \sum_{l \in \Theta \setminus k} m_{kl} \times \sum_{i \in \Omega} y_{ikl} \\ & + \sum_{k \in \Theta} g_k \times h_k, \end{aligned} \quad (1)$$

s.t.

$$\sum_{k \in \Theta} h_k = p, \quad (2)$$

$$\sum_{k \in \Theta} (z_{ik} + u_{ik}) = \sum_{j \in \Omega} W_{ij}, \quad i \in \Omega, \quad (3)$$

$$\sum_{l \in \Theta} (x_{ilj} + v_{ilj}) = W_{ij}, \quad (i, j) \in \Omega^2, \quad (4)$$

$$z_{ik} \leq \theta \times F_{ik} \times r_{ik}, \quad (i, k) \in \Omega \times \Theta, \quad (5)$$

$$\sum_{i \in \Omega} x_{ilj} \leq \theta \times F_{lj} \times r_{lj}, \quad (l, j) \in \Theta \times \Omega, \quad (6)$$

$$\sum_{l \in \Theta} y_{ikl} + \sum_{j \in \Omega} (x_{ikj} + v_{ikj}) = \sum_{l \in \Theta} y_{ilk} + (z_{ik} + u_{ik}), \quad (i, k) \in \Omega \times \Theta, \quad (7)$$

$$z_{ik} + u_{ik} + x_{ikj} + v_{ikj} + y_{ikl} + y_{ilk} \leq Q \times h_k, \quad (i, j, k, l) \in \Omega^2 \times \Theta^2, \quad (8)$$

$$h_k \in \{0, 1\}, \quad k \in \Theta, \quad (9)$$

$$z_{ik}, u_{ik}, x_{ilj}, v_{ilj}, y_{ikl} \geq 0, \quad (i, j, k, l) \in \Omega^2 \times \Theta^2. \quad (10)$$

TABLE 1: Summary of notations.

Input parameters	
Ω	Set of nodes representing service stores
Θ	Set of potential hub locations, $\Theta \subset \Omega$
W_{ij}	Package demand from node i to j
F_{ij}	Taxi flow from node i to j
r_{ij}	Proportion of taxi drivers who are willing to carry packages from node i to j , namely, "WTCP%"
θ	Average number of packages that could be contained in a taxi trunk
g_k	Cost for establishing and operating hub k
c_{ij}	Incentive payment per package for taxi drivers from node i to j
m_{kl}	Transport cost per package from hub k to l by metro
t_{ij}	Transport cost per package from node i to j by truck
p	Number of hubs to be established
Variables	
h_k	Binary variable indicating whether a hub is established at node k . 1 if so, 0 otherwise
z_{ik}	Package flow routed from node i to hub k by taxi
u_{ik}	Package flow routed from node i to hub k by truck
y_{ikl}	Package flow emanating from node i routed from hub k to hub l by metro
x_{ijl}	Package flow emanating from node i routed from hub l to node j by taxi
v_{ilj}	Package flow emanating from node i routed from hub l to node j by truck

Objective function (1) is set to minimize the total cost (TC), consisting of 6 terms, which indicate

- (i) The cost to transport packages
 - (1) From origin stores to hubs by taxi;
 - (2) From hubs to destination stores by taxi;
 - (3) From origin stores to hubs by truck;
 - (4) From hubs to destination stores by truck;
 - (5) Between hubs by metro;

- (vii) The cost to establish and to operate the hubs, respectively.

Constraint (2) guarantees that there are exactly p hub facilities to be established. Constraint (3) and constraint (4) represent that for commodity i , and the total package flow originated from node i and destined to node j is in accordance with the demand. Constraints (5) and (6) ensure that package flows transported by taxi between demand nodes and hubs are constrained by taxi flows, the WTCP%, and the capacity of the taxi trunk. Constraint (7) is the flow conservation equations for each commodity i at each hub k , of which the left and right sides are outgoing and incoming flows, respectively. Constraint (8) indicates that the package flows related to hub k are greater than zero only if hub k is established, where Q is a large number. Constraints (9) and (10) specify the binary and non-negative types of decision variables.

The proposed model generalizes and is an extension of two classic types of HLPs. If no taxi drivers are willing to carry packages (*i.e.*, $r_{ij} = 0$), or if the payments for incentive c_{ij} are set to be relatively high, the package flows by taxi become zero. The spoke links are serviced by truck only. In this case, the model becomes a typical multiassignment p -hub median problem without capacity constraints. If the costs to transport packages by truck t_{ij} are set to be relatively high, the model tends to minimize the amount of trucks and to maximize the package flows transported by taxi with capacitated spoke links. In this case, the model becomes similar to a capacitated multiassignment p -hub covering problem.

3.3. Modified Genetic Algorithm Method. The developed MILP model to solve the HLPs is NP-hard due to the interrelationship between locating hub facilities and designing network topology. Past studies focusing on exact algorithms, *e.g.*, branch-and-bound [64], branch-and-cut [65], Lagrangian relaxation [66], and Benders decomposition [67], mainly handle the HLPs with limited scale. To solve the HLPs with a larger scale, heuristic algorithms—*e.g.*, the general variable neighborhood search approach [68], the memetic algorithm mapping two local search heuristics developed by Marić et al. [69], and the genetic algorithm (GA) adopted by Lin et al. [55] for capacitated p -hub median problems—are able to provide the near-optimal solutions with less computation time.

In this study, we propose a modified GA method to solve the large-scale HLP problems. The HLP model consists of binary variables, indicating hub locations, and non-negative continuous variables indicating package flows. The modified GA considers the set of binary variables as an individual. For each individual, the fitness function is the objective function of the model mentioned above, where binary variables are set fixed. The detailed algorithm is presented in Appendix with the parameters empirically set as in Table 2.

To investigate the validity and efficiency of the modified GA, we conduct a series of computational experiments comparing the computation times and optimal solutions generated by the GA with those solved by exact algorithms in CPLEX (with default parameters) [70], listed in Table 3. We use (N, H, p) to denote the problem scale, where N is the number of OD nodes, H is the number of candidate hubs, and p is the number of hubs to establish. Table 3 shows that when N is greater than 110 and/or H is greater than 80, CPLEX fails to provide a feasible solution in some cases within max time limit (*i.e.*, 24 hours).

The results show that the computation time of the exact algorithm increases rapidly with the number of stores and hubs. In terms of the quality of solutions, if optimal solutions can be efficiently provided by the exact algorithms, the GA achieves the same or similar results. If suboptimal solutions

TABLE 2: The parameters of GA.

Parameter	Value
Population size K	50
Desired average tournament size F_t	5.4
Crossover fraction P_c	0.7
Mutation fraction P_m	0.1
Stall generation limit G_s	50
Function tolerance τ	0.01
Max time limit T_{\max}	24 (hours)

with gaps can be provided by the exact algorithms, the GA can even achieve better. A feasible solution can still be provided by the GA when the exact algorithm fails to provide a feasible solution in reasonable time.

4. Case Study: An Example of Shanghai

4.1. Data and Study Area. The study area is encircled by the outer-ring expressway of Shanghai, China, covering 680 square km with great population densities and high economic activities. We tessellate the study area into 171 identical square zones with the length of 2 km. In each zone, one service store is designated to service the area. There are 106 zones containing at least one metro station, which are considered as the candidate locations to establish hub facilities. In addition, the zones with main land use of agriculture, industry, or nature parks are excluded from the analysis due to scarce demand for delivery service in these areas. Thus, 127 zones are selected for the optimization of the multimodal PPS network with 94 candidate hub locations. The spatial distribution of zones and candidate hubs is presented in Figure 2.

630 million packages were delivered in Shanghai in 2015, with the spatial distribution presented in Figure 3. The distribution is heterogeneous, and, in general, the demand concentrates in the central areas. In the top ten zones with the highest demands, 31.1% of the total packages are sent out from these areas and 17.2% of the packages are delivered into the areas.

Based on the automatic vehicle location data of about 13,000 taxis—accounting for one fourths of the total taxis operated in Shanghai—in April 2015, we extract the origin and destination of the taxi trips and scale up the number of the trips to synthesize the entire taxi service in Shanghai. The results show that most taxi trips are originated from or destined to metro stations, where the zones with metro stations generate 90.1% of taxi trips. Figure 4(a) presents the spatial distribution of the origins of taxi trips, while Figure 4(b) shows the distribution of the destinations of taxi trips. The two figures suggest that it is reasonable to utilize metro stations as transfer locations between metros and taxis.

We empirically calculate the cost to establish and operate a hub as 8k CNY per day, based on the average cost to lease a shop in metro stations (according to the data from 58.com Inc., a China's Craigslist equivalent), the area of hubs for package storage, and the equipment and labor costs in Shanghai according to the Shanghai Statistic Yearbook in 2016. The cost to carry the packages by truck is

estimated according to the pricing plan of renting a medium-sized truck from Lalamove, an on-demand logistics company providing intracity delivery and courier services in Shanghai (for each truck trip: 65 CNY for the first 5 km and 4 CNY/km for more than 5 km (source: Lalamove)). The unit cost for transporting a package by metro is set as 5% of the regular fare (for each customer: 3 CNY for the first 6 km and 1 CNY per 10 km for more than 6 km, at most 15 CNY (source: Shanghai Shentong Metro)). Each taxi and truck is able to carry 10 and 50 packages, respectively. The average distances between the zones are calculated as the Euclidean distances between the centroids of each zone.

4.2. Scenario Analysis. Among a number of factors affecting the system performance, we designed three scenarios to evaluate the proposed multimodal PPS network from the following perspectives:

- (i) Number of hubs;
- (ii) Proportion of taxi drivers who are willing to carry packages, named as “WTCP%”:
 - (1) WTCP% independent from the incentives
 - (2) WTCP% dependent on the incentives.

Each scenario contains several subscenarios. Table 4 summarizes the attributes of each scenario and sub-scenario in details. Among the subscenarios, A6, B3, and C3 are the same, while B1 and C1 are the same.

Scenario A consists of 7 subscenarios. In the scenario, the impacts of different numbers of hubs p (i.e., 5, 6, 8, 10, 12, 15, and 20) are tested. The WTCP% is fixed: 50% taxi drivers are willing to carry packages. To compute the delivery cost by taxi on each spoke link, we set that a taxi driver is able to receive an extra 5% of the regular trip fare (for each taxi trip: 14 CNY for the first 3 km, 2.5 CNY/km for 3–15 km, and 3.8 CNY for more than 10 km (source: Shanghai Municipal Transportation Commission)) for every additional package to deliver. With the capacity of 10 packages, a taxi driver may get at most 50% more than the regular fare.

Scenario B consists of 5 subscenarios. Different WTCP% (i.e., 0%, 25%, 50%, 75%, and 100%) are tested with the incentive fixed at 5% of the trip fare. The number of hubs is fixed to 15. The subscenario B1 represents a metro-truck only network without taxi. The formulation becomes a typical multiassignment p -hub median problem without capacity constraints.

Scenario C consists of 5 subscenarios where C1 is the same as B1. Different from scenario B, the WTCP% depends on the incentive. We assume that, with an extra 0%, 2.5%, 5%, 7.5%, and 10% of regular taxi fare for each package, 0%, 25%, 50%, 75%, and 100% of taxi drivers are willing to carry packages. The number of hubs is also fixed to 15.

4.2.1. Scenario A: Number of Hubs. Figure 5(a) illustrates the trends of total cost and transport cost with increased number of hubs, in which the difference of two series of values represents the cost to establish and to operate the hubs. More hubs lead to more packages transported by taxi, which

TABLE 3: Comparison of results and computation times of the algorithms.

Scale of the problem	Exact algorithm in CPLEX			Modified GA	
	Computation time (min)	Best solution	Gap (%)	Computation time (min)	Best solution
(40, 28, 5)	8.6	83,139	0.0	26.7	83,139
(40, 28, 15)	15.4	159,712	0.0	46.6	159,712
(70, 30, 8)	201.5	358,149	0.0	183.9	358,656
(70, 40, 14)	1,440.0*	378,673	3.1	892.4	374,123
(100, 30, 15)	1,440.0*	818,480	5.6	1,056.1	782,291
(100, 75, 15)	1,440.0*	700,527	14.8	1,440.0*	670,920
(110, 30, 15)	1,440.0*	901,690	20.5	1,440.0*	858,458
(110, 80, 20)	1,440.0*	n.f.s.p.	9.0	1,440.0*	781,913
(127, 94, 15)	1,440.0*	n.f.s.p.	23.3	1,440.0*	973,549
(127, 94, 20)	1,440.0*	n.f.s.p.	13.4	1,440.0*	977,518

*The upper time limit, i.e., 24 hours; n.f.s.p.: no feasible solution provided.

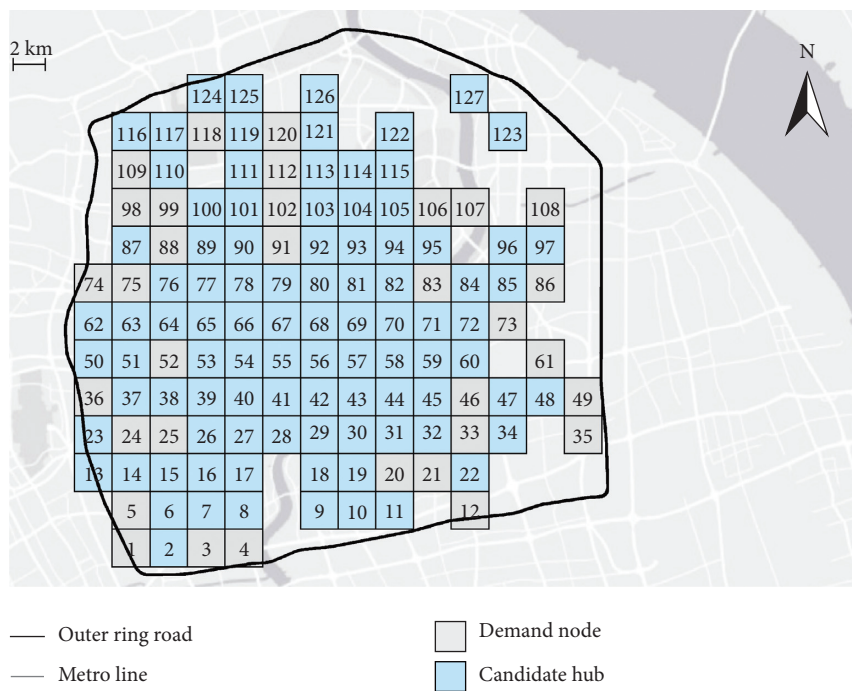


FIGURE 2: The study area of Shanghai, China (source: authors' revision based on OpenStreetMap).

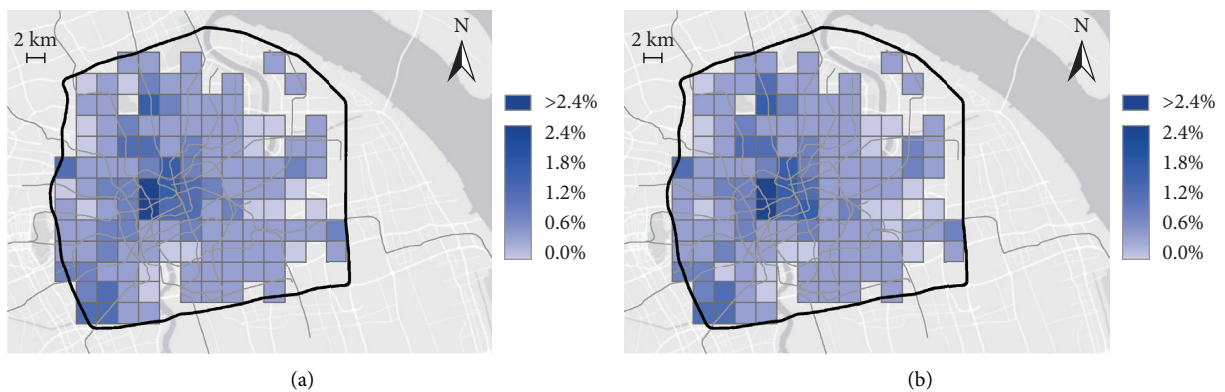


FIGURE 3: Spatial distribution of demand for package delivery (source: authors' revision based on the Shanghai Municipal Postal Administration). (a) Package demand distribution: outgoing and (b) package demand distribution: incoming.

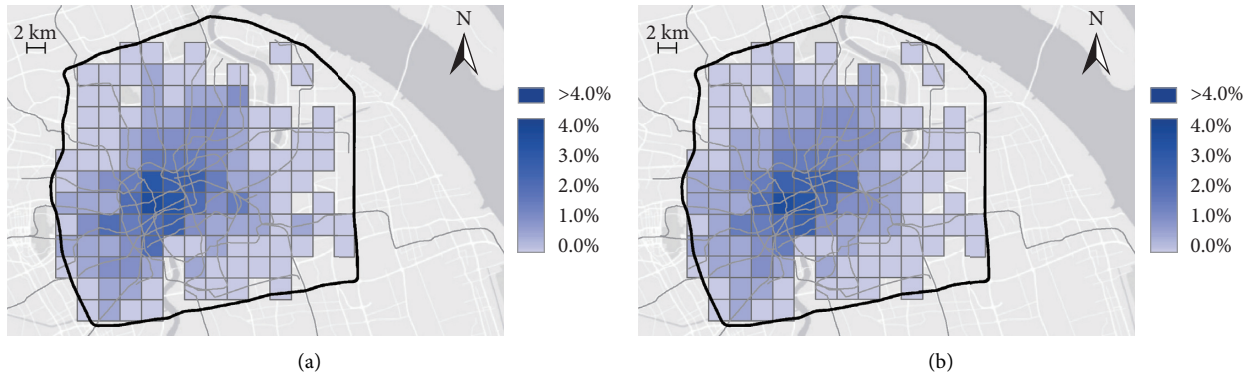


FIGURE 4: Spatial distribution of taxi trips (source: authors’ revision based on the data provided by Shanghai Qiangsheng Taxi). (a) Taxi flow distribution: outgoing and (b) taxi flow distribution: incoming.

TABLE 4: Design of the scenarios.

Scenario	Number of hubs	WTCP%	Incentives
A			
A1	5	50	5.0% of trip fare
A2	6	50	5.0% of trip fare
A3	8	50	5.0% of trip fare
A4	10	50	5.0% of trip fare
A5	12	50	5.0% of trip fare
A6	15	50	5.0% of trip fare
A7	20	50	5.0% of trip fare
B			
B1	15	0	Not available
B2	15	25	5.0% of trip fare
B3	15	50	5.0% of trip fare
B4	15	75	5.0% of trip fare
B5	15	100	5.0% of trip fare
C			
C1	15	0	Not available
C2	15	25	2.5% of trip fare
C3	15	50	5.0% of trip fare
C4	15	75	7.5% of trip fare
C5	15	100	10.0% of trip fare

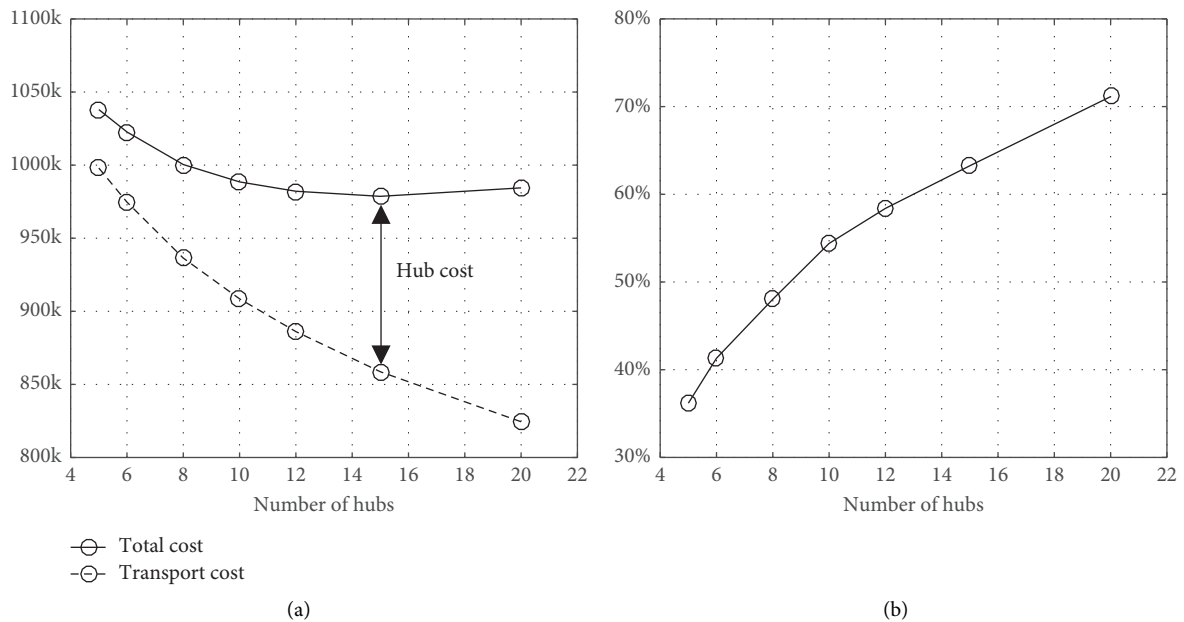
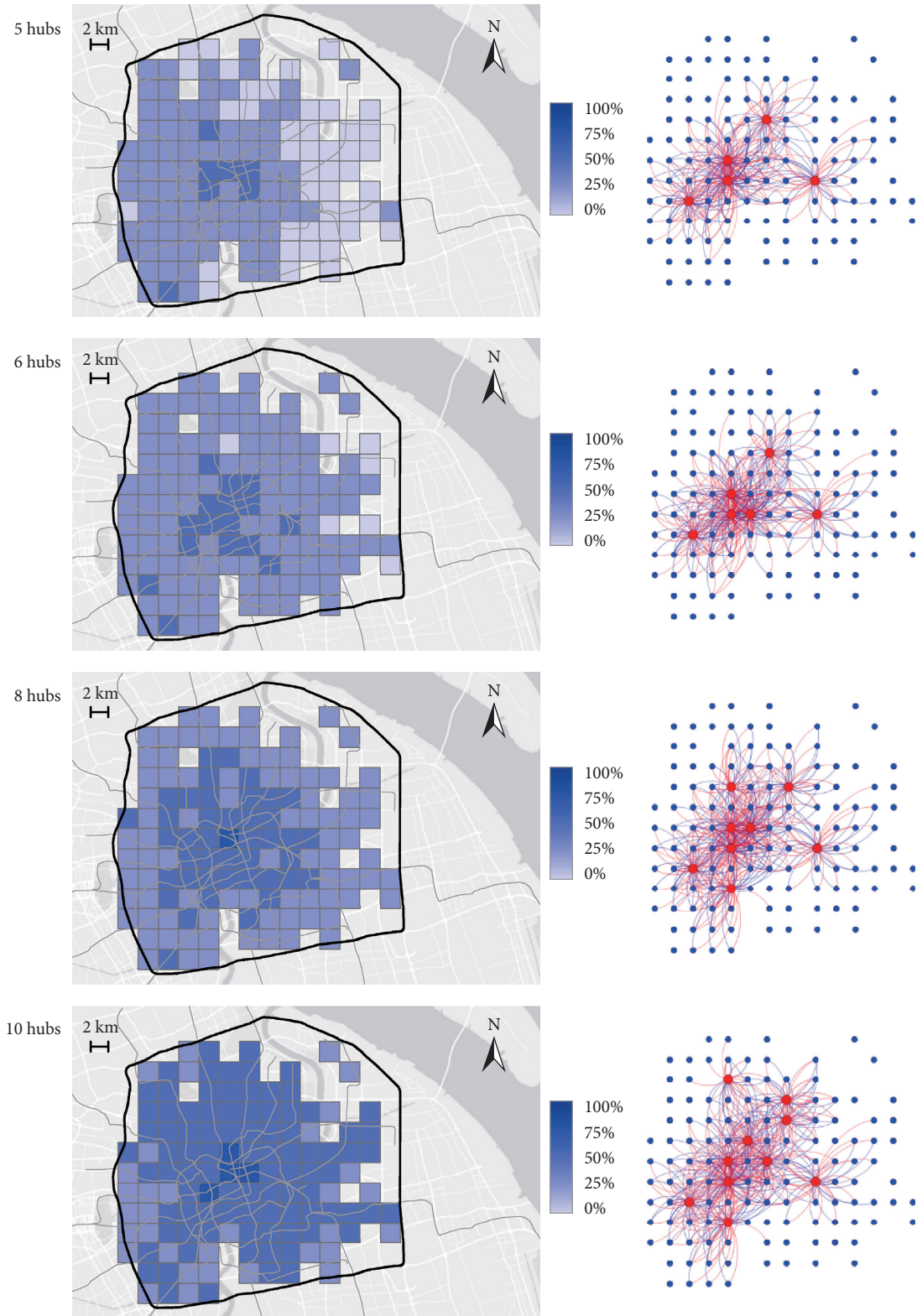


FIGURE 5: System cost (a) and proportion of packages transported by taxi on spoke links (b) by number of hubs.



(a)

FIGURE 6: Continued.

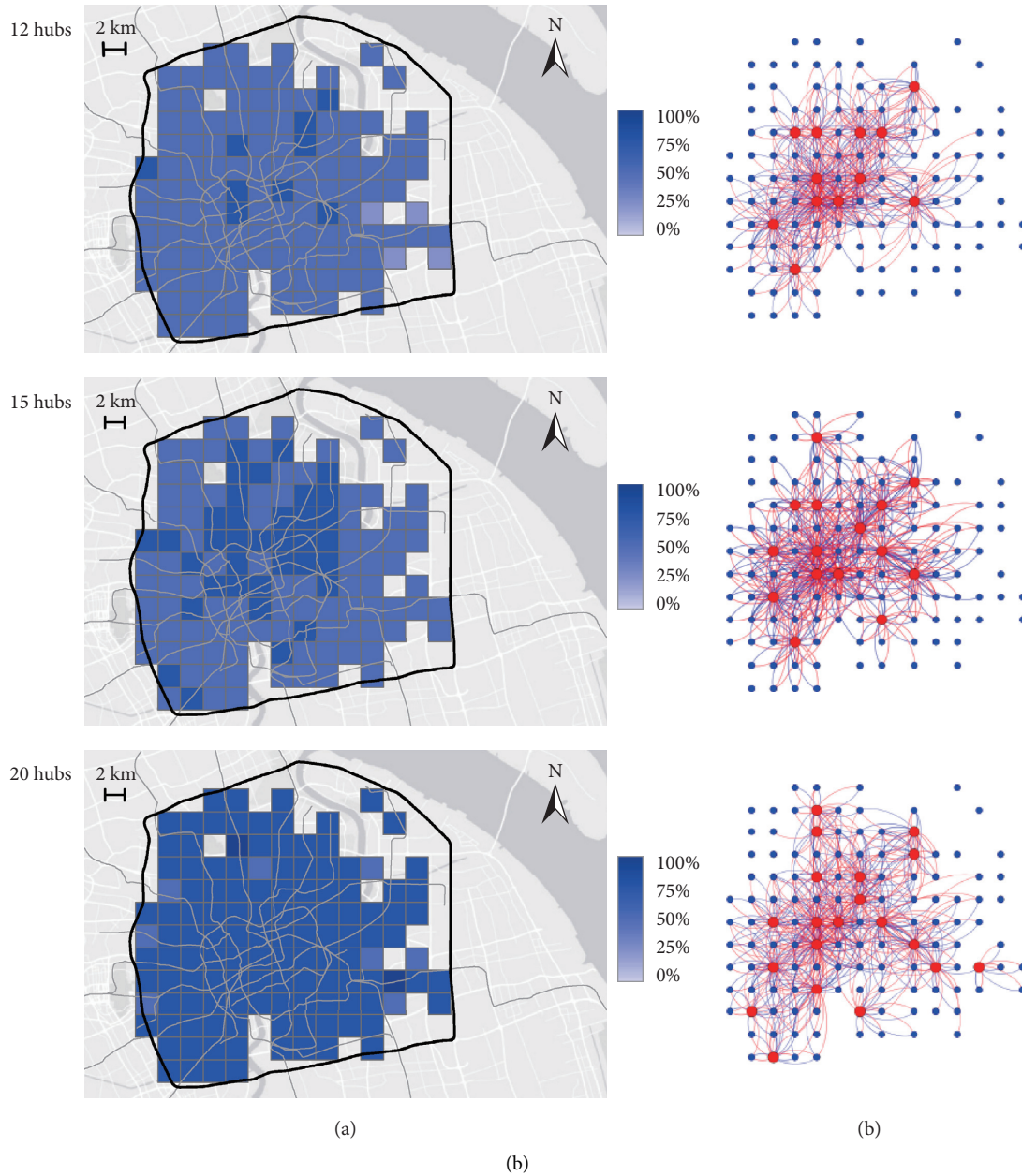


FIGURE 6: Proportion of package demand transported by taxi in each zone (a) and the spatial distribution of hubs (b).

reduces the transport costs on spoke links, as shown in Figure 5(b). Nonetheless, the marginal savings of transport cost declines with more hubs established. With 5 additional hubs established, the increase of the hub cost is 40k CNY. From 5 hubs to 10 hubs, 18.2% of the packages are shifted from the truck to taxi while the transport cost reduces by 89.5k CNY. From 15 hubs to 20 hubs, the packages' modal shift from the truck to taxi is 7.9% with only 34.2k CNY of transportation cost saved. According to the figures, the total cost reaches minimum with 15 hubs. Beyond 15 hubs, the cost to set up an extra hub becomes greater than the reduction of the transportation cost.

Figure 6 presents the proportions of packages transported by taxi and the spatial distribution of hubs by

subscenario. With 5 hubs, the system mostly assigns the hubs into the central area with greater demand. As a result, the periphery zones close to the outer-ring expressway are underserved by taxis. Among all 127 zones, there is no zone in which more than 50% of the packages can be served by taxi. The rest of the packages are transported by truck with a higher cost. With 6, 8, 10, 12, 15, and 20 hubs, the system covers more periphery zones and the number of zones where over 50% of demand can be served by taxis increases to 2, 11, 31, 68, 110, and 127, respectively.

The optimal locations of hubs in each multimodal PPS network are demonstrated in figures. A link connecting to a service store (blue dot) and a hub (red dot) represents the package transported between a service store and a hub by

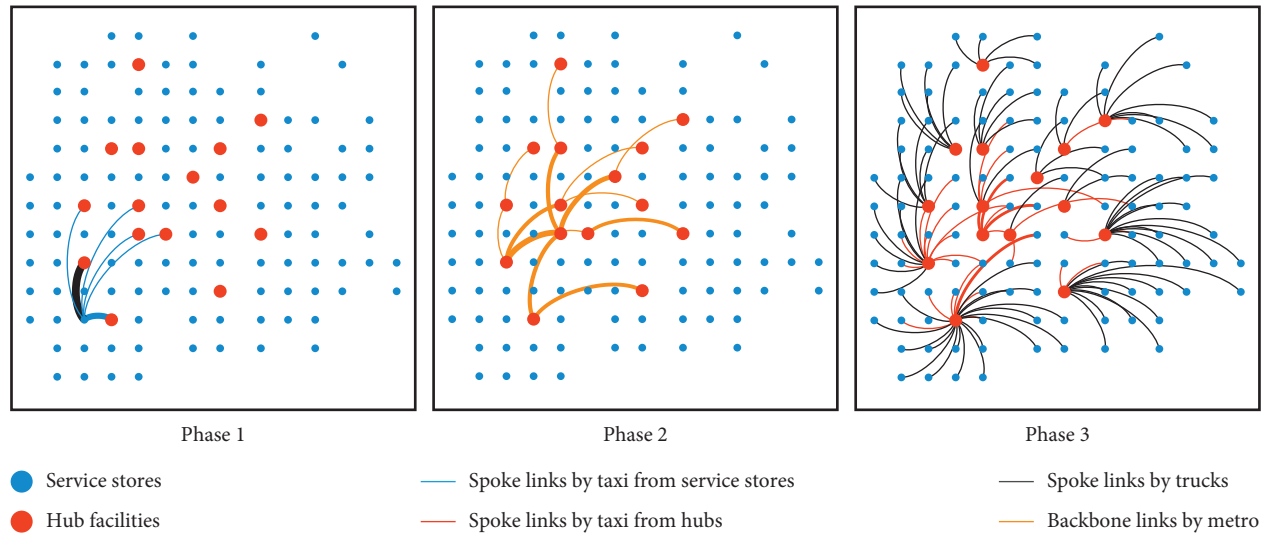


FIGURE 7: Package routing procedures.

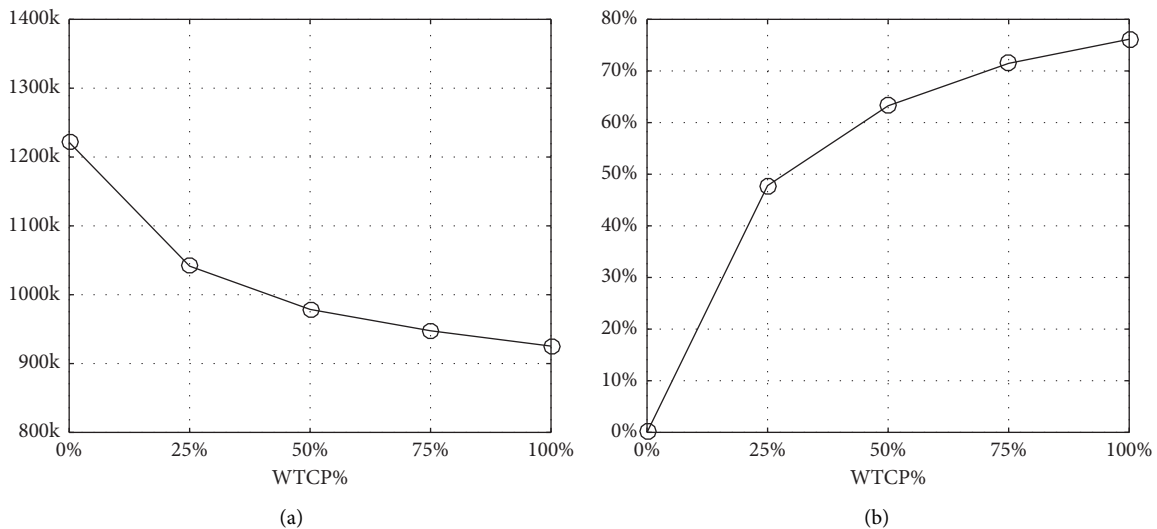


FIGURE 8: Total cost (a) and proportion of packages transported by taxi on spoke links (b) with different WTCP% (independent from payments for incentive).

taxi. The color of a link is the same as its origin node. The width of the link represents the package flow through the link. In the figures, there are several hub facilities clustered together in the central area. One plausible reason is that the package demand and taxi flow are both higher in the central area. The establishment of hubs in these zones is able to service more demand with limited resources. If more hub facilities are allowed, some hubs spread out near the outer-ring expressway to expand the coverage of demand.

Take the scenario with 15 hubs as an example. The detailed routing procedures for packages from an origin service store to all destination stores are illustrated in Figure 7. The routing process consists of three phases. In the first phase, most of the packages are transported by the taxi to the close hubs. Due to the constrained carrying capacity between the service store and hubs, the rest are transported

to hub by trucks. In phase 2, the packages are transported by metro to the hubs connecting to their destination stores. Finally, the packages are routed from the hubs to the respective destination stores in phase 3. On spoke links originated from the hubs in the central area, the packages are mostly transported by taxis, while on the spoke links originated from the hubs in other areas, most packages are transported by trucks due to the insufficiency of taxis.

4.2.2. Scenario B: WTCP% Independent from Incentives.

Under this scenario, the payments for incentive are independent from the WTCP%. If there are no taxi drivers willing to carry packages, the PPS network becomes a metro-truck system, which generates relatively high transport costs on spoke links. As shown in Figures 8(a) and 9(b), if WTCP

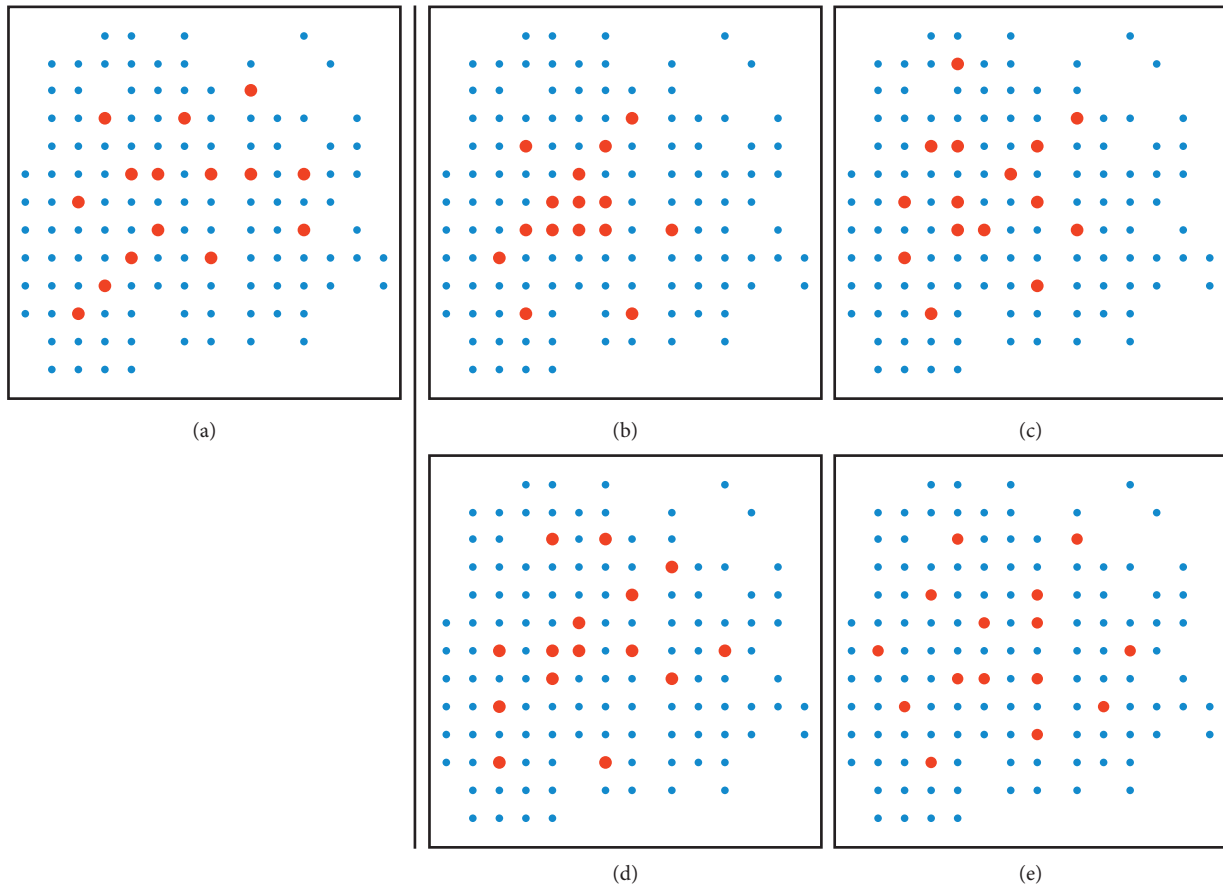


FIGURE 9: Optimal hub locations of scenario B: (a) 0%, 9.45 km, i.e., hub location of the metro-truck network without taxis. (b) 25%, 7.16 km, (c) 50%, 8.13 km, (d) 75%, 8.85 km, and (e) 100%, 8.92 km.

% increases, thanks to lower delivery costs comparing with trucks, the total cost decreases and more packages are carried by taxis on spoke links.

With more taxis willing to carry packages, the optimal hub locations become more dispersed in the city. Figure 9 illustrates the specific hub locations of the five subscenarios under scenario B, with the WTCP% and the average hub distance listed in the caption. If no taxi drivers are willing to carry packages, the hub locations are optimized without considering the distribution of taxi flows. If 25% of taxis are willing to carry packages, the optimal network tends to cluster hubs in the central area of the city where the package demands and taxi supplies are both high. The layout allows more service stores in the central area linking to hubs. With the increase of WTCP%, the central area can be serviced by fewer hubs and some hubs are relocated to peripheral areas to cover more package demands.

With more taxis involved, more trucks are expected to be saved in the logistics system. We divide the study area into three parts—central, middle, and outer parts—according to the locations of Shanghai inner-, middle-, and outer-ring expressways (see Figure 10(a)). With WTCP% increasing from 0% to 100%, 89.32%, 76.43%, and 59.70% of truck flow is saved in the central, middle, and outer parts, respectively (see Figure 10(b)). The central part benefits the most from the PPS network, followed by the middle and outer part. This

result implies that the PPS network could mitigate the negative effects of urban logistics on traffic congestion and air pollution in the urban areas.

4.2.3. Scenario C: WTCP% Independent from Incentives.

Under this scenario, the WTCP% depends on incentive payment—the unit cost of taxi delivery. Figures 11(a) and 11(b) present the trends of total cost and proportion of package flows delivered by taxis on spoke links, respectively. Although the increased WTCP% allows more packages to shift from the truck to taxi, the increase of incentive raises the total costs of the system. With greater incentives, the PPS network prefers trucks to transport packages on most spoke links, leading to the reduction of taxi delivery. The results show that under the linear assumption of incentive-WTCP% relationship, the optimal payment for incentive is around 2.5% of regular taxi fare per package, with 25% of WTCP%. In this case, despite of the fact that the proportion taxi usage is not the highest, it generates the minimum total cost due to lower payments for incentive.

5. Conclusion and Discussion

This study envisions a multimodal PPS network integrating metro, taxi, and truck with a hub-and-spoke network. On spoke links, the PPS network balances the usage of taxis and



FIGURE 10: Truck flow of different parts of Shanghai. (a) Study area divided into three parts and (b) truck flow (in- and out-flow) of each part.

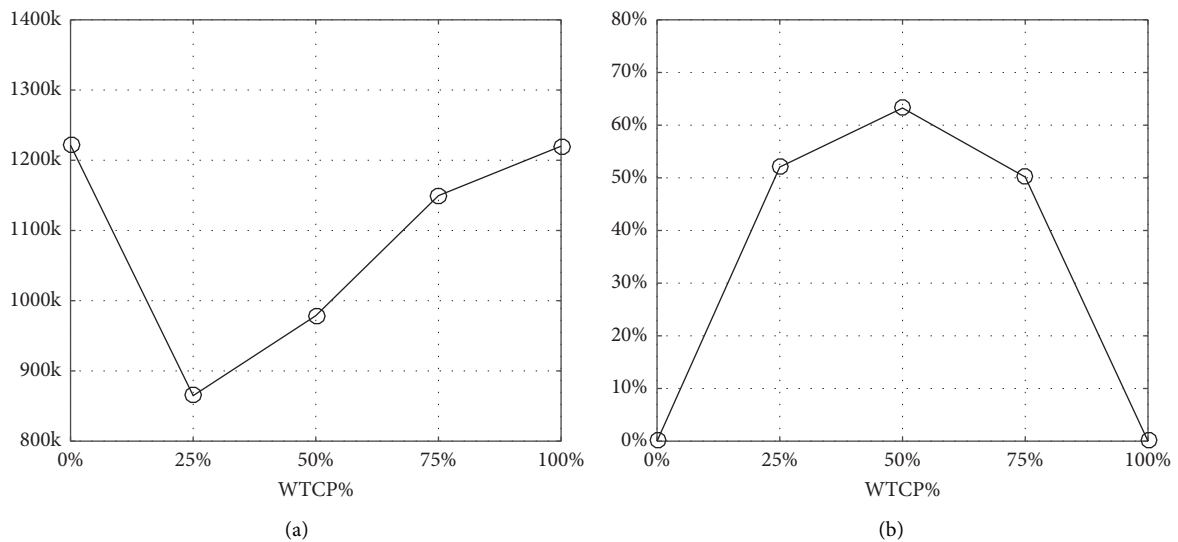


FIGURE 11: Total cost (a) and proportion of packages transported by taxi on spoke links (b) with different WTCP% (dependent on payment for incentive).

trucks for package transport according to the unit costs of these two modes and capacity constraints of taxis. The design of the multimodal PPS network is formulated into a HLP with the mixed integer linear programming framework. The developed model is an extension to the two classic types of HLPs: the multiassignment p -hub median problem without capacity constraints if the spoke links are serviced by truck only, and a capacitated multiassignment p -hub covering problem if the model tends to minimize the amount of trucks and to maximize the package flows transported by taxi with capacitated spoke links. A modified GA is developed taking into account the constraints of carrying capacity by taxi.

To demonstrate the potentiality of the multimodal PPS network for urban logistics, the network is adopted based on

the real-world data of Shanghai. A series of scenarios are designed to assess the performance of the system from two perspectives, the number of hubs and the proportion of taxi drivers who are willing to carry packages. The scenarios show that with increased number of hubs, the spatial distribution of hubs disperses from the city center to peripheral areas and more areas can be serviced by taxis. More hubs lead to more packages transported by taxi, which reduces the costs on spoke links, but the marginal savings of transport cost declines as well. There is, nevertheless, a trade-off between the operation cost saving by taxis and the establishment cost of an extra hub. The analysis also presents that with given number of hubs, if the WTCP% is independent from the incentive payments, with more taxis willing to carry packages, the total cost of the system keeps decreasing.

```

 $I_1 \leftarrow$  First parent;  $I_2 \leftarrow$  Second parent
 $N_p \leftarrow$  Number of potential hub locations
 $i \leftarrow 0$ ;  $j \leftarrow N_p + 1$ ;
while  $i < j$ 
  for  $k \leftarrow (i + 1)$  to  $(j - 1)$ 
    if  $I_1(k) = 1$  and  $I_2(k) = 0$ 
       $i \leftarrow k$ ; break
    end if
  end for
   $i \leftarrow N_p$ 
  for  $k \leftarrow (j - 1)$  to  $(i + 1)$ 
    if  $I_1(k) = 0$  and  $I_2(k) = 1$ 
       $j \leftarrow k$ ; break
    end if
  end for
   $j \leftarrow 0$ 
  if  $i < j$ 
    Exchange  $(I_1(i), I_2(i))$  and  $(I_1(j), I_2(j))$  with probability  $P_c$ 
  end if
end while

```

ALGORITHM 1: Crossover operation.

However, if the proportion of taxis willing to carry packages increases with the incentive payments to taxi drivers, an optimal value of incentives exists, by balancing the operation costs of taxis and trucks.

For future works, some hypothetical assumptions made in this study can be further released. For instance, the current network requires the packages to be routed via at least one hub, while a network that allows direct connections between service stores could extend the network coverage. In addition, the influence of various partitioning methods of the study area on the resulting network can be further evaluated. It is also recommended to consider the willingness of taxi drivers to participate in PPS activities as a decision variable in network optimization. It can be an effective means to adjust the carrying capacities since more taxis may be willing to participate in the PPS activities with greater incentives. Finally, the PPS network may lead to the rebalancing of taxis, which may result in different optimized network patterns.

Appendix

Steps and Pseudocodes of the Modified GA

The modified GA iterates from Step 3 to 6 and stops if the convergence criterion is satisfied.

Step 1. Coding: a hub location arrangement is represented by an individual consisting of a binary string of length N_p . $I(k) = 1$ if node k is selected to locate a hub facility. Otherwise, $I(k) = 0$.

Step 2. Initialization: a population of individuals is randomly generated with a size of K . For each individual, p genes are selected from in total n genes without replacement and assigned as 1. The other genes

equal 0. Each individual has exactly p number of “1,” representing p nodes to locate hub facilities.

Step 3. Fitness evaluation: the fitness function is set as the objective function of the model developed in Section 3.2. Giving selected hub locations, the sub-problem becomes a linear programming problem involving continuous variables x , y , z , u , and v that can be solved efficiently to evaluate the fitness of each individual.

Step 4. Selection: the fine-grained tournament selection strategy (FGTS) is adopted to select K individuals from the population [71]. Denote F_t as the desired average tournament size. The strategy performs weighted sampling of $|F_t| + 1$ with replacement from the population k_1 times and performs weighted sampling of $|F_t|$ with replacement k_2 times. The weight of an individual equals its fitness value. For each sample, the one with the lowest fitness value is selected. The values of k_1 and k_2 are determined by the following equations:

$$\begin{aligned} k_1 + k_2 &= K, \\ k_1 \times (|F_t| + 1) + k_2 \times |F_t| &= K \times F_t. \end{aligned} \quad (\text{A.1})$$

Step 5. Crossover: two offsprings from a pair of parents are produced. The basic crossover operator randomly exchanges the codes of each gene. The number of “1” in the resulting offspring may not equal p . To address this problem, we simultaneously exchange the codes for two genes to ensure that each offspring has p “1” values. Algorithm 1 describes the crossover.

Step 6. Mutation: the gene code of an individual is randomly shifted from 0 to 1 or from 1 to 0. To ensure that there are p number of “1” in an individual after the mutation operation, we change the codes of two genes


```

 $I \leftarrow$  An individual
 $N_p \leftarrow$  Number of potential hub locations
 $O \leftarrow$  Set of the locations of genes in  $I$  with the code of one
 $Z \leftarrow$  Set of the locations of genes in  $I$  with the code of zero
 $n_o \leftarrow$  Number of ones in  $I$ 
 $n_z \leftarrow$  Number of zeros in  $I$ 
 $n \leftarrow \min(n_o, n_z)$ 
for  $k \leftarrow 1$  to  $n$ 
    Change the codes of the genes ( $I(O(k)), I(Z(k))$ ) with probability  $P_m$ 
end if

```

ALGORITHM 2: Mutation operation.

that have different codes simultaneously. Algorithm 2 describes the mutation.

Convergence criterion: the algorithm stops when (1) the average relative change in the fitness function value over stall generation limit G_s is less than function tolerance τ or (2) the computation time exceeds time limit T_{\max} .

Data Availability

The data used to support the results of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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References

- [1] National Bureau of Statistics of China, *China Statistical Yearbook 2018*, China Statistics Press Beijing, Beijing, China, 2018.
- [2] European Commission, *Green Paper, towards a New Culture for Urban Mobility*, European Commission, Brussels, Belgium, 2007.
- [3] A. Sampaio, M. Savelsbergh, L. Veelenturf, and T. van Woensel, "Crowd-based city logistics," in *Sustainable Transportation and Smart Logistics*, pp. 381–400, Elsevier, Amsterdam, Netherlands, 2019.
- [4] A. van Binsbergen and J. Visser, "New urban goods distribution systems," in *Proceedings of the Conference on Urban Transport Systems*, Miami, FL, USA, March 1999.
- [5] C. Shaefer and N. Dalkmann, "A new and innovative approach for bus systems in rural areas," in *Proceedings of the European Transport Conference*, Strasbourg, France, October 2003.
- [6] A. Trentini and N. Mahl  n  , "Toward a shared urban transport system ensuring passengers & goods cohabitation," *TeMA Journal of Land Use, Mobility and Environment*, vol. 3, no. 2, 2010.
- [7] A. Trentini and N. Malhene, "Flow management of passengers and goods coexisting in the urban environment: conceptual and operational points of view," *Procedia—Social and Behavioral Sciences*, vol. 39, pp. 807–817, 2012.
- [8] B. Li, D. Krushinsky, H. A. Reijers et al., "The share-a-ride problem: people and parcels sharing taxis," *European Journal of Operational Research*, vol. 238, no. 1, pp. 31–40, 2014.
- [9] N.-Q. Nguyen, N.-V.-D. Nghiem, P.-T. Do, K.-T. LE, M.-S. Nguyen, and N. Mukai, "People and parcels sharing a taxi for Tokyo city," in *Proceedings of the Sixth International Symposium on Information and Communication Technology—SoICT 2015*, pp. 90–97, Hue, Vietnam, December 2015.
- [10] B. Li, D. Krushinsky, T. Van Woensel, and H. A. Reijers, "The share-a-ride problem with stochastic travel times and stochastic delivery locations," *Transportation Research Part C: Emerging Technologies*, vol. 67, pp. 95–108, 2016.
- [11] R. Masson, A. Trentini, F. Lehu  d   et al., "Optimization of a city logistics transportation system with mixed passengers and goods," *EURO Journal on Transportation and Logistics*, vol. 6, no. 1, pp. 81–109, 2017.
- [12] V. Ghilas, E. Demir, and T. V. Woensel, "The pickup and delivery problem with time windows and scheduled lines," *INFOR: Information Systems & Operational Research*, vol. 54, no. 2, pp. 1–21, 2016.
- [13] V. Ghilas, E. Demir, and T. V. Woensel, "A scenario-based planning for the pickup and delivery problem with time windows, scheduled lines and stochastic demands," *Transportation Research Part B: Methodological*, vol. 91, pp. 34–51, 2016.
- [14] E. Fatnassi, J. Chaouachi, and W. Klibi, "Planning and operating a shared goods and passengers on-demand rapid transit system for sustainable city-logistics," *Transportation Research Part B: Methodological*, vol. 81, pp. 440–460, 2015.
- [15] B. Yildiz and M. Savelsbergh, "Service and capacity planning in crowd-sourced delivery," *Transportation Research Part C: Emerging Technologies*, vol. 100, pp. 177–199, 2019.
- [16] M. SteadieSeifi, N. P. Dellaert, W. Nuijten, T. Van Woensel, and R. Raoufi, "Multimodal freight transportation planning: a literature review," *European Journal of Operational Research*, vol. 233, no. 1, pp. 1–15, 2014.
- [17] P. Arnold, D. Peeters, and I. Thomas, "Modelling a rail/road intermodal transportation system," *Transportation Research Part E: Logistics and Transportation Review*, vol. 40, no. 3, pp. 255–270, 2004.
- [18] B. Groothedde, C. Ruijgrok, and L. Tavasszy, "Towards collaborative, intermodal hub networks: a case study in the fast moving consumer goods market," *Transportation Research Part E*, vol. 41, no. 6, pp. 567–583, 2005.

- [19] Y. Qu, T. Bektaş, and J. Bennell, "Sustainability SI: multimode multicommodity network design model for intermodal freight transportation with transfer and emission costs," *Networks and Spatial Economics*, vol. 16, no. 1, pp. 303–329, 2016.
- [20] F. Fotuhi and N. Huynh, "Reliable intermodal freight network expansion with demand uncertainties and network disruptions," *Networks and Spatial Economics*, vol. 17, no. 2, pp. 405–433, 2017.
- [21] H. Kim and M. S. Ryerson, "The q-Ad hoc hub location problem for multi-modal networks," *Networks and Spatial Economics*, vol. 17, no. 3, pp. 1015–1041, 2017.
- [22] M. E. O'Kelly, "The location of interacting hub facilities," *Transportation Science*, vol. 20, no. 2, pp. 92–106, 1986.
- [23] M. E. O'Kelly, "Activity levels at hub facilities in interacting networks," *Geographical Analysis*, vol. 18, no. 4, pp. 343–356, 1986.
- [24] M. E. O'Kelly, "A quadratic integer program for the location of interacting hub facilities," *European Journal of Operational Research*, vol. 32, no. 3, pp. 393–404, 1987.
- [25] J. F. Campbell, "Integer programming formulations of discrete hub location problems," *European Journal of Operational Research*, vol. 72, no. 2, pp. 387–405, 1994.
- [26] J. F. Campbell, "Hub location and the p-hub median problem," *Operations Research*, vol. 44, no. 6, pp. 923–935, 1996.
- [27] J. F. Campbell, "Hub location for time definite transportation," *Computers & Operations Research*, vol. 36, no. 12, pp. 3107–3116, 2009.
- [28] J. Ebery, "Solving large single allocation p-hub problems with two or three hubs," *European Journal of Operational Research*, vol. 128, no. 2, pp. 447–458, 2001.
- [29] N. Ghaffarinasab and B. Y. Kara, "Benders decomposition algorithms for two variants of the single allocation hub location problem," *Networks and Spatial Economics*, vol. 19, no. 1, pp. 83–108, 2019.
- [30] M. Vidović, S. Zečević, M. Kilbarda et al., "The p-hub model with hub-catchment areas, existing hubs, and simulation: a case study of Serbian intermodal terminals," *Networks and Spatial Economics*, vol. 11, no. 2, pp. 295–314, 2011.
- [31] X. Sun, W. Dai, Y. Zhang et al., "Finding-hub median locations: an empirical study on problems and solution techniques," *Journal of Advanced Transportation*, vol. 2017, Article ID 9387302, 23 pages, 2017.
- [32] B. Y. Kara and B. C. Tansel, "On the single-assignment p-hub center problem," *European Journal of Operational Research*, vol. 125, no. 3, pp. 648–655, 2000.
- [33] B. Qu and K. Weng, "Path relinking approach for multiple allocation hub maximal covering problem," *Computers & Mathematics with Applications*, vol. 57, no. 11–12, pp. 1890–1894, 2009.
- [34] H. Karimi and M. Bashiri, "Hub covering location problems with different coverage types," *Scientia Iranica*, vol. 18, no. 6, pp. 1571–1578, 2011.
- [35] S. Gelareh and D. Pisinger, "Fleet deployment, network design and hub location of liner shipping companies," *Transportation Research Part E: Logistics and Transportation Review*, vol. 47, no. 6, pp. 947–964, 2011.
- [36] S. Alumur and B. Y. Kara, "Network hub location problems: the state of the art," *European Journal of Operational Research*, vol. 190, no. 1, pp. 1–21, 2008.
- [37] J. F. Campbell and M. E. O'Kelly, "Twenty-five years of hub location research," *Transportation Science*, vol. 46, no. 2, pp. 153–169, 2012.
- [38] R. Z. Farahani, M. Hekmatfar, A. B. Arabani et al., "Hub location problems: a review of models, classification, solution techniques, and applications," *Computers & Industrial Engineering*, vol. 64, no. 4, pp. 1096–1109, 2013.
- [39] C.-H. Lee, H.-B. Ro, and D.-W. Tcha, "Topological design of a two-level network with ring-star configuration," *Computers & Operations Research*, vol. 20, no. 6, pp. 625–637, 1993.
- [40] M. Labbé and H. Yaman, "Solving the hub location problem in a star-star network," *Networks*, vol. 51, no. 1, pp. 19–33, 2008.
- [41] I. Contreras, E. Fernández, and A. Marín, "Tight bounds from a path based formulation for the tree of hub location problem," *Computers & Operations Research*, vol. 36, no. 12, pp. 3117–3127, 2009.
- [42] I. Contreras, E. Fernández, and A. Marín, "The tree of hubs location problem," *European Journal of Operational Research*, vol. 202, no. 2, pp. 390–400, 2010.
- [43] E. Martins de Sá, I. Contreras, J.-F. Cordeau et al., "The hub line location problem," *Transportation Science*, vol. 49, no. 3, pp. 500–518, 2015.
- [44] T. Aykin, "Lagrangian relaxation based approaches to capacitated hub-and-spoke network design problem," *European Journal of Operational Research*, vol. 79, no. 3, pp. 501–523, 1994.
- [45] C.-C. Lin and S.-H. Chen, "An integral constrained generalized hub-and-spoke network design problem," *Transportation Research Part E: Logistics and Transportation Review*, vol. 44, no. 6, pp. 986–1003, 2008.
- [46] J. G. Kliniewicz, "Hub location in backbone/tributary network design: a review," *Location Science*, vol. 6, no. 1–4, pp. 307–335, 1998.
- [47] H. Yaman, "The hierarchical hub median problem with single assignment," *Transportation Research Part B: Methodological*, vol. 43, no. 6, pp. 643–658, 2009.
- [48] N. Bolandabb, "Preprocessing and cutting for multiple allocation hub location problems," *European Journal of Operational Research*, vol. 155, no. 3, pp. 638–653, 2004.
- [49] V. Rodriguez, M. Alvarez, and L. Barcos, "Hub location under capacity constraints," *Transportation Research Part E: Logistics and Transportation Review*, vol. 43, no. 5, pp. 495–505, 2007.
- [50] D. Chauhan, A. Unnikrishnan, and M. Figliozzi, "Maximum coverage capacitated facility location problem with range constrained drones," *Transportation Research Part C: Emerging Technologies*, vol. 99, pp. 1–18, 2019.
- [51] J. Puerto, A. B. Ramos, A. M. Rodríguez-Chía, and M. C. Sánchez-Gil, "Ordered median hub location problems with capacity constraints," *Transportation Research Part C: Emerging Technologies*, vol. 70, pp. 142–156, 2016.
- [52] I. Correia, S. Nickel, and F. Saldanha-da-Gama, "Multi-product capacitated single-allocation hub location problems: formulations and inequalities," *Networks and Spatial Economics*, vol. 14, no. 1, pp. 1–25, 2014.
- [53] D. Bryan, "Extensions to the hub location problem: formulations and numerical examples," *Geographical Analysis*, vol. 30, no. 4, pp. 315–330, 1998.
- [54] H. Yaman and G. Carello, "Solving the hub location problem with modular link capacities," *Computers & Operations Research*, vol. 32, no. 12, pp. 3227–3245, 2005.
- [55] C.-C. Lin, J.-Y. Lin, and Y.-C. Chen, "The capacitated p-hub median problem with integral constraints: an application to a Chinese air cargo network," *Applied Mathematical Modelling*, vol. 36, no. 6, pp. 2777–2787, 2012.
- [56] I. Correia, S. Nickel, and F. Saldanha-da-Gama, "Single-assignment hub location problems with multiple capacity levels," *Transportation Research Part B: Methodological*, vol. 44, no. 8–9, pp. 1047–1066, 2010.

- [57] S. Elhedhli and H. Wu, "A Lagrangean heuristic for hub-and-spoke system design with capacity selection and congestion," *INFORMS Journal on Computing*, vol. 22, no. 2, pp. 282–296, 2010.
- [58] I. Contreras, J.-F. Cordeau, and G. Laporte, "Exact solution of large-scale hub location problems with multiple capacity levels," *Transportation Science*, vol. 46, no. 4, pp. 439–459, 2012.
- [59] G. Nagy and S. Salhi, "The many-to-many location-routing problem," *Top*, vol. 6, no. 2, pp. 261–275, 1998.
- [60] M. Wasner and G. Zäpfel, "An integrated multi-depot hub-location vehicle routing model for network planning of parcel service," *International Journal of Production Economics*, vol. 90, no. 3, pp. 403–419, 2004.
- [61] J. U. Sun, "An integrated hub location and multi-depot vehicle routing problem," *Applied Mechanics and Materials*, vol. 409–410, pp. 1188–1192, 2013.
- [62] G. Musolino, C. Rindone, A. Polimeni, and A. Vitetta, "Planning urban distribution center location with variable restocking demand scenarios: general methodology and testing in a medium-size town," *Transport Policy*, vol. 80, pp. 157–166, 2019.
- [63] A. T. Ernst and M. Krishnamoorthy, "Exact and heuristic algorithms for the uncapacitated multiple allocation p-hub median problem," *European Journal of Operational Research*, vol. 104, no. 1, pp. 100–112, 1998.
- [64] L. Cánovas, S. García, and A. Marín, "Solving the uncapacitated multiple allocation hub location problem by means of a dual-ascent technique," *European Journal of Operational Research*, vol. 179, no. 3, pp. 990–1007, 2007.
- [65] S. García, M. Landete, and A. Marín, "New formulation and a branch-and-cut algorithm for the multiple allocation p-hub median problem," *European Journal of Operational Research*, vol. 220, no. 1, pp. 48–57, 2012.
- [66] H. Pirkul and D. A. Schilling, "An efficient procedure for designing single allocation hub and spoke systems," *Management Science*, vol. 44, no. 12, pp. S235–S242, 1998.
- [67] R. S. de Camargo, G. de Miranda Jr., and H. P. L. Luna, "Benders decomposition for hub location problems with economies of scale," *Transportation Science*, vol. 43, no. 1, pp. 86–97, 2009.
- [68] A. Ilić, D. Urošević, J. Brimberg, and N. Mladenović, "A general variable neighborhood search for solving the uncapacitated single allocation p-hub median problem," *European Journal of Operational Research*, vol. 206, no. 2, pp. 289–300, 2010.
- [69] M. Marić, Z. Stanimirović, and P. Stanojević, "An efficient memetic algorithm for the uncapacitated single allocation hub location problem," *Soft Computing*, vol. 17, no. 3, pp. 445–466, 2013.
- [70] CPLEX, "IBM ILOG V12.8 user's manual for CPLEX," 2017.
- [71] V. Filipović, "Fine-grained tournament selection operator in genetic algorithms," *Computing and Informatics*, vol. 22, no. 2, pp. 143–161, 2012.