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A Vehicle Routing Problem for Multi-depot Collaborative Delivery Considering Common and Neighboring Customers

Yanbing Gao[1]

[1] Business School of Sichuan University, China

Correspondence: Yanbing Gao, Business School of Sichuan University, Chengdu 610065, China. E-mail: gaoyanbing@qq.com

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Author Bio

Yanbing Gao (born 1997), male; Han Chinese; hometown: Zhaotong, Yunnan; educational level: master's degree; research direction: management science.

Abstract

Facing the challenges of delivery cost, efficiency, and security in modern logistics systems, this study investigates a realistic scenario where multiple logistics companies jointly serve a common customer base, and customers' parcels can be picked up by their neighboring customers. By integrating mobile lockers and drones into the delivery process, we propose a multi-depot collaborative delivery vehicle routing problem with common and neighboring customers, and formulate a corresponding mixed-integer programming model. To solve the problem efficiently, a hybrid heuristic algorithm combining Adaptive Large Neighborhood Search and Tabu Search is developed. Numerical experiments demonstrate that collaboration among depots based on common and neighboring customers offers significant advantages: It not only reduces delivery costs but also improves the utilization efficiency of mobile lockers and reduces the required number of lockers. Moreover, the greater the number of depots participating in collaborative delivery, the more pronounced the benefits.

Keywords: mobile lockers, common customers, neighboring customers, collaborative delivery

1. Introduction

With the rapid development of the internet economy, the express logistics industry is undergoing tremendous growth. Under the pressure of an enormous volume of parcels, logistics systems are facing significant challenges. How to deliver packages to customers in a cost-effective, efficient, and secure manner has become an urgent issue [1]. Regarding logistics cost control, Dolan [2] pointed out that last-mile delivery accounts for a substantial proportion of the total logistics cost, approximately 53%. More recent statistics indicate that this proportion has risen to around 78% [3]. In terms of delivery efficiency, a report by Zebra revealed that 32% of consumers expect to receive their parcels within two hours, while 44% prefer delivery within three to four hours. Additionally, a survey conducted in the United States showed that 57% of customers reported their packages were delivered to insecure locations, 16% indicated their parcels had been stolen [4].

To address the challenges faced by the express logistics industry, researchers have proposed a variety of innovative delivery methods, such as fixed parcel lockers, mobile lockers, drone delivery, and vehicle-drone collaborative delivery systems. In practical logistics distribution scenarios, multiple logistics companies often serve the same group of customers, resulting in the presence of common customers across enterprises. Additionally, during the delivery process, a customer's demand can be fulfilled by a neighboring customer on their behalf, thereby enhancing delivery efficiency. Based on these considerations, this study addresses the problem from the perspectives of cost-efficiency, operational efficiency, security, and reliability. Specifically, we propose a multi-depot collaborative delivery vehicle routing problem with common and neighboring customers (MCDVRPCNC), which incorporates both common customer sharing among logistics companies and the delegation of deliveries to neighboring customers.

2. Literature Review

The MCDVRPCNC problem is essentially a variant of the vehicle routing problem (VRP). It encompasses two key sub-problems: the vehicle routing problem for mobile lockers (VRPML) and the vehicle routing problem for collaborative delivery (VRPCD).

Regarding the VRPML problem, Schwerdfeger and Boysen (2020)[5] investigated the issue of updating mobile locker locations in response to changes in recipient locations during last-mile delivery, and proposed a corresponding optimization model. Li et al. (2021)[6] explored the layout problem of a two-stage unmanned mobile locker delivery system, where the first stage involves autonomous mobile lockers transporting parcels from the distribution center to designated sites, and the second stage involves delivery personnel transferring parcels from lockers to customers at these sites. Schwerdfeger and Boysen (2022)[7] further examined the movement of mobile lockers, proposing six delivery configurations and developing an optimization model incorporating five mobile locker concepts as well as one for fixed lockers. Lan et al. (2022)[8] considered company costs, customer satisfaction, and income satisfaction of crowdsourced workers, formulating a multi-objective optimization model involving distribution hubs and crowdsourcing personnel. Kötschau et al. (2023)[9] introduced a service model that integrates mobile lockers, fixed lockers, and home delivery. This model, which accounts for variable pickup times and customer travel distances, aims to maximize the number of customers served. Wang et al. (2024)[10] addressed route planning for mobile lockers under uncertain demand by proposing an optimization approach based on a recourse strategy. Experimental results showed that this method significantly improves service reliability with only a slight increase in operational costs. Korkmaz et al. (2025)[11] studied the routing problem of mobile lockers under horizontal collaboration, formulated a mixed-integer programming model, and developed a heuristic algorithm for its solution. Results demonstrated that horizontal collaboration effectively reduces delivery costs.

Most studies on the VRPCD problem focus on truck-drone cooperative delivery systems. Murray and Chu (2015)[12] were among the first to introduce the concept of truck-drone collaboration into the traveling salesman problem. Chung et al. (2020)[13] provided a comprehensive review of mathematical models, solution strategies, synchronization issues, and challenges associated with drone operations and truck-drone collaborative systems. Manshadian et al. (2023)[14] investigated truck-drone collaborative routing in the context of urban disinfection under disaster conditions and proposed a hybrid heuristic combining simulated annealing and tabu search. Najy et al. (2023)[15] extended the study of truck-drone tandem delivery into the inventory routing problem, introducing an exact branch-and-cut method along with a heuristic algorithm. Rave et al. (2023)[16] applied the truck-drone system to rural parcel delivery, developed a corresponding mixed-integer programming model, and designed an adaptive large neighborhood search heuristic to solve the problem.

Although extensive research has been conducted on both the VRPML and VRPCD problems, certain gaps remain. In particular, few studies have considered scenarios where multiple logistics depots serve common customers, or where a customer's delivery demand can be fulfilled by a neighboring customer. Therefore, the MCDVRPCNC problem addressed in this study presents a novel and meaningful research direction with significant academic and practical value.

3. Problem Description

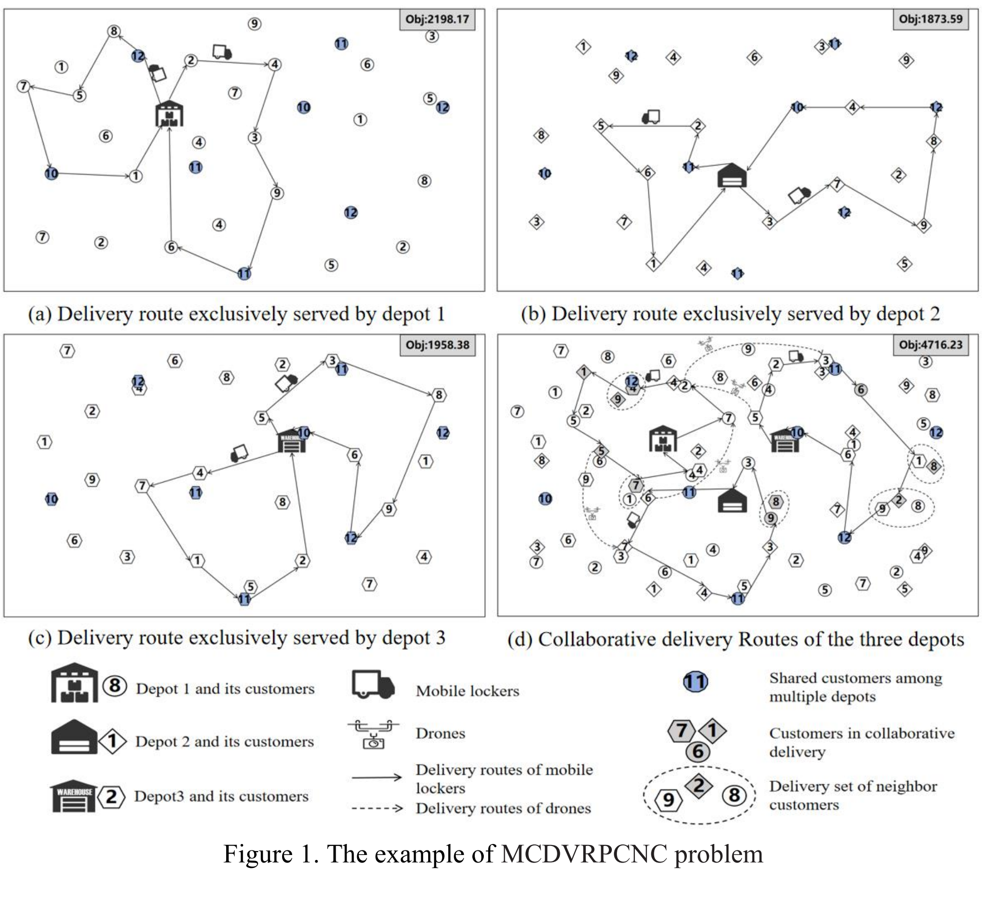
The MCDVRPCNC problem incorporates multiple delivery options and explicitly considers the presence of common customers and neighboring customers. By treating multiple distinct depots as an integrated system, this problem emphasizes inter-depot collaboration to collectively fulfill parcel deliveries. We use a complete undirected graph $G(N, E)$ to represent the delivery network, where N denotes the set of locations for depots and customer pickup points. Let $N = D \cup N_d$, where D is the set of depots, $D = \{d_1, d_2, ..., d_n\}$, and N_d is the set of customer pickup locations. Let C represent the set of all customers awaiting delivery, c_i denote the customer set to be served by depot d_i, and A denote the set of mobile lockers shared by all depots.

When formulating the delivery plan, we assume all depots collaboratively participate in the delivery process and jointly formulate a delivery plan for the customers they share. This includes determining whether parcel transfers between mobile lockers are needed or whether parcels should be delivered directly to a customer's neighboring pickup location. Therefore, for a customer associated with a certain depot, there are four possible delivery modes: (1) Delivery by a mobile locker directly to the customer's pickup location; (2) Delivery by a mobile locker directly to a neighboring customer's pickup location; (3) Parcel transfer between mobile lockers before final delivery to the designated pickup location; (4) Parcel transfer between mobile lockers before final delivery to a neighboring customer's pickup location. For the parcel transfer between mobile lockers, this work assumes the use of drones.

Drones are fast, low-cost, lightweight, and unaffected by road conditions, making them well-suited for executing parcel transfers between mobile lockers. Since such transfers may occur frequently during the delivery process, drones are assumed to be mounted on the mobile lockers for deployment as needed.

Figure 1 is a simple example of the MCDVRPCNC problem, showing the delivery route map when three depots create their delivery plans individually and when they create a delivery plan as a whole. When the delivery plans are created individually, the delivery routes for depot 1 is 0 → 12 → 8 → 5 → 7 → 10 → 1 → 0 and 0 → 2 → 4 → 3 → 9 → 11 → 6 → 0, with a delivery cost of 2198.17; the delivery routes for depot 2 is 0 → 11 → 2 → 5 → 6 → 1 → 0 and 0 → 3 → 7 → 9 → 8 → 12 → 4 → 10 → 0, with a delivery cost of 1873.59; the delivery routes for depot 3 is 0 → 5 → 3 → 8 → 9 → 12 → 6 → 10 → 0 and 0 → 4 → 7 → 1 → 11 → 2 → 0, with a delivery cost of 1957.38. The total delivery cost for the three depots is 6030.14. When the three depots create a delivery plan as a whole, the delivery routes for the three depots are 0 → 7 → 2 → 4 → 1 → 5 → 5 → 7 → 4 → 0, 0 → 5 → 2 → 3 → 6 → 1 → 2 → 12 → 6 → 10 → 0, and 0 → 6 → 7 → 4 → 11 → 3 → 9 → 3 → 0, with a delivery cost of 4716.23. Compared to creating delivery plans individually, the delivery cost is reduced by approximately 21.79%, and the number of mobile lockers used is reduced by 50%, with only 3 drones used to complete the parcel exchange tasks between the mobile lockers.

The assumptions for the MCDVRPCNC problem are as follows: (1) Multiple depots correspond to different logistics companies, and these logistics companies have a good partnership and can share key information such as customer locations and parcel volumes. (2) The mobile lockers are consistent and are shared by all logistics companies, allowing free movement between different logistics companies. (3) The mobile lockers depart from the depot and may not return to the originating depot after completing the delivery task, but it is necessary to ensure that the number of lockers at each depot is the same at the beginning and end of the delivery. (4) Each customer has different delivery demands at different depots. (5) Each customer may be visited by multiple mobile lockers, but no more than the number of depots that have delivery demands for that customer. (6) The collaboration between mobile lockers occurs at the customer location, not at the depot, and the time required for collaboration is ignored. (7) Customers have multiple delivery locations and corresponding delivery time windows. Deliveries must be completed within the time window, and customer delivery demands can be crowdsourced by neighboring customers. (8) neighboring customers can crowdsourcing delivery demands for multiple customers, but there are quantity limits.



(a) Delivery route exclusively served by depot 1 (b) Delivery route exclusively served by depot 2

(c) Delivery route exclusively served by depot 3 (d) Collaborative delivery Routes of the three depots

Figure 1. The example of MCDVRPCNC problem

4. MILP Formulation

The MCDVRPCNC problem considers multiple depots as a whole, integrates customer information from each depot, and develops an overall collaborative delivery plan. The symbols and variables involved in the problem are shown in Table 1 and Table 2, respectively.

Table 1. The symbols in the MILP model of MDCVRPCNC problem

Symbols	Description
D, D'	The set of depots and virtual depots, $D=\{d_1,d_2,...,d_n\}$, $D'=\{d'_1,d'_2,...,d'_n\}$
c_i	The set of customers corresponding to depot d_i
C	The set of customers at all depots, $C=\{c_1,c_2,...,c_n\}$
cd_i	The set of depots that have delivery demands from customer *i*
N_d	The set of delivery locations for all customers
N_d^h	The set of delivery locations for customer *h*
q_{ij}	The delivery demand of customer *i* at depot *j*
A	The set of mobile lockers
U	The set of drones
N'_{is}	The set of neighboring customers of customer *i* that can be crowdsourced when customer *i* is at location *s*
N''_{is}	When customer *i* is at location *s*, they are able to crowdsourcing the set of neighboring customers of customer *i*
r_i	The crowdsourced delivery range of customer *i*, which is determined by their delivery demand and the delivery demand of their neighbor customers that can be crowdsourced
cq_i	The maximum crowdsourcing capacity of customer *i*, which is determined by their delivery demand. The higher the delivery demand, the lower the maximum crowdsourcing capacity
C_1, C_2, C_3, C_4	The unit travel cost of the mobile locker, the fixed cost of the mobile locker, the unit crowdsourcing cost of the customer, and the unit travel cost of the drone
AD, UD	The maximum travel distance of the mobile locker and the drone
AQ, UQ	The load capacity limits of the mobile locker and the drone
β	The maximum number of collaborations for the delivery demand of customer *h* at depot *j*
$dist_{ij}$	The distance between node *i* and node *j*, which also represents the time required for the mobile locker to travel from node *i* to node *j*
$[e_h^j, l_h^j]$	The time window at delivery location *j* for customer *h*
φ_h^j	The service duration of the mobile locker at delivery location *j* of customer *h* is determined by delivery demand of customer *h*
$[0, T_i]$	The operating hours of depot *i*
θ	The ratio of the travel speeds of the drone and the mobile locker

Table 2. The variables in the MILP model of MDCVRPCNC problem

Variables	Description
x_{ijk}	1: mobile locker *k* moves from node *i* to node *j*; 0: otherwise
z_{ijksh}	1: The delivery demand of customer *i* at depot *j* is delivered by mobile locker *k* at location *s*, delivered to customer *h*; 0: otherwise
Y_{ijks}	1: The delivery demand of customer *i* at depot *j* is directly delivered by mobile locker *k* at location *s*; 0: otherwise
z'_{ijksh}	1: The delivery demand of customer *i* from depot *j* is delivered through collaboration by mobile locker *k* at location *s*, where it is delivered to customer *h*; 0: otherwise

Y'_{ijks}	1: The delivery demand of customer *i* from depot *j*, after coordination, is directly delivered by mobile locker *k* at location *s*; 0: otherwise
X_{ijkh}	1: The delivery demand of customer *i* from depot *j* is transferred from mobile locker *k* to mobile locker *h* after coordination; 0: otherwise
α_{ij}	1: The delivery demand of customer *i* from depot *j* requires coordination; 0: otherwise
γ_i^k	1: The mobile locker *k* visits location *i*; 0: otherwise
q_{ijk}	The load for mobile locker *k* during the period from node *i* to node *j*
uq_{iju}	The load for drone *u* during the period from node *i* to node *j*
X_{uhksm}^{ij}	1: Drone *u* picks up the delivery demand of customer *i* at depot *j* is from mobile locker *k* at location *h* and transfers it to mobile locker *m* at location *s*; 0: otherwise
S_i^k	The start service time of mobile locker *k* at location *i*
at_i^k	The arrival time of mobile locker *k* at location *i*
w_h	1: Customer *h* crowdsourced the delivery demand of non-collaborative customers; 0: otherwise
w'_h	1: Customer *h* crowdsourced the delivery demand of collaborative customers; 0: otherwise
η_{iu}^+	1: Drone *u* takes off from location *i*; 0: otherwise
η_{iu}^-	1: Drone *u* lands at location *i*; 0: otherwise
τ_{iuk}^+	1: Drone *u* takes off from mobile locker *k* at location *i*; 0: otherwise
τ_{iuk}^-	1: Drone *u* lands at mobile locker *k* at location *i*; 0: otherwise
ζ_{iuk}	1: Drone *u* services mobile locker *k* at location *i*; 0: otherwise
ft_i^u	The start service time of drone *u* at location *i*, with the collaborative time disregarded
y_{iju}	1: Drone *u* moves from node *i* to node *j*; 0: otherwise
λ_k	1: Mobile locker *k* is applied; 0: otherwise
x'_{ijk}	1: The delivery demand of customer *i* at depot *j* is initially loaded onto mobile locker *k*.; 0: otherwise
x''_{ijk}	1: The delivery demand of customer *i* at depot *j* is ultimately loaded onto mobile locker *k*; 0: otherwise

The objective function is to minimize the logistics delivery cost, which includes the fixed cost of mobile lockers, the unit travel cost of mobile lockers, the crowdsourcing cost for customers, and the unit travel cost of drones.

$$\begin{aligned} Min\ F = {} & \mathrm{C}_1 \sum_{k\in A} \sum_{i\in N_d \cup D} \sum_{j\in N_d \cup D'} x_{ijk} \cdot dist_{ij} + \mathrm{C}_2 \sum_{k\in A} \lambda_k \\ & + \mathrm{C}_3 \sum_{i\in C} \sum_{j\in D} \sum_{s\in N_d^i} \sum_{h\in N_{is}''} \sum_{m\in N_d^h} \sum_{k\in A} (z_{ijkmh} + z'_{ijkmh}) \cdot q_{ij} \\ & + \mathrm{C}_4 \sum_{u\in U} \sum_{i\in N_d} \sum_{j\in N_d} y_{iju} \cdot dist_{ij} \end{aligned} \tag{1}$$

To ensure that each mobile locker is used correctly, and that it must leave after visiting each delivery location, constraints (2) and (3) are established.

$$\sum_{j\in N_d \cup D'} x_{ijk} = \sum_{j\in N_d \cup D} x_{jik}, \forall i \in N_d, k \in A \tag{2}$$

$$\sum_{i\in D} \sum_{j\in N_d} x_{ijk} \le \lambda_k, \forall k \in A \tag{3}$$

For each customer, it is ensured that every customer is delivered to, which is represented by constraints (4) to (7).

$$\sum_{j\in N_d\cup D'} x_{ijk} \le 1, \forall h\in C, i\in N_d^h, k\in A \tag{4}$$

$$\sum_{m\in N_d^i}\sum_{h\in N_{im}''}\sum_{s\in N_d^h}\sum_{k\in A}(z_{ijksh}+z'_{ijksh}) \le 1, \forall i\in C, j\in cd_i \tag{5}$$

$$\sum_{s\in N_d^i}\sum_{k\in A}(Y_{ijks}+Y'_{ijks}) \le 1, \forall i\in C, j\in cd_i \tag{6}$$

$$\sum_{s\in N_d^i}\sum_{k\in A}(Y_{ijks}+Y'_{ijks}) + \sum_{m\in N_d^i}\sum_{h\in N_{im}''}\sum_{s\in N_d^h}\sum_{k\in A}(z_{ijksh}+z'_{ijksh}) = 1, \forall i\in C, j\in cd_i \tag{7}$$

Constraint (4) ensures that each customer's demand at a depot can only be delivered at one delivery location. Constraint (5) determines whether the delivery demand of customer i is fulfilled by a neighboring customer. Constraint (6) specifies whether the delivery demand of customer i is directly delivered by a mobile locker. Constraint (7) ensures that a customer's delivery demand is either fulfilled by a neighboring customer or directly delivered by a mobile locker.

If a customer's delivery demand is fulfilled through collaborative delivery between different mobile lockers, constraints (8) to (61) are applied.

$$\alpha_{ij} = max(X_{ijkh}, \forall k,h\in A, k\ne h), \forall i\in C, j\in cd_i \tag{8}$$

$$\begin{aligned} X_{ijkm} = max(\mathrm{X}^{ij}_{uhksm}, \forall u\in U, h,s\in N_d, h\ne s), \forall i\in C, j\in cd_i, \\ k,m\in A, k\ne m \end{aligned} \tag{9}$$

$$\sum_{m\in A/\{k\}} X_{ijkm} \le 1, \forall i\in C, j\in cd_i, k\in A \tag{10}$$

$$\sum_{k\in A}\sum_{h\in A} X_{ijkh} \le \beta, \forall i\in C, j\in cd_i \tag{11}$$

$$\mathrm{X}^{ij}_{uhksm} \le \gamma_h^k\cdot\gamma_s^m, \forall h,s\in N_d, h\ne s; k,m\in A, k\ne m; i\in C, j\in cd_i, u\in U \tag{12}$$

$$\sum_{s\in N_d^i}\sum_{k\in A} Y'_{ijks} \le \alpha_{ij}, \forall i\in C, j\in cd_i \tag{13}$$

$$\sum_{m\in N_d^i}\sum_{h\in N_{im}''}\sum_{s\in N_d^h}\sum_{k\in A} z'_{ijksh} \le \alpha_{ij}, \forall i\in C, j\in cd_i \tag{14}$$

$$\sum_{i\in N_d\bigcup D}\sum_{j\in N_d\cup D'} x_{ijk}\cdot dist_{ij} \le AD, \forall k\in A \tag{15}$$

$$\sum_{k\in A}\sum_{j\in N_d} x_{ijk} = \sum_{k\in A}\sum_{j\in N_d} x_{jik}, \forall i\in D \tag{16}$$

$$\sum_{i\in D}\sum_{j\in N_d} x_{ijk} \le 1, \sum_{i\in N_d}\sum_{j\in D} x_{ijk} \le 1, \forall k\in A \tag{17}$$

$$\sum_{j\in N_d\cup D} x_{jik} = \gamma_i^k, \forall i\in N_d, k\in A \tag{18}$$

$$\sum_{s\in N_d^h}\sum_{i\in N_h'}\sum_{j\in cd_i}\sum_{k\in A}(z_{ijksh}+z'_{ijksh})\cdot q_{ij}\le cq_h,\forall h\in C \tag{19}$$

$$w_h=\max(z_{ijksh},\forall s\in N_d^h,i\in N'_{hs},j\in D,k\in A),\forall h\in C \tag{20}$$

$$w'_h=\max(z'_{ijksh},\forall s\in N_d^h,i\in N'_{hs},j\in D,k\in A),\forall h\in C \tag{21}$$

$$\sum_{m\in N_d^h}\sum_{i\in N''_{hm}}\sum_{s\in N_d^i}\sum_{k\in A}(z_{hjksi}+z'_{hjksi})\le(1-w_h)\cdot(1-w'_h),\forall h\in C,\exists j\in cd_h \tag{22}$$

$$\sum_{i\in C}\sum_{j\in cd_i}x'_{ijk}\cdot q_{ij}\le AQ,\forall k\in A \tag{23}$$

$$\sum_{i\in C_j}\sum_{k\in A}x'_{ijk}\cdot q_{ij}=\sum_{i\in C_j}q_{ij},\forall j\in D \tag{24}$$

$$\begin{aligned}&\sum_{j\in N_d\cup D,j\ne i}x_{jik}\cdot q_{jik}-\sum_{j\in N_d\cup D,j\ne i}x_{ijk}\cdot q_{ijk}=\sum_{j\in D}(Y_{cjki}+Y'_{cjki})\cdot q_{cj}+\\&\sum_{h\in N'_{ci}}\sum_{j\in D}(z_{hjkic}+z'_{hjkic})\cdot q_{hj}-(\sum_{u\in U}\sum_{j\in D\cup N_d,j\ne i}y_{jiu}\cdot uq_{jiu}-\sum_{u\in U}\sum_{j\in D'\cup N_d,j\ne i}y_{iju}\cdot uq_{iju})\\&,\forall c\in C,i\in N_d^c,k\in A\end{aligned} \tag{25}$$

$$q_{ijk}\le AQ,\forall i,j\in N_d\cup D,k\in A \tag{26}$$

$$Y_{ijks}\le x'_{ijk},\forall i\in C,j\in cd_i,k\in A,s\in N_d^i \tag{27}$$

$$\sum_{m\in N_d^i}\sum_{h\in N''_{im}}\sum_{s\in N_d^h}z_{ijksh}\le x'_{ijk},\forall i\in C,j\in cd_i,k\in A \tag{28}$$

$$Y_{ijks}\le\gamma_s^k,\forall i\in C,j\in cd_i,k\in A,s\in N_d^i \tag{29}$$

$$z_{ijksh}\le\gamma_s^k,\forall h\in C,s\in N_d^h,i\in N'_{hs},j\in cd_i,k\in A \tag{30}$$

$$Y'_{ijks}\le\gamma_s^k,\forall i\in C,j\in cd_i,k\in A,s\in N_d^i \tag{31}$$

$$z'_{ijksh}\le\gamma_s^k,\forall h\in C,s\in N_d^h,i\in N'_{hs},j\in cd_i,k\in A \tag{32}$$

$$x''_{ijk}=\sum_{m\in A/\{k\}}X_{ijmk}\cdot(1-\sum_{h\in A/\{k\}}X_{ijkh}),\forall i\in C,j\in cd_i,k\in A \tag{33}$$

$$Y'_{ijks}\le x''_{ijk},\forall i\in C,j\in cd_i,k\in A,s\in N_d^i \tag{34}$$

$$\sum_{m\in N_d^i}\sum_{h\in N''_{im}}\sum_{s\in N_d^h}z'_{ijksh}\le x''_{ijk},\forall i\in C,j\in cd_i,k\in A \tag{35}$$

$$(1-x'_{ijk})\cdot\sum_{m\in A/\{k\}}X_{ijkm}\le(1-x'_{ijk})\cdot\sum_{h\in A/\{k\}}X_{ijhk},\forall i\in C,j\in cd_i,k\in A \tag{36}$$

$$X_{ijhk} \le 1 - x'_{ijk}, \forall i \in C, j \in cd_i; h,k \in A, h \ne k \tag{37}$$

$$\sum_{k \in A} x'_{ijk} = 1, \forall i \in C, j \in cd_i \tag{38}$$

$$x'_{ijk} \le \sum_{h \in N_d} x_{jhk}, \forall i \in C, j \in cd_i, k \in A \tag{39}$$

$$\sum_{j \in N_d/\{i\}} y_{jiu} = \sum_{j \in N_d/\{i\}} y_{iju}, \forall i \in N_d, u \in U \tag{40}$$

$$\sum_{j \in D} y_{jiu} = \sum_{j \in D'} y_{iju} = 0, \forall i \in N_d, u \in U \tag{41}$$

$$\sum_{j \in N_d \cup D, j \ne i} y_{jiu} \cdot uq_{jiu} - \sum_{j \in N_d \cup D', j \ne i} y_{iju} \cdot uq_{iju} = \sum_{h \in C} \sum_{q \in D} \sum_{j \in N_d} \sum_{k \in A} \sum_{m \in A/\{k\}} (\mathrm{X}^{hq}_{ujkim} - \mathrm{X}^{hq}_{uikjm}) \cdot q_{hq}, \forall i \in N_d, u \in U \tag{42}$$

$$uq_{iju} = uq_{jiu} = 0, \forall i \in N_d, j \in D, u \in U \tag{43}$$

$$uq_{iju} \le UQ, \forall i, j \in N_d, j \ne i, u \in U \tag{44}$$

$$\eta^+_{iu} = (1 - \sum_{j \in D \cup N_d, j \ne i} y_{jiu}) \cdot \sum_{h \in D \cup N_d, h \ne i} y_{ihu}, \forall i \in N_d, u \in U \tag{45}$$

$$\eta^-_{iu} = (1 - \sum_{h \in D \cup N_d, h \ne i} y_{ihu}) \cdot \sum_{j \in D \cup N_d, j \ne i} y_{jiu}, \forall i \in C, u \in U \tag{46}$$

$$\tau^+_{iuk} = \eta^+_{iu} \cdot \gamma^k_i, \forall i \in N_d, u \in U, k \in A \tag{47}$$

$$\tau^-_{iuk} = \eta^-_{iu} \cdot \gamma^k_i, \forall i \in N_d, u \in U, k \in A \tag{48}$$

$$\sum_{i \in N_d} \tau^+_{iuk} = \sum_{i \in N_d} \tau^-_{iuk}, \forall u \in U, k \in A \tag{49}$$

$$\sum_{i \in N_d \cup D} \sum_{j \in N_d \cup D'} y_{iju} \cdot dist_{ij} \le UD, \forall u \in U \tag{50}$$

$$e^i_h \sum_{j \in N_d \cup D, j \ne i} x_{ijk} \le S^k_i \le l^i_h \sum_{j \in N_d \cup D, j \ne i} x_{ijk}, \forall h \in C, i \in N^h_d, k \in A \tag{51}$$

$$S^k_i + \varphi + dist_{ij} - (1 - x_{ijk}) \cdot M \le S^k_j, \forall i, j \in N_d, k \in A \tag{52}$$

$$dist_{ij} - (1 - x_{ijk}) \cdot M \le S^k_j, \forall i \in D, j \in N_d, k \in A \tag{53}$$

$$S^k_i + \varphi + dist_{ij} - (1 - x_{ijk}) \cdot M \le T_j, \forall i \in N_d, j \in D', k \in A \tag{54}$$

$$x_{ijk} \cdot dist_{ij} = x_{ijk} \cdot at^k_j, \forall i \in D', j \in N_d, k \in A \tag{55}$$

$$x_{ijk} \cdot (S^k_i + \varphi + dist_{ij}) = x_{ijk} \cdot at^k_j, \forall i, j \in N_d, i \ne j, k \in A \tag{56}$$

$$\zeta_{iuk} = \sum_{j \in N_d \cup D, j \ne i} y_{jiu} \cdot \gamma^k_i, \forall i \in N_d, u \in U, k \in A \tag{57}$$

$$at_i^k \cdot \tau_{iuk}^{+} \le ft_i^u \le (S_i^k + \varphi) \cdot \tau_{iuk}^{+}, \forall i \in N_d, u \in U, k \in A \tag{58}$$

$$ft_j^u \cdot \zeta_{juk} \le (S_j^k + \varphi) \cdot \zeta_{juk}, \forall j \in N_d, u \in U, k \in A \tag{59}$$

$$ft_i^u \cdot \tau_{iuk}^{-} \le (S_i^k + \varphi) \cdot \tau_{iuk}^{-}, \forall i \in N_d, u \in U, k \in A \tag{60}$$

$$ft_i^u + dist_{ij} / \theta - (1 - y_{iju}) \cdot M \le ft_j^u, \forall i, j \in N_d, i \ne j, u \in U \tag{61}$$

Constraints (8)–(12) ensure whether the delivery demand of customer i at depot j is served collaboratively. If collaboration occurs, the demand cannot be split and must not exceed the maximum allowed number of collaborations. Constraints (13) and (14) specify that crowdsourcing or direct delivery after collaboration can only occur if collaboration takes place. Constraint (15) sets the travel distance limit for mobile lockers. Constraints (16) and (17) ensure that each mobile locker departs from and returns to a depot, maintaining the same number of mobile lockers before and after at each depot. Constraint (18) restricts mobile locker visits to nodes. Constraints (19)–(22) govern customer crowdsourcing. Constraint (23) imposes load limits when mobile lockers leave depots. Constraint (24) ensures all demands at each depot are fulfilled. Constraint (25) maintains load balance during mobile locker loading and unloading. Constraint (26) limits mobile locker loads during delivery. Constraints (27)–(35) define the delivery modes for customer i's demand at depot j. Constraints (36)–(39) regulate collaboration between mobile lockers. Constraints (40) and (41) restrict drone visits. Constraints (42)–(44) impose load limits and ensure load balance for drones. Constraints (45)–(49) govern drone take-off and landing. Constraint (50) sets the travel distance limit for drones. Constraints (51)–(56) ensure path continuity for mobile lockers. Constraint (57) requires drones to service mobile lockers. Constraints (58)–(61) ensure path continuity for drones.

Constraints (61) to (76) define the range of decision variable values.

$$x_{ijk} \in \{0,1\}, \forall i \in N_d \cup D, j \in N_d \cup D', k \in A \tag{62}$$

$$z_{ijksh}, z'_{ijksh} \in \{0,1\}, \forall i, h \in C, j \in D, k \in A, s \in N_d^h, i \ne h \tag{63}$$

$$Y_{ijks}, Y'_{ijks} \in \{0,1\}, \forall i \in C, j \in D, k \in A, s \in N_d^i \tag{64}$$

$$X_{ijkh} \in \{0,1\}, \forall i \in C, j \in D, k, h \in A, k \ne h \tag{65}$$

$$\alpha_{ij} \in \{0,1\}, \forall i \in C, j \in D \tag{66}$$

$$\gamma_i^k \in \{0,1\}, \forall i \in N_d, k \in A \tag{67}$$

$$\lambda_k \in \{0,1\}, \forall k \in A \tag{68}$$

$$q_{ijk} \ge 0, \forall i \in N_d \cup D, j \in N_d \cup D', j \ne i, k \in A \tag{69}$$

$$\mathrm{X}_{uhksm}^{ij} \in \{0,1\}, \forall i \in C, j \in D, u \in U, k, m \in A, m \ne k, h, s \in N_d, h \ne s \tag{70}$$

$$S_i^k, at_i^k \ge 0, \forall i \in N_d, k \in A \tag{71}$$

$$ft_i^k \ge 0, \forall i \in N_d, k \in U \tag{72}$$

$$w_h, w'_h \in \{0,1\}, \forall h \in C \tag{74}$$

$$y_{iju} \in \{0,1\}, \forall i \in N_d \cup D, j \in N_d \cup D', u \in U \tag{75}$$

$$x'_{ijk}, x''_{ijk} \in \{0,1\}, \forall i \in C, j \in D, k \in A \tag{76}$$

5. Solution Algorithm

The MCDVRPCNC problem involves formulating an overall delivery plan for all depots, considering the customers shared by different depots and the neighboring customers around them. It is a highly complex combinatorial optimization problem, which makes it difficult to solve using professional solvers like Gurobi or Cplex. For such high-complexity problems, heuristic algorithms are one of the most effective methods of solution. Common heuristic algorithms include Genetic Algorithms (GA), Simulated Annealing (SA), Tabu Search (TS), and Adaptive Large Neighborhood Search (ALNS), among others. This paper combines the TS algorithm and the ALNS algorithm to design a hybrid heuristic solution algorithm, the ALNS-TS algorithm, to solve the MCDVRPCNC problem.

5.1 Initial Solution Generation

For the initial solution of the MCDVRPCNC problem, this paper generates it randomly. The generated initial solution includes delivery plans in which each depot independently serves the customers it owns. The initial solution generation algorithm is shown in Algorithm 1.

Algorithm 1: MCDVRPCNC initial solution generation algorithm

Procedure MCDVRPCNC initial solution generation (**Input:** Depot set *D*, customer delivery location set, customer delivery demands and time windows, mobile locker capacity, etc.)

Initialize an empty delivery plan S_0
for $d_i \in D$ **do**
  Randomly generate the set of "customer–delivery location" pairs *N*
  Initialize an empty delivery route *r*; $Creat\_new\_route\_flag \leftarrow True$
  while *N* is not empty **do**
    if $Creat\_new\_route\_flag \leftarrow True$ **then**
      Add path *r* to S_0; Initialize an empty delivery route *r*
    end if
    $i \leftarrow 0$
    while $i < |N|$ **do**
      $(c,l) \leftarrow N(i)$
      if (c,l) insert to *r* **then**
        Insert (c,l) into *r*; $Creat\_new\_route\_flag \leftarrow True$
        Remove (c,l) from *N*
      else
        $i \leftarrow i+1$
      end if
    end while
  end while
end for
Output: S_0
end Procedure

5.2 Design of Hybrid Heuristic Algorithm

The proposed hybrid heuristic algorithm combines Adaptive Large Neighborhood Search (ALNS) and Tabu Search (TS) for improved optimization performance. According to the characteristics of MCDVRPCNC, several destroy and repair operators have been designed, as follows.

(1) Random removal operator (RRO). For the vehicle route in the current solution, randomly select a point in the route, remove it from the path, and obtain the destroyed vehicle route and the nodes to be scheduled.

(2) Maximum delivery cost path removal operator (MDCPRO). For the current solution, remove the path with the maximum delivery cost.

(3) Random insert operator (RIO). For the unscheduled nodes, obtain the list of possible insertion positions in the disrupted solution, and randomly choose an insertion position to insert the node.

(4) Greedy insert operator (GIO). For the unscheduled nodes, obtain the list of possible insertion positions in the disrupted solution, and select the insertion position with the minimum insertion cost for the node.

(5) Time Window Sorting Insertion Operator (TWSIO). For the current solution, randomly swap two nodes with similar time windows.

Based on the ALNS algorithm, several local search operators are designed. To optimize the search space, tabu search is incorporated into the ALNS, resulting in the design of a hybrid heuristic algorithm, ALNS-TS, suitable for the problem addressed in this paper, as shown in Algorithm 2.

Algorithm 2: MCDVRPCNC ALNS-TS algorithm

Procedure MCDVRPCNC ALNS-TS algorithm (**Input:** Initial solution S_0; Destroy operators; Repair operators; Maximum number of iterations $iter_{max}$, etc.)

$S^* \leftarrow S_0$; $iter \leftarrow 0$; Initialization operator selection probability *P*

while $iter < iter_{max}$ **do**

$S_C \leftarrow S^*$

Select the destruction operator (*DO*) and repair operator (*RO*) based on the selection probability *P*

$S'_C \leftarrow DO(S_C); S''_C \leftarrow RO(S'_C)$

if $f(S''_C) < f(S^*)$ **then**

$S^* \leftarrow S''_C$; $iter \leftarrow 0$

else

$iter \leftarrow iter + 1$

end if

Update the operator selection probability *P*; Reset the tabu list

end while

Output: S^*

end procedure

6. Numerical Experiment

This section analyzes the impact of shared and neighboring customers on logistics distribution through numerical experiments. The basic parameters for the numerical experiments are as follows: The cost of customer self-pickup is denoted as $\pi^k(h) = \sum_{a\in A}\sum_{j\in N_h}\sum_{i\in N_V} y^k_{hjia} \cdot dist^2_{ij}$; the load capacity of the mobile locker and drone are 1000 and 100, respectively; the unit travel costs for the mobile locker and drone are 1 and 0.1, respectively; the travel speed ratio between the drone and mobile locker is 10; the maximum number of package collaboration is limited to 1. The numerical experiments in this section are conducted using Python 3.11, and the operating environment is an AMD Ryzen 7 6800HS with Radeon Graphics, 8 physical cores, 16 logical processors, and 16GB of RAM.

6.1 Data Generation

As real customer data from logistics companies is difficult to obtain, this chapter modifies the VRPTW benchmark dataset to generate the data used for the numerical experiments in this chapter. The benchmark datasets used are Solomon (1987) and Homberger and Gehring (1999) (http://vrp.galgos.inf.puc-rio.br/index.php/en/). Based on the benchmark datasets, the data generation steps for the numerical experiments in this section are as follows:

(1) Number of depots and Customers: The number of depots in the data is 2, 3, 4, and 5. The number of customers for each depot is 20, 30, 40, 50, 60, 70, 80, 90, and 100, randomly selected from the benchmark data.

(2) Ratio of Common Customers: The proportion of customers shared by different depots as a percentage of the total customer count is 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%.

(3) neighboring Customers: For each customer, their neighboring customers are determined by the crowdshipping range of other customers. That is, for customer *h*, the customers who can crowdship *h*'s delivery demand are considered its neighboring customers.

(4) Delivery Locations: For each customer, 1 to 3 delivery locations and time windows are randomly selected.

Based on the above data generation steps, a total of 324 data instances were generated, denoted as "X-Y-Z", where "X" is the number of depots, "Y" is the number of customers per depot, and "Z" is the proportion of common customers.

6.2 The Differences Between Collaborative Delivery and Solo Delivery

This subsection analyzes the differences between collaborative delivery and solo delivery from two perspectives: delivery cost and the number of mobile lockers used.

Based on the 324 data instances obtained, we analyze the impact on delivery costs when using collaborative and solo delivery for each depot. Figures 2 to 5 show the cost differences between collaborative and solo delivery for different customer quantities (50, 80, and 100) and various shared customer proportions (0%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%) when the depot quantities are 2, 3, 4, and 5, respectively.

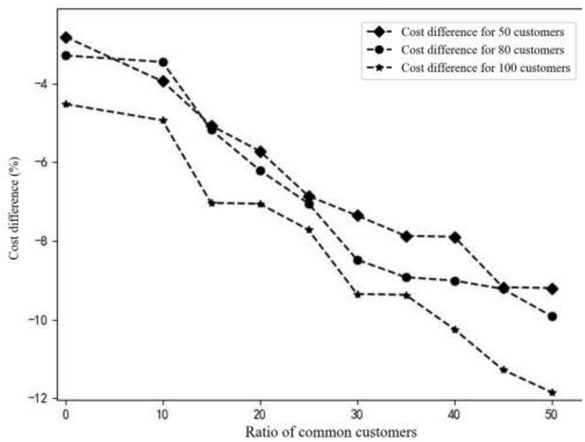


Figure 2. Cost difference between collaborative and solo delivery for 2 depots

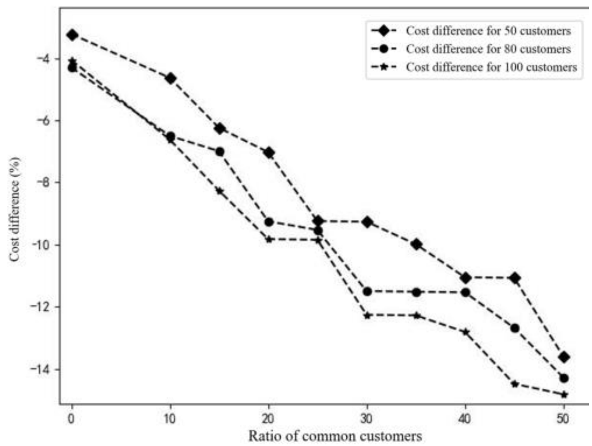


Figure 3. Cost difference between collaborative and solo delivery for 3 depots

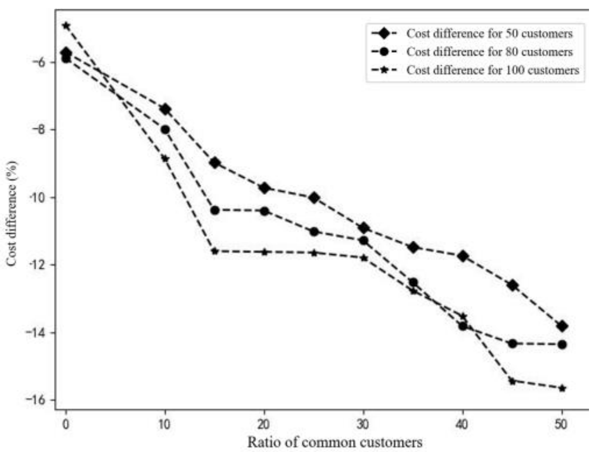


Figure 4. Cost difference between collaborative and solo delivery for 4 depots

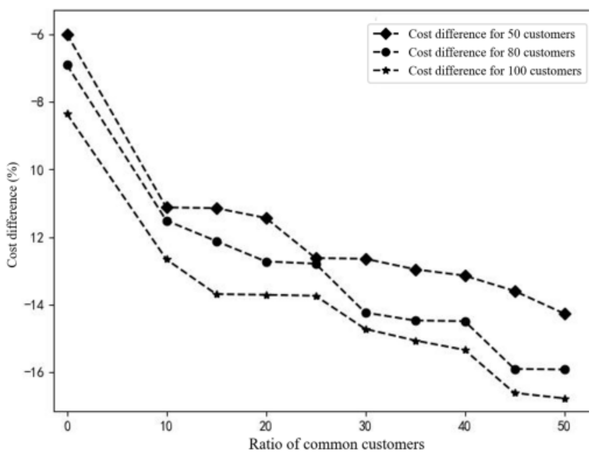


Figure 5. Cost difference between collaborative and solo delivery for 5 depots

From Figures 2 to 5, it can be seen that, when the number of depots is fixed, as the number of customers increases, collaborative delivery between multiple depots always results in cost savings. The delivery costs considering collaboration are lower than the costs when each depot delivers individually, and the cost difference increases as the proportion of shared customers between the depots increases. Therefore, under the shared customers between depots, considering collaborative delivery can effectively reduce delivery costs and improve delivery quality.

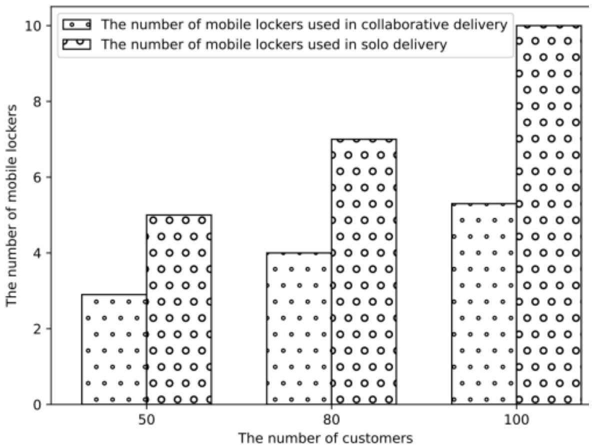


Figure 6. The number of mobile lockers used in collaborative and solo delivery with 2 depots

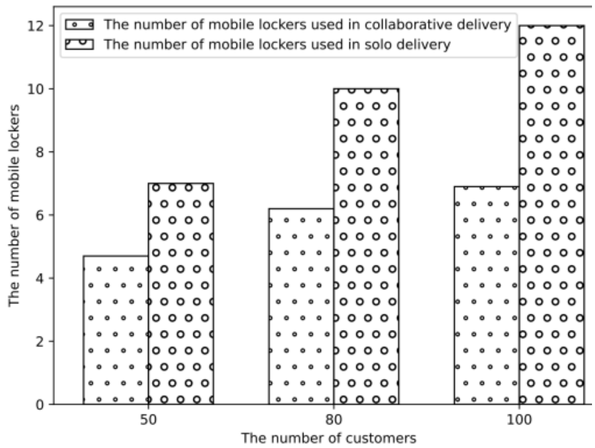


Figure 7. The number of mobile lockers used in collaborative and solo delivery with 3 depots

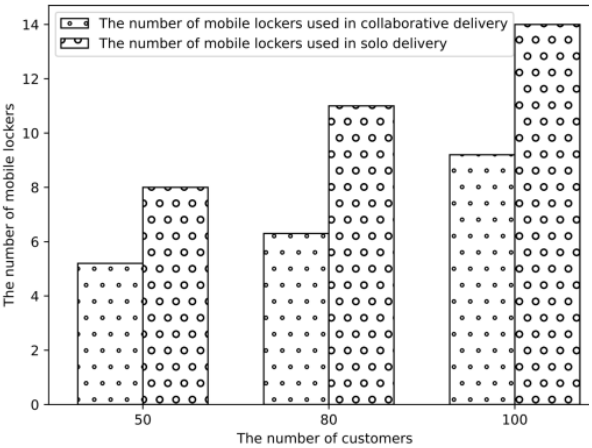


Figure 8. The number of mobile lockers used in collaborative and solo delivery with 4 depots

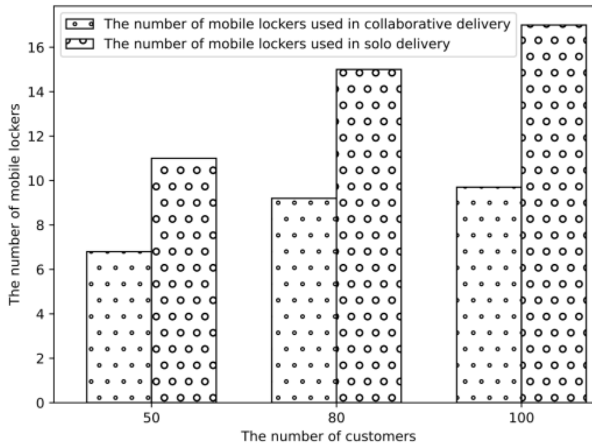


Figure 9. The number of mobile lockers used in collaborative and solo delivery with 5 depots

Collaborative delivery not only outperforms solo delivery in terms of delivery costs but also has advantages in terms of the number of mobile lockers used. Figures 6 to 9 show the number of mobile lockers used under different customer quantities and shared customer proportions when the depot quantities are 2, 3, 4, and 5. It can be observed that the number of mobile lockers used for collaborative delivery is lower than that used for solo delivery. This is because by sharing mobile lockers between depots, collaboration allows parcels from one depot to be delivered by mobile lockers departing from another depot, making full use of the lockers' storage, thus reducing the total number of mobile lockers.

6.3 The Impact of the Number of Collaborative Deliveries of Mobile Lockers

Collaborative delivery not only effectively reduces delivery costs but also improves the utilization of the mobile lockers' capacity, reducing the number of mobile lockers used. This is achieved through package collaboration between depots. In this chapter's numerical experiments, it was assumed that the maximum number of package collaborations was 1. This section relaxes this limit and analyzes the impact of the number of collaborations on delivery costs. Figures 10 and 11 show the variations in collaborative delivery costs and individual delivery costs for different collaboration frequencies (1, 2, 3, 4, and 5) under various depot numbers, customer quantities, and shared customer ratios. The depots considered are 2, 3, 4, and 5; customer quantities are 30 and 50; and shared customer ratios are 0%, 10%, 15%, 20%, 25%, 30%, 35%, 40%, 45%, and 50%.

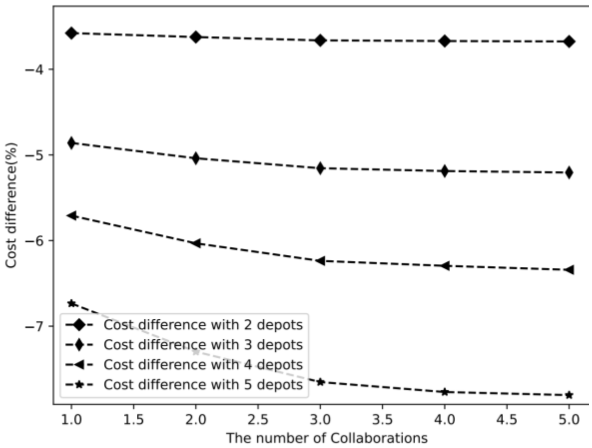


Figure 10. The delivery cost difference under varying numbers of depots with 30 customers

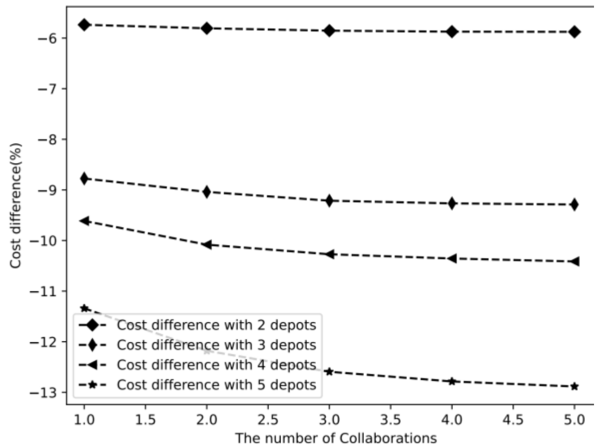


Figure 11. The delivery cost difference under varying numbers of depots with 50 customers

From Figures 10 and 11, it can be seen that the upper limit of package collaborations has a significant impact on delivery costs. When the number of customers to be delivered by each depot is the same, the difference in costs between collaborative delivery and individual delivery increases with the upper limit of package collaborations. However, when the collaboration frequency exceeds 3, the advantage in delivery cost reduction becomes smaller, and increasing the number of collaborations does not lead to a larger cost difference. The effect of the collaboration frequency is influenced by the number of depots. When there are more depots, the impact of the collaboration frequency on the cost is more significant, and even when the collaboration frequency exceeds 3, there is still a noticeable effect.

7. Conclusion

This study investigates the problem of collaborative delivery among multiple logistics depots by considering four key dimensions: cost-effectiveness, operational efficiency, safety, and reliability. Specifically, it addresses scenarios where depots share common customers and where customer packages may be delivered by neighboring customers. To this end, a multi-depot collaborative delivery optimization model is proposed, incorporating both shared and neighboring customer dynamics. A hybrid heuristic algorithm, ALNS-TS, is developed to solve the model efficiently. Experimental results indicate that depot collaboration based on shared customers yields significant benefits. These include notable reductions in delivery costs, improved utilization of mobile locker capacity, and decreased usage of mobile locker units. Furthermore, the advantages become more pronounced as the number of collaborating depots increases, suggesting that depot-level cooperation holds strong potential for addressing the growing challenges in modern logistics systems.

While this study incorporates the concepts of shared and neighboring customers, it assumes, in a simplified manner, that logistics enterprises freely share resources such as vehicles and customer information. It does not explicitly account for inter-enterprise competition, including task allocation and profit-sharing mechanisms. Future research may explore collaborative delivery under competitive settings, considering the strategic interactions and negotiations among competing logistics firms.

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