Urban Logistics Delivery Route Planning Based on a Single Metro Line

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ABSTRACT This paper proposed a framework to integrate metro for urban logistics delivery in order to avert the conflicts with ground transportation, reduce delivery cost, transport distance and delivery time of vehicles. Integrating metro-based Underground Logistics System (ULS) with ground delivery vehicles (GDVs), an urban logistics delivery path optimization model based on a single metro line was built to improve delivery efficiency. In handling this model, total transport cost was taken as the objective function by considering the capacity limitations of GDVs and soft customer time window (CTW), vehicle routing problem with Time Windows (VRPTW) was also taken into account. By means of the saving algorithm (CW algorithm) and the improved Tabu Search algorithm (CWTS), our established model was solved to optimize the delivery routes under metro-based ULS. Through the case analysis of a Logistics Transport Enterprise (LTE) in Nanjing, it was shown that our proposed algorithm consistently outperformed Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) in taking less computation time and obtaining better results. Our proposed delivery mode also had a great advantage compared to the traditional truck delivery (TD) alone in terms of saving cost and guaranteeing the quality of service (QoS). The sensitivity analysis of the capacity offered an optimal GDV capacity setting to reduce total delivery cost.

INDEX TERMS CW algorithm, metro delivery, route planning, TS algorithm, urban logistics, VRPTW.

I. INTRODUCTION

With the continuously growing share of the population living in urban areas, the freight demand has become fragmented and the volume of cargoes customers ask to deliver has greatly increased Lagorio et al. [1]. The fast pace of life requires our logistic system to provide reliable and efficient service, meaning our existing delivery modes urgently need to be modified and transformed. Many cities have adopted novel delivery modes such as Unmanned Vehicle Delivery (UVD) James [2], Sonneberg et al. [3] to relieve the shipping pressure. However, for taking up too many road resources, the aboveground freight transport has been recognized as a great disturbance to the reasonable usage of urban space and the smooth operation of urban transportation. The limited aboveground space has also restricted the development of logistics Dablanc et al. [4].

The limited road resources and terrible traffic congestion have made many scholars focus their researches on underground space, studies suggested that reasonably exploiting underground space can provide viable solutions to serious aboveground issues Kaliampakos and Mavrikos [5], Edelenbos et al. [6] and Zhao et al. [7], for it can satisfy the need for efficiency and sustainability Broere [8]. However, compared with passenger transport, urban logistics delivery is still mainly implemented aboveground. If transferred underground wholly or partially, not only can it alleviate the severity of urban traffic congestion and the air pollution Broere [8], but the overall layout of urban transportation can also be refreshed and optimized Cui and Nelson [10].

Research of ULS has been going on for nearly 30 years Dong et al. [11] and its benefits are quite obvious. ULS occupies little floor space, it can greatly abate the influence of extreme weather events on the timeliness of logistics delivery and provide safer and more reliable services Pielage [12], so it can be drawn on as a complementary method of freight delivery to reduce the transportation pressure, thus highway maintenance costs and the number of truck accidents would be reduced. In terms of urban freight transportation, except for ULS, no alternative transportation modes were available for sustainability Dong et al. [13], so the underground
transportation pattern should be seriously taken into account as a practicable transportation mode and is worthy of discussing.

Appropriate selection of delivery vehicles is quite critical in ULS, most applications are still in their infancy and their practicability, transport efficiency and prospects for high penetration in urban logistics need to be further demonstrated. Many scholars have considered pipelines as the delivery vehicle, which can’t be widely spread because its capacity limitations and the huge cost for building facilities for its implementation. Using pipeline for underground transportation also faces various obstacles, such as interfacing with other transport modes and its competition with traditional transportation Egbutike et al. [14]. In the short term, pipeline transportation can’t come into practice for its complex planning and lack of appropriate standards for its operation Vance and Mills [15]. Although some scholars suggested that normal vehicles can be operated underground for freight transportation, such as building an underground parking lot for underground guided vehicles (UGVs) for the use of loading and unloading Gao et al. [16], it will also generate huge waiting cost and too much underground space will be taken up. After all, there is still a lack of a standardized way of unified transportation of cargoes and the acceptability of these newly proposed facilities remains to be investigated.

The existing metro resources can be integrated into ULS and used in a large prospect. At present, many urban rail transit networks in the world have been initially formed, there is surplus capacity in general off-peak hours and suburban lines Jiang et al. [17], [18], so its operation won’t disturb the normal operation of existing metro systems Dong et al. [11]. Researches Hu et al. [19], Hu et al. [20], He et al. [21] of ULS network planning suggested that adding metros to the urban logistics delivery network and transporting goods through metro can not only make full use of the remaining capacity of metros, but also alleviate the problems of traffic congestion and environmental pollution. Most studies emphasize on fully utilizing metros for saving costs, but the transport process of these studies is not complete because in city logistics, metro transportation alone is not enough, the ‘door to door’ delivery still needs the participation of GDVs.

It is found that integrating metro system with ground delivery (GD) makes logistics delivery stable and smooth Kikuta et al. [22], the metro-based ULS network planning method was developed considering QoS and freight flow embracing aboveground and underground transportation Dong et al. [11]. However, its framework does not extend from one dimension (spatial) to two dimensions (spatiotemporal), the route planning of joint delivery of metro with GDVs is not mentioned and there is a lack of quantitative analysis.

The VRP Dantzig and Ramser [23] was introduced when studying the problem of gasoline transportation, it can be expounded that vehicles are optimally routed to deliver cargoes to customers with exact demand Wang et al. [24].

| Problem Variant | Fleet Size | Fixed Costs | Routing Costs |
|-----------------|-----------|-------------|---------------|
| VRPFD           | Limited   | Considered  | Dependent     |
| HVRPFD          | Limited   | Not considered | Dependent     |
| SDVRP           | Limited   | Not considered | Dependent     |
| FSMED           | Unlimited | Considered  | Site-Dependent |
| FSMD            | Unlimited | Not considered | Dependent     |
| FSMF            | Unlimited | Considered  | Independent   |

Many studies have concentrated on the solutions of some variants of this problem. In the VRP with Time Windows (VRPTW) Thangiah et al. [25], the cargoes of customers should be delivered within a specific time interval and the order of deliveries is often predetermined, which is more like the urban logistic delivery problem addressed in this paper. For solution search, ACO Dorigo et al. [26], PSO Poli et al. [27] and the Tabu Search algorithm Glover [28] are usually applied. The variants of VRP are shown in TABLE 1. Most studies about VRP didn’t consider multiple modes of transportation, especially concerning metros.

This paper proposed to construct an urban metro-based delivery network to further demonstrate the application of VRPTW in logistic system, which successively includes three stages: the route from the delivery center to the metro entry station, also named as truck delivery (TD) part; the metro delivery (MD) part indicates the route of the metro entry station to the metro exit station; the GD part refers to the route from the metro exit station to the customers.

In the beginning, the LTE receives the freights that are ordered from inner-city customers in the delivery center Hu et al. [29], these freights are sorted, organized, packed and labelled for loading, then LTE dispatches the transport truck to transport these cargoes to the prescribed metro entry station, the first stage of transportation is finished. When receiving these cargoes, they are lowered to the platform and then loaded and transported along the subway line, after arriving at the platform of the metro exit station in the designed delivery route, they are docked and lifted to the outbound station aboveground Hu et al. [30], and the second stage of transportation is ended. At last, the GDVs pick up these freights and start transporting these cargoes at the aboveground outbound station according to our delivery plan, the third stage is completed and the whole delivery process is accomplished.

The total delivery process based on a single Metro Line is shown in FIGURE 1, where in addition to the delivery center, metro entry stations and exit stations, there are also scattered customer locations. Vehicles include metros that can transport cargoes, transport trucks that stay in the delivery center, and GDVs that stay near the metro exit station. The delivery center selects a Metro Line as the main line for its logistics activities. Each delivery center has multiple secondary delivery centers (metro exit stations). A related path optimization model concerning the mentioned three stages was
established, in which the capacity of GDVs and CTW are comprehensively considered and quantified. At last, CWTS was designed to solve the model.

Though studies of ULS have gradually stepped into urban logistic research and matured, few dabble in intra-city freight delivery, so metros are not been considered and utilized. Besides, few studies of ULS can integrate existing transportation resources and combine them to provide efficient and reliable logistic service. In previous studies, the delivery process of ULS on route planning is incomplete, in which the GD part (the third stage) is not fully considered. In our proposed delivery plan, the interests of customers (violation of CTW) and LTE (risk of overloading) were considered, which were also not shown in prior researches. The performance of solution methods that most scholars widely adopted is inferior to our proposed CWTS.

Compared with previous studies, the contributions of this paper include the follows:

(1) The developed path optimization model includes three stages considering the aboveground and underground transportation, which offers a new way to urban logistics delivery;

(2) The transportation mode proposed in this paper, if applied, can save transport costs, shorten delivery distance and time, so the QoS can also be guaranteed;

(3) The effectiveness of the combination of the two algorithms was verified in this paper through the comparison with ACO and PSO and it provides a new method for solving VRPTW.

The rest of the paper is organized as follows. Section 2 introduces the modelling methodology of the metro-based delivery plan. Section 3 provides the solution methods to copy with the proposed model. Section 4 presents the case study through real data, algorithm and model comparisons, the sensitivity analysis on the critical parameter and implications are also given in this section. Finally, conclusions of this paper and some future research directions are discussed in Section 5.

II. MODELLING METHODOLOGY
A. MODEL ASSUMPTIONS
The basic assumptions of the model are as follows:

(1) The type, size and weight of the cargoes meet the requirements of MD;

(2) The transport cost is only related to the number of cargoes (customer demand) and the transport distance, the influence of other factors is not considered;

(3) The transportation of freights on metro lines will not affect the quality of passenger service, including shipping cargoes at metro stations and the use of transportable metros for transporting cargoes;

(4) There will be a certain amount of time loss when transshipped by different transportation modes;
(5) As shown in the right part of FIGURE 1, after completing the delivery task, the GDV must return to its original departure station (metro exit station), which is not required for metros;
(6) Customers require delivery within the specified CTW. If not delivered on time, that will incur a certain penalty cost.

**B. PARAMETERS AND DECISION VARIABLES**

The parameters and decision variables involved in the model are as follows:

| Symbol | Description |
|--------|-------------|
| $V_D$ | Collection of the metro entry station $d$; |
| $V_K$ | Collection of the metro exit station $k$; |
| $V_C$ | Collection of customer $j$ (terminal GD node); |
| $V_R$ | Collection of metro $r$; |
| $V_v$ | Collection of GDV $v$; |
| $c_{dk}$ | The unit freight transport cost from the delivery center to the entry station $d$, which is the same from the entry station $d$ to the exit station $k$; |
| $q_j$ | The demand of the $j$th customer; |
| $c_{ij}$ | The unit freight transport cost of the GDV delivery from node $i$ to $j$; |
| $q_{LD}$ | The volume of freights that violates the vehicle capacity limitation; |
| $T_w$ | The length of time that violates CTW; |
| $Q_v$ | The maximum capacity of the GDV $v$; |
| $s_{ej}$ | The service start time of customer point $j$; |
| $s_{lj}$ | The service end time of customer point $j$; |
| $e_j$ | The lower bound constraint of CTW of customer $j$; |
| $l_j$ | The upper bound constraint of CTW of customer $j$. |

Decision variable $x_{dk}^{jr}$: If the cargoes of customer $j$ are delivered from the metro entry station $d$ to the exit station $k$ via metro $r$, the value is 1, otherwise it is 0;

Decision variable $y_{ij}^{vy}$: If the cargoes of customer $j$ are delivered from the metro exit station $k$ to customer $j$ via vehicle $v$, the value is 1, otherwise it is 0.

**C. OBJECTIVE FUNCTION**

The delivery process is divided into three stages. Including the TD from the delivery center to the metro entry station, the MD from the metro entry station to the exit station, and the GD from the metro exit station to each customer point.

\[
\begin{align*}
\min F &= C + P \\
C &= \sum_{d \in V_D} \sum_{k \in V_K} \sum_{j \in V_C} \sum_{r \in V_R} c_{dk} q_j x_{dk}^{jr} + \sum_{i \in V_K \cup V_C} \sum_{j \in V_C} c_{ij} y_{ij}^{vy} \quad (1) \\
P &= \alpha q_{LD} + \beta T_w \quad (2)
\end{align*}
\]

Eq. (1) represents the objective function, which is designed to minimize total cost.

Eq. (2) represents that when the required data of this model is provided, the cost of TD in the first part is often determined.

Therefore, to simplify the formulated objective function, the costs of the first two parts are combined. The first term denotes the combined first two parts, and the second term represents the GD part.

Eq. (3) represents the penalty cost, where $\alpha$ and $\beta$ are penalty factors of each situation mentioned below respectively. The first term denotes that, in handling the maximum capacity of vehicles, overloading of GDVs was tolerated. The second term represents soft CTW, meaning it was tolerated thatfreights were not delivered on time. But the above two situations would incur a certain penalty cost. This is a way to transform overload risk and poor QoS into cost.

**D. RESTRICTIONS**

\[
\begin{align*}
\sum_{v \in V_v} y_{ij}^{vy} &= \sum_{d \in V_D} \sum_{r \in V_R} x_{dk}^{jr}, \quad \forall k \in V_K; \ r \in V_R \quad (4) \\
\sum_{i \in V_K \cup V_C} \sum_{j \in V_C} q_i y_{ij}^{vy} &\leq Q_v, \quad \forall v \in V_v \quad (5) \\
\sum_{j \in V_C} y_{ij}^{vy} &= \sum_{j \in V_C} y_{ij}^{vy} \leq 1, \quad \forall i \in V_K \cup V_C; \ v \in V_v \quad (6) \\
\sum_{d \in V_D} \sum_{k \in V_K} \sum_{r \in V_R} x_{dk}^{jr} &= 1, \quad \forall j \in V_C \quad (7) \\
\sum_{i \in V_K \cup V_C} \sum_{v \in V_v} y_{ij}^{vy} &= 1, \quad \forall j \in V_C \quad (8) \\
r_{0d} + t_{dk} + t_{jv} &\leq s_{ej}, \quad \forall d \in V_D, \ k \in V_K, \ r \in V_R, \ j \in V_C; \ v \in V_v \quad (9) \\
s_{lj} &\leq s_{ej}, \quad \forall i, j \in V_C; \ v \in V_v \quad (10) \\
s_{lj} &= s_{ej} + s_j, \quad \forall j \in V_C \quad (11) \\
e_j &\leq s_{ej} \leq l_j, \quad \forall j \in V_C \quad (12) \\
x_{dk}^{jr} &\in [0, 1], \quad \forall d \in V_D; \ k \in V_K; \ r \in V_R \quad (13) \\
y_{ij}^{vy} &\in [0, 1], \quad \forall k \in V_K; \ j \in V_C; \ v \in V_v \quad (14)
\end{align*}
\]

Eq. (4) indicates that if the goods of customer $j$ was delivered via the metro line from the entry station $d$ to the exit station $k$, then the GDV should start transferring from site $k$.

Eq. (5) represents the capacity limitation of the GDV $v$.

The problem to be solved by this model is VRPTW. Eq. (6) ensures that the GDV returns to the metro exit station where it departs.

Eqs. (7) and (8) are constraints of decision variables, indicating that the cargoes of customer $j$ can be served by only one metro and one GDV.

Eq. (9) is the service start time constraint of the $k_{ih}$ customer point adjacent to the exit station, where ‘0’ denotes the delivery center, the first term of which denotes the delivery time of TD from the delivery center to the metro entry station.

Eq. (10) represents the relationship between the service end time of the former customer point and the service start time of the next customer point.

Eq. (11) represents the relationship among the start time, end time and service time of the customer point.
Eq. (12) represents the CTW constraints of customer points. Eqs. (13) and (14) are 0-1 constraints of decision variables.

III. SOLUTION METHODS

As shown in FIGURE 2, the overall flow chart of the proposed methodology consists of one main module and two sub-modules.

This paper employs the improved TS algorithm combined with CW algorithm Clarke and Wright [31] (CWTS) to cope with the model mentioned in the Section 2. Known for its solving speed, simplicity, efficiency and robustness Cordeau et al. [32], the TS algorithm is widely adopted in addressing VRP. The optimal solution of TS algorithm was strongly dependent on the initial solution Liu et al. [33], however, most scholars’ means of constructing the initial solution adopted insertion heuristic Chiang and Russell [34], Archetti et al. [35] and Gendreau et al. [36], which was arbitrary and despotistic, so the performance of the initial solution is far from expected. The result of CW algorithm is generally an approximate solution because its fuzziness will increase with the enlargement of solution space Fan and Qin [37] and it was often integrated with other heuristic algorithms Ding and Zou [38], Wang et al. [39] to effectively handle VRP with uncertain number of vehicles, the superiority of this algorithm is as well particularly prominent in VRP Dror and Trudeau [40]. Since these two algorithms have such distinctive properties, it is determined that the CW algorithm is used to assist and improve the results of the improved TS algorithm, that is by using the CW algorithm result as the initial solution of the improved TS algorithm, intensification and diversification are examined thus we are able to give full play to the advantages of them both.

The problem can be decomposed into two parts: one is the customer allocation of the metro exit station and the metro schedule adjustment of the MD part, and the second is the optimization of the path of GDVs.

(1) Initialization of customer allocation of metro exit stations and metros

The customer points are allocated to the metro exit stations according to the random division method, and the transit volume of each metro exit station is calculated. Then assign the customer points to metros that can transport cargoes. From this, the initial solution of the delivery plan is obtained.

(2) CW algorithm to construct the initial solution of the routes of GDVs

Construct the initial solution of the route of GDVs from the metro exit station to the customer points. This part is completed by CW algorithm. The specific method is as follows:

**Step1:** Initialize the delivery route of each vehicle, and each customer needs to be delivered by one vehicle, that is, each point is connected to the base point (assuming '0') separately, forming a sub-loop \(0 \rightarrow j \rightarrow 0(j = 1, 2, 3, \cdots, n)\);

**Step2:** Calculate the saving value of fusing any two paths, and delete the fusing path that does not meet the CTW requirements:

\[
S(i, j) = c_{0i} + c_{ij} + c_{0j} - (c_{0i} + c_{ij} + c_{0j})
\]

(15)

Eq. (15) represents the basic calculating method of the CW algorithm, where \(i\) and \(j\) are the customer points. A simple illustration of loops graph mentioned is shown in FIGURE 3.

**Step3:** Update the vehicle arrival time and capacity at the nodes on the path, and sort all the saving values \(S(i, j)\) that meet CTW and capacity requirements in descending order;

**Step4:** Determine whether the maximum saving value is greater than zero, if yes, continue, otherwise output the result;

**Step5:** Update the path collection and return to Step2.

(3) The improved TS algorithm to optimize the initial solution of the routes of GDVs
Optimize the initial solution of the routes of GDVs constructed by CW algorithm, this part is completed by the improved TS algorithm. The specific method is as follows:

**Step1:** Perform initialization, set the tabu list to empty, set the tabu-size, and calculate the neighborhood and candidate set of the initial solution. The procedures of constructing the neighborhood are inspecting all customers, then removing them from the current paths, at last inserting them into other feasible path locations in turn. The candidate set includes the neighborhood of the non-taboo list and that meets the aspiration criterion;

**Step2:** Determine whether the terminating condition is met. If so, it is determined whether the current solution has missing elements or whether there are violations of constraints. If all the above do not appear, output the optimal solution to end the loop; if they appear, the penalty cost is calculated and a newly born candidate set should be considered. Otherwise, continue with the following steps;

**Step3:** Calculate the fitness value of the optimal solution from the candidate set according to the fitness function, and compare the fitness value with that of the historical optimal solution to determine whether the solution has improved. If so, the candidate solution is updated to the new current solution; otherwise, move directly to Step4;

**Step4:** Update the tabu list, neighborhood, and candidate set, and return to Step2.

(4) Adjust the customer allocation of freight metros

The optimized GD paths are assigned to the freight metros, and the network of customer allocation of the freight metros is obtained. By changing the allocation, observing the changes in the delivery time, and whether it meets the requirements of the CTW, the customer allocation of freight metros and the route optimization results of the delivery plan are remodeled and thus determined.

### IV. IMPLEMENTATION AND ANALYSIS

#### A. BACKGROUND

A real situation of a LTE in Nanjing, planning to deliver goods to 30 customer points in the urban area, was employed to prove the effectiveness the CWTS and the practicability of the proposed model. The location, demand, CTW, service time of each customer point and the distance and time between the metro entry and the exit stations are shown in **TABLE 2**.

#### B. OPTIMIZATION RESULTS

Repeat the operation 100 times and get the optimal total delivery cost of 2249.5, the delivery routes obtained by CWTS are shown in **FIGURE 5**.

| ID | Coordinate | Demand | CTW (h) | Service time (h) |
|----|------------|--------|---------|-----------------|
| 1  | (5, 10)    | 18     | (6, 10.6)| 0.15            |
| 2  | (12, 10)   | 25     | (7, 11.7)| 0.15            |
| 3  | (10, 25)   | 9      | (6.8, 12.3)| 0.15        |
| 4  | (7, 16)    | 27     | (7.5, 13.4)| 0.15        |
| 5  | (15, 8)    | 19     | (6.4, 14.5)| 0.15        |
| 6  | (12, 16)   | 22     | (8.3, 12.5)| 0.15        |
| 7  | (5, 16)    | 6      | (8.7, 11.5)| 0.2           |
| 8  | (5, 14)    | 9      | (10.5, 13.7)| 0.2           |
| 9  | (16, 12)   | 26     | (10.2, 15)| 0.2           |
| 10 | (4, 10)    | 29     | (9.8, 13)| 0.2           |
| 11 | (7, 12)    | 12     | (9.6, 12.4)| 0.15        |
| 12 | (13, 15)   | 14     | (9, 14)| 0.2           |
| 13 | (4, 16)    | 20     | (9.2, 11.5)| 0.2           |
| 14 | (4, 14)    | 5      | (10.6, 12.75)| 0.2         |
| 15 | (12, 22)   | 21     | (10.7, 14.8)| 0.15        |
| 16 | (8, 23)    | 12     | (8.8, 11.5)| 0.2           |
| 17 | (16, 14)   | 18     | (8.5, 13.2)| 0.2           |
| 18 | (18, 15)   | 19     | (8.1, 13.5)| 0.2           |
| 19 | (13, 10)   | 10     | (8.3, 14.6)| 0.15         |
| 20 | (8, 14)    | 15     | (10.5, 13.75)| 0.15       |
| 21 | (15, 18)   | 11     | (10.1, 12.5)| 0.15         |
| 22 | (13, 25)   | 12     | (10.4, 13.25)| 0.2         |
| 23 | (16, 17)   | 6      | (9.2, 12.6)| 0.2           |
| 24 | (12, 14)   | 27     | (8.3, 11.5)| 0.15         |
| 25 | (9, 14)    | 5      | (7.7, 10.5)| 0.15         |
| 26 | (17, 16)   | 17     | (7.5, 11.4)| 0.15         |
| 27 | (12, 15)   | 15     | (8.2, 13.5)| 0.2           |
| 28 | (14, 10)   | 6      | (9.3, 12.5)| 0.2           |
| 29 | (16, 13)   | 30     | (9.1, 11.3)| 0.15         |
| 30 | (12, 13)   | 19     | (8.9, 12.25)| 0.15        |

As shown in **FIGURE 4**, Metro Line 4 is selected as the delivery metro line, Xianlin Lake Station is chosen as the entry station while Jimingsi Station and Jiuhuashan Station (assuming ‘A’ and ‘B’) are selected as the exit stations. The shipping time from the delivery center to the metro entry station is 25 minutes. The speed of the GDV is 10 km/h and its capacity is 120. The transport cost per unit distance for truck, metro, and GDV is 0.4, 0.05, and 0.2 respectively and the transit time is 5 minutes. The parameter settings of the proposed model are as follows: $\alpha = 1, \beta = 1$, the maximum number of iterations is 200, using MATLAB R2018a coding.
Using ‘0’ to indicate the delivery center, it can be seen in FIGURE 5 that the delivery plan requires a total of 5 GDVs to participate in the delivery, the overloading is not happened.

In order to compare with CWTS proposed in this paper, the delivery model is also solved by ACO and PSO. As self-organizing algorithms, they are widely adopted for their simple and feasible procedures and are typical methods to solve VRP. These two swarm intelligent algorithms were inspired and deprived from the living behaviors and mechanisms of insects and animals. ACO simulates the foraging behavior of ants, according to the secreted pheromones, the more ants on a path, the more likely the latecomer will choose the path, which shows a positive feedback mechanism. PSO is known for its rapid convergence rate, the basic idea of which is to simulate the random foraging behavior of birds, in order to reach the richest food-accumulated spot, self-experience and communication between populations are relied to adjust birds’ foraging direction and velocity. The delivery routes obtained by these two algorithms are shown in FIGURE 6.

It can be seen that 5 GDVs are required respectively in these two delivery plans, however, as shown in FIGURE 7, 3 out of 5 GDVs are overloaded in the results of ACO and 1 out of 5 GDVs is overloaded in the results of PSO. Though overloading is greatly excluded by introducing penalty cost (Eq. (3)), it still occurs and is unacceptable in the real world.

In a hope to make the most of the GDVs available in our metro-based ULS system while avoid overloading, the number of GDVs is slightly added to 6 in the results of ACO and PSO, the updated delivery routes are shown in FIGURE 8, the optimal delivery cost of ACO is 2312.5 and 2286.4 for PSO. In these 3 delivery plans (CWTS (5 GDVs), ACO (6 GDVs) and PSO (6 GDVs)), all goods ordered by customers are delivered within the CTW, with a punctuality rate of 100%.

C. ALGORITHM DISCUSSIONS

In this section, because the first two parts of delivery are viewed as fixed values (Eq. (2)), only the GD part is taken into account to facilitate the comparison of results.

The iterative process of CWTS, ACO and PSO is shown in FIGURE 9, the abscissa is the number of iterations and the ordinate is the total delivery distance of GDVs.
From the convergence curve (FIGURE 9), it can be seen that if solved by CWTS, the convergence is obtained after 80 generations while if solved by ACO and PSO, the convergence rate is lower and the delivery distance is longer compared with the result of CWTS. During the process of searching the optimal solution, for a better approximate solution has been given by CW algorithm from the outset, CWTS tends to continue searching along this solution and no other search directions are considered, so the descent rate is very fast and the optimal solution can be obtained easily. As for ACO, because of the positive feedback mechanism, many pheromones may leave on the path of a good solution, which attract more ants and divert their searching direction to this solution. Though it can converge rapidly, for the solution ACO obtained in the inception phase is a suboptimal solution, the mechanism makes it plunge into the local optimum. As for PSO, though it has remarkable global search ability, the parameters of which are difficult to determine and their selections are subjective. Improper initial parameters will weaken the optimization ability of the algorithm and slow its convergence rate, so the iterative process of PSO is not a continuous descent course, long periods of stagnation lead to a low rate of convergence.

FIGURE 10 also presents the computation time to run CWTS, ACO and PSO and objective values under these algorithms. FIGURE 10 (a) shows that the average computation time of running CWTS is 320s, which is much shorter than that of ACO and PSO and the solution efficiency is acceptable in the real world. The difference between the maximum and minimum computation time of ACO and PSO is larger than that of CWTS, denoting that CWTS is more stable than the two other algorithms.

Thanks to the initial solution obtained from CW algorithm and the strong global search ability of the improved TS algorithm, CWTS consistently outperforms ACO and PSO in terms of the extreme value or the average value (FIGURE 10 (b)-(d)). Compared with the routes of CWTS (FIGURE 5), the results of ACO and PSO (FIGURE 8) show few teardrop-shaped routes (ideal route shape in VRP) and exhibit serious phenomenon of path crossing. Too many intersecting routes represent the serious detour and unreasonable route planning [41]. The irrational allocation of delivery resources leads to the increase in the delivery cost, similar patterns can also be observed in the results of delivery distance and delivery time, especially in the results of ACO (FIGURE 8 (a)). The fluctuation range of the objective values of CWTS is small, which further proves the stability of CWTS.

The load ratio of GDVs of the 3 delivery plans is illustrated in FIGURE 11. For CWTS, 5 GDVs are adequate while 1 more GDV is needed in ACO and PSO to avoid overloading. In CWTS, 4 out of 5 GDVs’ load ratio exceeds 80% while only 2 GDVs can achieve this transport efficiency in the results of PSO and merely 1 in that of ACO, meaning that CWTS can make the most of GDVs available for dispatching and save transport resources. In contrast, the results of ACO
and PSO indicate that these 2 approaches can’t realize the coordination of minimizing delivery cost while retaining high transport efficiency.

**D. MODEL DISCUSSIONS**

In this section, this paper proceeds the route optimization of traditional TD, and compares it with the metro-based delivery plan, it can be formulated as follows:

\[
\text{min } Z = \sum_{i \in \{0\} \cup V_c} \sum_{j \in V_c} \sum_{v \in V_v} c_{ij} q_j y_{ij}
\]

\[\text{s.t. } (5), (6), (8), (10) - (12)\]

\[
\sum_{i \in \{0\} \cup V_c} \sum_{v \in V_v} y_{ij} = 1, \quad \forall j \in V_c
\]

\[
y_{ij} \in \{0, 1\}, \quad \forall i \in \{0\} \cup V_c, \quad j \in V_c, \quad v \in V_v
\]

Eq. (16) denotes the transport cost of TD.

Eq. (17) represents that the cargoes of customer \( j \) can be served by only one truck.

Eq. (18) is 0-1 constraint of decision variable.

As shown in FIGURE 12, it can be seen that in terms of transport cost, delivery distance, and average delivery time, the results (CWTS) of the metro-based delivery plan are better than those of the traditional TD. At the level of meeting the CTW, all the freights are delivered on time. While for traditional TD, the goods of 3 customers don’t arrive on time. This shows that the proposed metro-based delivery mode has a great advantage over traditional TD in that it can save logistics transport cost while guaranteeing the QoS.

**E. SENSITIVITY ANALYSIS**

This section conducts a sensitivity analysis of the capacity of GDVs. The delivery routes under different capacities are shown in FIGURE 13. When the number, location, and demand of customers are constant, because the delivery cost of freights from the delivery center to the metro entry station and the metro entry station to the exit station remains
unchanged, the shorter delivery distance of GDVs, the lower the total cost. Therefore, in this part, in order to simplify the calculation, only the delivery distance of GDVs is considered in the analysis.

FIGURE 14 shows the correlation among the capacity, the delivery distance, the number and the average load ratio of GDVs. It can be found that when the capacity of GDVs is less than 120, as the capacity increases, the delivery distance and the number of GDVs that are selected to transport are obviously reduced. However, when the capacity of GDVs reaches 120, as the capacity continues to grow, the delivery distance doesn’t change significantly and the number of GDVs remains the same. At this state, no matter how much capacity is added, because of the penalty function (Eq. (3)), customers must be served within the CTW, a drastic reduction in delivery distance and fewer GDVs can’t guarantee the QoS. High-capacity GDVs can’t be brought into full play due to the limitation of the CTW and their low load ratio also leads to the transport capacity redundancy. It can be drawn that if the GDV’s capacity can be set as 120, no extra GDVs are needed, the total delivery cost can be reduced and the GD can achieve a stable state.

F. IMPLICATIONS

The multi-stage ULS delivery plan based on the coalition of aboveground and underground transportation offers a reliable and efficient logistic delivery mode by incorporating truck, metro resources and GDVs. The proposed delivery framework consists of a mathematical model with penalty and an integrated algorithm (CWTS), thus which have significant theoretical and practical application values. LTE can curtail logistic delivery cost and improve QoS by referring to the proposed delivery mode and utilizing the existing transportation resources to refresh the urban logistics delivery layout. The managerial insights of our proposed delivery plan can be found as follows:

1. Our proposed delivery plan includes 3 parts: TD, MD and GD, which provides efficient logistic service and realize ‘door to door’ delivery. The advantages in our
The proposed model can be found that overloading and violation of CTW are avoided by considering VRPTW. The integrated algorithm (CWTTS) offers a novel and effective solution method to handle our proposed metro-based ULS:

(2) In the GD part of our delivery framework, when the capacity of GDVs increases to a fixed value, a stable state can be achieved and the logistics delivery system can operate smoothly, thus the given optimal capacity setting can help save total delivery cost and optimize system configuration;

(3) By considering metro-based ULS, our proposed delivery plan can efficiently utilize transportation resources, save delivery cost and guarantee QoS when compared with traditional TD. As the demand for freight delivery and efficiency is steadily increasing, traditional freight transportation modes need to be modified and an efficient delivery mode is urgently needed to be established, so our proposed delivery plan is of great theoretical and practical significance. Consequently, our proposed delivery framework can offer reliable and efficient logistic service and further encourage local government and LTE to embrace resource-friendly delivery modes.

V. CONCLUSION

This paper introduces metro-based ULS to establish the urban logistic delivery network, which considers the capacity of GDVs and the CTW. Taking transport cost as the objective function, an urban logistics delivery path optimization model based on a single metro line is established, where the violation of CTW and overloading are quantificationally taken into account. The improved TS algorithm and CW algorithm are combined to solve the proposed model. Based on the real data of a LTE in Nanjing, the effectiveness of the proposed algorithm (CWTTS) is verified through the comparison with ACO and PSO. The practicability of the proposed delivery model is also proved by the comparison with the traditional TD mode. Sensitivity analysis is also conducted to demonstrate the optimal capacity setting of GDVs. It is found that:

(1) Compared with ACO and PSO, the computation time of CWTTS is less and better results can be obtained in terms of delivery distance, delivery cost, delivery time;

(2) The load ratio of GDVs in the results of CWTTS is higher and fewer GDVs are required to complete the delivery task compared with that of ACO and PSO;

(3) Compared with traditional TD, our proposed metro-based delivery mode can save logistics delivery cost while guaranteeing QoS (no violation of CTW);

(4) Through the sensitivity analysis of the capacity, it is suggested that the optimal operating index setting of the GDV capacity should be 120 to reduce total delivery cost, with which the GD can also achieve a stable state.

Our proposed model shows that by introducing metro-based ULS, combined with GD, transport efficiency can be improved and the layout of urban logistics delivery can be optimized, which exhibits adequate advancement and functionality. However, some factors, such as the relationship between the perfection of customers and the interest consideration of LTE and the environmental advantages of our proposed delivery mode are not fully appraised. Future studies may focus on analyzing the correlation between the LTE and customers based on Stackelberg game, the qualitative and quantitative analysis of the comparison of environmental impacts between our proposed delivery mode and traditional TD pattern will also be conducted.

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