Integrating route optimization with vehicle and unloading dock scheduling in LCL cargo collection

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Abstract: Less Container Load (LCL) has become an increasingly important element in containerized cargo export, due to the involvement of numerous small & medium size enterprises. Traditional cargo collection and consolidation processes are extremely complex and inefficient, which provides an excellent opportunity for improvement through integration. In this paper, we design a two-stage model comprising vehicle route optimization for cargo collection and vehicle and unloading dock scheduling. In the first stage, namely, the route optimization model, the Clarke-Wright saving algorithm is used, with the objective of minimizing the total transport cost for a given shipment size, weight, and capacity constraint of cargo collection vehicles. In the second stage, the scheduling of both collection vehicles and unloading dock are modeled, using two sub-models for given constraints on the time window of the unloading docks and cargo collection routes. An application of this integrated model is illustrated based on the cargo collection problems in the hinterland of Shanghai port.

Keywords: Cargo Collection, LCL, Route Optimization, Vehicle Dispatching, Unloading Dock Scheduling, Integrated Scheduling

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1. Introduction

The collection and distribution of Less Container Load (LCL) shipments for consolidated container exports and imports present a major challenge for road traffic in the port hinterland, especially for major container ports surrounded by a large population center. Over the past 5 years, consolidated containers have accounted for about 3% of the total container throughput of Shanghai port, with each container (Twenty-foot Equivalent Unit, or TEU) including 7.5 LCL shipments (Liu and Zhao, 2017). If the 2016 container throughput of Shanghai Port is 37.13 million TEUs,[1] then the total number of consolidated containers being exported or imported is around 1.11 million TEU, which is equivalent to 8.33 million LCL shipments.

The existing practice for LCL cargo export in China is not efficient (Liu and Zhao, 2017). Most such shipments are delivered directly to the designated consolidation warehouses of the exporting port by individual shippers following the arrangement by forwarders, which method creates several potential problems. Firstly, vehicle utilization can be low, due to the mismatch between vehicle capacity and shipment size. Secondly, this method increases road traffic and the chance of congestion, especially in the metropolitan area and around the consolidation warehouse. Thirdly, it increases the chance of late delivery and missing the cut-off date for the scheduled ship. Wang (2013) pointed out the possibility of collecting the shipments from scattered shippers using a pickup reservation system. In mainland China, more than 60% of the international container import and export business is operated by international forwarder companies, such as DHL (German), Panalpina (Europe), Nippon Express (Japan) and CEVA (Middle East). The collection and delivery of LCL cargo in China follows a similar practice to that in other parts of the world. In addition, the development of E-Commerce has made it easy for small and medium size companies to become involved in

[1] www.portcontainer.com.

international trade, which may change the pattern of international trade and escalate the volume of LCL cargo. However, there is as yet no detailed research on the integration of route optimization and dock scheduling for cargo collections.

This study proposes a cargo collection system for LCL cargo exports, including having a Regional Distribution Center (RDC) or Cargo Collection Point (CCP) in each city. LCL shipments in each city will be delivered to the city's RDC or CCP, and shipments in each CCP will be collected by vehicles and taken to the nearest RDC following optimized routes. After being unloaded at the RDC, shipments will be sorted according to their shipping route and destination, then trucked to a designated consolidation warehouse. A two-stage integrated model combining collection route optimization with vehicle and unloading dock scheduling is established, taking into account the location of each CCP, shipment size, vehicle capacity, scheduling constraints and other coordination requirements of vehicles and unloading docks. In stage one, we find the optimal routes for cargo collection, given vehicle capacity and shipment size at each CPP, using the C-W saving algorithm (Clarke and Wright, 1964). In stage two, for given cargo collection routes from stage one, the scheduling of collecting vehicle and unloading dock arrangements are modeled into two sub-problems, which are coordinated by the time windows on the collection routes and the unloading docks.

This is the first study that attempts to optimize the LCL shipments collection problem. The development of such a cargo collection network can improve the efficiency of LCL cargo collection, reduce the impact of such cargo movement on road traffic, and reduce emissions from trucking activity, especially in metropolitan areas. As shown from the results, applying this model can reduce road mileage by a quarter compared with direct deliveries to the RDC. Even more savings are possible if transportation from the RDC to a consolidation warehouse, as well as imported LCL container deliveries, is also accounted for. Further, cargo sorting in an RDC can reduce the workload at consolidation warehouses, thus increasing their operational efficiency.

The next section provides a review of existing literature on similar problems. It is followed by a description of the problem and the model. Section 4 demonstrates the application of the model on the cargo collection problems of Shanghai Port. Section 5 concludes.

2. Literature review

The Cargo Collection Routing Problem (CCRP) is a special case of the Vehicle Routing Problem (VRP). Academic research into the CCRP has mainly focused on the logistics of automobile parts. For example, Nemoto et al. (2010) implemented an optimized cargo collection system (Milk Run) at a Toyota facility in Thailand, which improved its control over the procurement process and reduced vehicle usage and traffic congestion. Akiyama and Yano (2010) introduced 3rd Party Logistics to centralize collection and distribution for retail stores in Japan, which reduces vehicle operations by about 2,700 trips a day. Brar and Saini (2011) proved that the implementation of centralized cargo collection can not only better support production, but also effectively reduce inventory costs.

Bredstrom and Rönnqvist (2007) studied the combined vehicle routing and scheduling problem with a time window, in which synchronization constraints are used to model situations when two customers require simultaneous services. Sadjadi et al. (2009) considered a customized optimization model based on the actual demand of an automobile manufacturer, and established a mixed integer programming of VRP, which was solved by a genetic algorithm. Xu et al. (2011) established a VRP model with vehicle volume, maximum mileage and time window constraints in the cargo collection of auto parts, and designed the heuristic saving algorithm. Baohe and Lin (2012) studied a VRP model with fuzzy time window, and designed a fuzzy time window vehicle scheduling plan based on the Ant Colony Algorithm. Salhi et al. (2013) considered the problem of multi-vehicle vehicle routing and vehicle routing with backhaul. Hosseini et al. (2014) analyzed the transport problems of direct delivery, cross docking and cargo collection, and established an integer programming model using the Harmony Search (HS) algorithm based on the simulated annealing algorithm. Combined with an integrated model of cross docking and cargo collection, Shi et al. (2014) used discrete event simulation to study the auto parts supply chain management problem. Wen et al. (2014) tried to minimize VRP costs with time-dependent speed data and congestion charges. Kumar et al. (2016) used a self-learning particle swarm optimization approach to study a multi-objective and multi-factor routing problem with a time window. Szczepański et al. (2017) applied the Rich VRP model in a simulation environment, and used it to verify a freight delivery schedule in urban areas.

Taking dock scheduling into consideration, Deshpande et al. (2007) designed a heuristic dock assignment approach to simulate the performances of terminal operations of less-than-truckload freight carriers, the variable of the hybrid operation model being freight volume. Based on random variation in freight volumes, Yu et al. (2008) developed a model that used an on-line policy for door allocations to minimize the expected man-hours. Ou et al. (2010) established a Parallel Machine Scheduling Model with multiple unloading servers to study the problem of 3rd party vehicles in the collection of goods and at unloading docks. Carpov et al. (2012) added self-adaptive random parameters to solve a parallel machine problem on the basis of First-Come First-Served (FCFS). Bazgosha et al. (2017) developed parallel and serial schedule generation schemes to study a transshipment scheduling problem with multiple identical loading/unloading stations. However, these are not strictly VRP research, nor do all these consider the limits of cargo unloading time.

With respect to VRP research with unloading docks constraints, Rieck and Zimmermann (2010) studied the Capacity-limited Vehicle Routing Problem (CVRP), and after considering the complexity of actual operation, incorporated the unloading dock constraint so as to achieve coordinated cargo flow. Lin and Xu (2015) analyzed the vehicle dispatching problem with time windows that include a penalty, and designed a two-stage algorithm to study the influence of dock constraints on the vehicle traveling cost. In the above papers, a vehicle only travels on one route, and the unloading arrangements are based on a simple policy such as FCFS, which does not consider cargo unloading time windows. Ma et al. (2016) studied the integration of vehicle scheduling and unloading dock allocations, setting the routing plan of collection vehicles according to the unloading dock assignments. It took the running time of different routes as the known conditions, without introducing the CCRP model into actual nodes on the transport network. Hu et al. (2017) applied VRP to minimize the energy consumption of Rail-guided vehicles under a time window and conflict-avoidance constraints, considering the route-specific weight. It provides a conflict-free transport service under two-sided loading/unloading operations among different docks in a warehouse, rather than among different CCPs.

Compared with the above studies, we integrate the VRP with the scheduling of vehicles and unloading docks, taking into consideration many real world factors such as the time windows for working time, vehicle cargo collection and unloading at docks, as well as the capacity constraints of the vehicle, freight volume, and the distances between CCPs. In addition, this is the first research that applies an integrated model to the LCL cargo collection network in a port hinterland. Such a model, if implemented, could improve the efficiency of LCL cargo exporting, and significantly reduce road traffic.

3. Problem Statement and Methodology

We model the cargo collection activities for LCL cargo exports in the hinterland of a coastal port A. Several regional distribution centers (RDC) are required at about S km from A. Each RDC covers the surrounding cities (H_1, …, H_i, ..., H_m), and each has a CCP. Cargo owners send their shipments to the nearest CCP, instead of the LCL consolidation warehouses at the port. The RDC also functions as a CCP in its own city, which is named H_0. LCL shipments in H_0 are stored directly in the RDC. The distance between each RDC is about S' km (Figure 1). The operations of cargo collection vehicles and the RDC (in the dotted box) are the research target of this paper. The vehicles for collecting cargoes are identical vans of 9.6 meters long. They are unloaded at the RDC, re-loaded in a different truck, and transferred to the port city according to their shipping destination for consolidation into full containers.

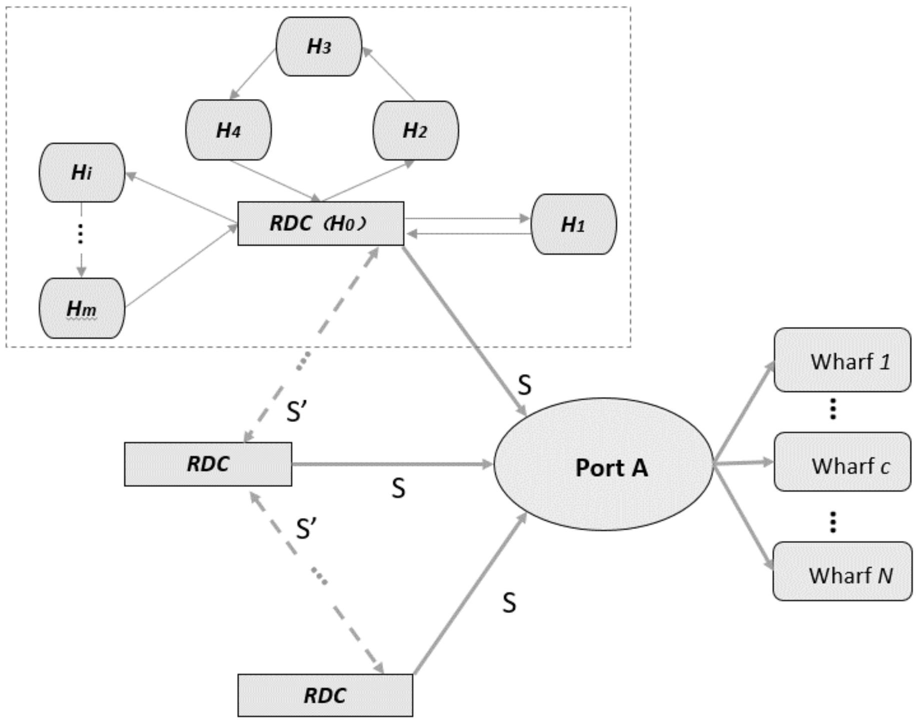

Figure 1. Illustration of cargo collection model

We approach the above problem in two stages: Route optimization for cargo collection; and scheduling for vehicle and unloading dock in the RDC. A mixed integer programming model is designed for the route optimization and scheduling problems, which are introduced in the following sections.

3.1. Stage One: Vehicle Route Optimization Model (VROM)

This section presents the mixed integer programming model for the route optimization problem. To simplify the model, a set of assumptions are required, and these are listed below:

① The number of shipping orders in each CCP is known;
② The LCL cargo is packed on standard pallets (1.2m*1.0m), the average height of each heavy-duty standard pallet is 1 m, and each shipment includes 4 pallets;
③ Different shipments can be transported in the same vehicle;
④ All shipments are collected according to pick-up instructions, and no splitting of a shipment is allowed;
⑤ The spatial distribution of CCPs is known, and therefore the transport distances between different CCPs are also known;
⑥ There is adequate transport capacity to meet the demand of LCL cargo exports;
⑦ The vehicles are identical, and their limits on volume (Q) and weight (G) are known;
⑧ One shipment includes 4 pallets and the weight limit of each shipment is 1.73 tons.

The sets, parameters, and variables are defined below.

$\boldsymbol{R}=\{0,1,\dots,m\}$ is the set of CCPs. There are a total of m CCPs, which are indexed by i, f, j. 0 is the index for RDC. The CCPs and RDC are represented by H_i ($i \in [0,\dots,m]$ in Figure 1.
$\boldsymbol{D}=\{1,\dots,n\}$ is the set of actual cargo collection routes, indexed by d.
$\boldsymbol{V}=\{1,\dots,p\}$ is the collection of vehicles, indexed by k.
c, unit transport costs per km.
s_{ij}, the transport distance from i to j, $i, j \in \boldsymbol{R}$.
g_i, the weight of LCL cargo in i^{th} CCP, $i \in \boldsymbol{R}$.
q_i, the volume of LCL cargo in i^{th} CCP, $i \in \boldsymbol{R}$.

$$x_{ijd} = \begin{cases} 1, \text{there is a direct road connection from } i \text{ to } j \text{ on route } d \\ 0, \text{otherwise.} \end{cases}$$

$$y_{id} = \begin{cases} 1, \text{CCP } i \text{ is on route } d \\ 0, \text{otherwise.} \end{cases}$$

The above two binary variables are added to allow specifying the loading sequence of different CCPs on the same route and to confirm whether CCP i is on route d.

The mathematical model of the collection route optimization problem is as follows:

$$\min Z = c \sum_{i=1}^{m} \sum_{j>i}^{m} \sum_{d=1}^{n} s_{ij} x_{ijd} \tag{1}$$

s.t.

$$\sum_{i=1}^{m} g_i * y_{id} \leq G, d \in \boldsymbol{D} \tag{2}$$

$$\sum_{i=1}^{m} q_i * y_{id} \leq Q, d \in \boldsymbol{D} \tag{3}$$

$$\sum_{j=1}^{m} x_{0jd} = 1, d \in \boldsymbol{D} \tag{4}$$

$$\sum_{i=1}^{m} x_{i0d} = 1, d \in \boldsymbol{D} \tag{5}$$

$$\sum_{i=0}^{m} x_{ifd} - \sum_{j=0}^{m} x_{fjd} = 0, d \in \boldsymbol{D}, f \in \boldsymbol{R} \tag{6}$$

$$\sum_{d=1}^{n} y_{id} = 1, i \in \boldsymbol{R} \tag{7}$$

Equation (1) is the objective function, which is to find the x_{ijd} that minimizes the total transportation cost. Equations (2) and (3) specify weight and size limits of all the cargoes loaded on route d. Equations (4) and (5) prescribe the RDC as the starting and ending points of any route. Equation (6) shows the principle of vehicle flows, i.e., the number of vehicles arriving at and leaving from a CCP should be equal. Equation (7) expresses that all CCPs can be covered, and that each can only be served once by one vehicle on one route.

3.2 Stage Two: Vehicle and Unloading Dock Scheduling Integration Model

This stage includes two sections: Vehicle Dispatching and Unloading Dock Scheduling. In the first section, we input the following conditions into the Vehicle Dispatching Model (VDM): The capacities of vehicles by volume and weight; their earliest departure time; optimized routes as ascertained in stage one; and the duration and unloading time window of each route. Through this, the schedule for vehicle assignment is obtained.

In the second section, the vehicle schedules obtained in the first step of stage two are used as the inputs to the Unloading Dock Scheduling Model (UDSM). In addition, the following information is required: Earliest departure time of each vehicle; the duration and unloading time window of each route; and the duration and working time window of each unloading dock. If there is a feasible solution, the integrated scheduling based on collection vehicles, dispatching, and unloading docks scheduling is obtained; otherwise, we will adjust the time windows of different collection routes, and then return to the first section until a feasible solution is found.

The detailed processes are shown in Figure 2.

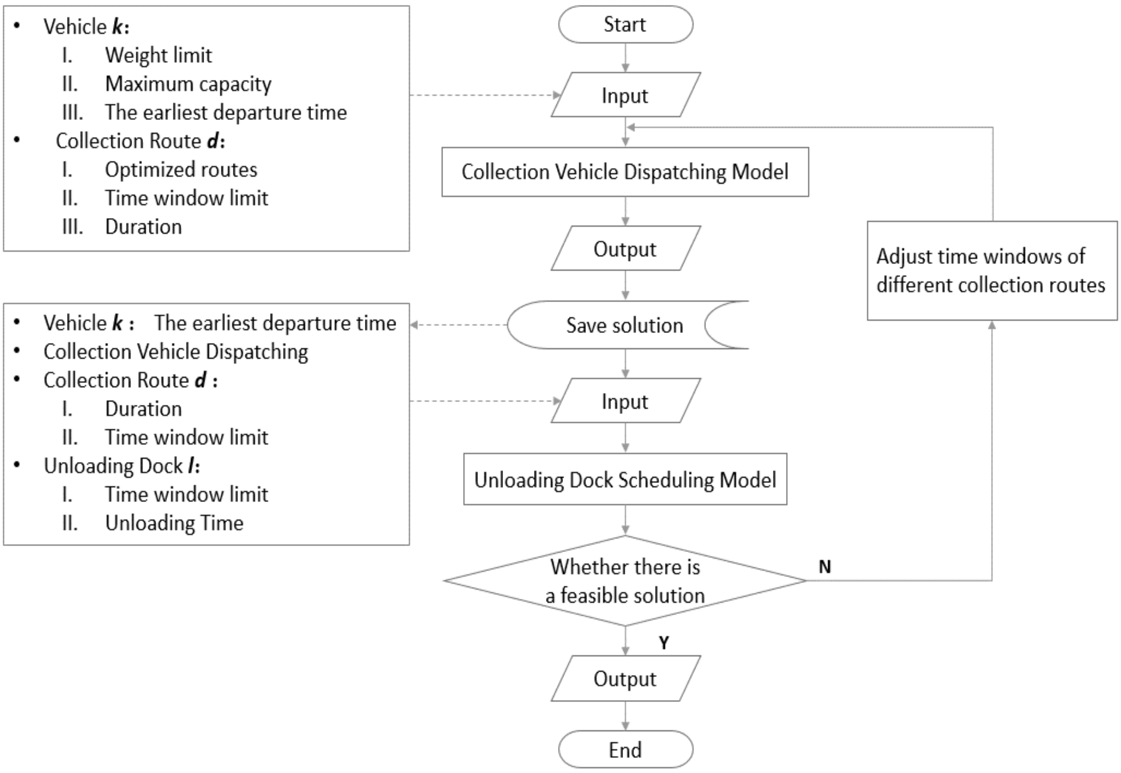

Figure 2. Detailed processes of two-stage scheduling model

Model Assumption:

① All collection vehicles must be unloaded at the unloading dock after each cargo collection route;
② One route can only be served by one vehicle;
③ One dock can only unload one vehicle at a time;
④ Each cargo collection route has an unloading time window constraint, i.e., the LCL cargo of each route must be unloaded within its unloading time window;
⑤ Each unloading dock has a working time window limit, i.e., the available unloading time of the dock must be within its working time window;
⑥ Time logic constraints: The time of starting to unload each cargo collection must be later than the completion time of its route.

The sets, parameters and variables are explained as follows:

$\boldsymbol{D_0}$=$\{0, 1, \ldots, n, n+1\}$ is the set of all cargo collection routes indexed by *d, r*. *0* and *n+1* are virtual routes, representing the beginning and ending tasks for each vehicle.

$\boldsymbol{U}$=$\{1, \ldots, w\}$ is the set of unloading docks, indexed by *l*.

$\boldsymbol{V}$=$\{1, \ldots, p\}$ is the set of vehicles, indexed by *k*.

T_d, the duration of route *d*, $d \in \boldsymbol{D}$.

s_d, total mileage of route *d*, $d \in \boldsymbol{D}$.

w_d, total shipments loaded on route *d*.

t, time required to load each shipment.

v, the average speed of vehicles.

[DE_d, DL_d], unloading time window for route *d*, $d \in \boldsymbol{D}$.

[UE_l, UL_l], working time window for unloading dock *l*, $l \in \boldsymbol{U}$.

TS_k, earliest departure time for vehicle *k*, $k \in \boldsymbol{V}$.

TU_l, unloading time for dock *l*, $l \in \boldsymbol{U}$.

M_{tm}, a large constant representing the maximum value of all time windows.

e_{dk}, the time for vehicle *k* to start route *d*, $d \in \boldsymbol{D}$, $k \in \boldsymbol{V}$.

As the duration and unloading time window for each route is different, in order to specify multiple route task sequences completed by vehicle *k* and dock *l*, the following two binary variables, a_{drk} and b_{drl}, are added:

$$a_{drk} = \begin{cases} 1, \text{vehicle } k \text{ firstly completes route } d, \text{and then completes route } r \\ 0, \text{otherwise.} \end{cases}$$

If a vehicle is only assigned one route, it will be expressed as both a_{0rk} and $a_{d,n+1,k}$, as it needs to start and end at the virtual route.

$$b_{drl} = \begin{cases} 1, \text{dock } l \text{ firstly completes route } d, \text{and then completes route } r \\ 0, \qquad \text{otherwise.} \end{cases}$$

If a dock is only assigned to unload a vehicle for one route, it will be expressed as both b_{0rl} and $b_{d,n+1,l}$.

u_{dl}, the unloading start time of dock *l* for route *d*, $d \in \boldsymbol{D}$, $l \in \boldsymbol{U}$.

(1) Collection Vehicle Dispatching

$$\min Z' = \sum_{k=1}^{p}\sum_{r=1}^{n} a_{0rk} \tag{8}$$

s.t.

$$\sum_{r=0}^{n+1} a_{0rk} = 1, k \in \boldsymbol{V} \tag{9}$$

$$\sum_{d=0}^{n+1} a_{d,n+1,k} = 1, k \in \boldsymbol{V} \tag{10}$$

$$\sum_{d=0}^{n+1} a_{drk} = \sum_{d=0}^{n+1} a_{rdk}, k \in \boldsymbol{V}, r \in \boldsymbol{D} \tag{11}$$

$$\sum_{d=0}^{n+1}\sum_{k=1}^{p} a_{drk} = 1, r \in \boldsymbol{D} \tag{12}$$

$$TS_k \sum_{r=0}^{n+1} a_{drk} \le e_{dk} \le M_{tw} \sum_{r=0}^{n+1} a_{drk}, k \in \boldsymbol{V}, d \in \boldsymbol{D} \tag{13}$$

$$s_d = \sum_{i=1}^{m}\sum_{j>i}^{m} s_{ij} x_{ijd}, d \in \boldsymbol{D} \tag{14}$$

$$T_d = \frac{s_d}{v} + w_d \cdot t, d \in \boldsymbol{D} \tag{15}$$

$$e_{dk} + T_d + max\{TU_l\} - M_{tw}(1 - a_{drk}) \le e_{rk}, d, k \in \boldsymbol{V}, \boldsymbol{r} \in \boldsymbol{D} \tag{16}$$

$$DE_d \sum_{r=0}^{n+1}\sum_{k=1}^{p} a_{drk} \le \sum\nolimits_{k=1}^{p} e_{dk} + T_d \le DL_d \sum_{r=0}^{n+1}\sum_{k=1}^{p} a_{drk}, d \in \boldsymbol{D} \tag{17}$$

$$\begin{gathered} a_{drk} = 1 \; if \; d \ne n+1, r \ne d, or \; r \ne 0; otherwise \; \alpha_{drk} = 0 \\ d, r \in \boldsymbol{D_0}, r \in \boldsymbol{D_o}, k \in \boldsymbol{V} \end{gathered} \tag{18}$$

$$e_{dk} \ge 0, d \in \boldsymbol{D_o}, k \in \boldsymbol{V} \tag{19}$$

Equation (8) states the objective, which is to minimize the number of vehicles required for the collection activity. The decision variables include a_{drk} and e_{dk}. Equations (9) and (10) define the starting and ending tasks of each vehicle as virtual tasks 0 and n+1; Equations (11) and (12) require that each cargo collection route can only be completed once by one vehicle; Equation (13) specifies that the start time for vehicle k to take route d must be later than the vehicle's earliest departure time. If vehicle k does not travel on route d, e_{dk}=0; Equation (14) states the total distance of route *d*; Equation (15) defines the duration for route *d*, which is the sum of the transit time ($\frac{s_d}{v}$) and the loading time ($w_d \cdot t$); Equations (16) and (17) are derived from the constraints of collection vehicles and unloading docks: Equation (16) represents that the unloading buffer time, $max\{TU_l\}$, must be after when the vehicle finishes a route and before the start of the next task; Equation (17) indicates that the time after completing a loading task must be within the unloading time window; Equation (18) specifies the value of decision variables a_{drk}, which requires ① there is no route after n+1; ② vehicle k cannot travel on the same route ($r \neq d$); and ③ there is no other route before route *0*; Equation (19) defines the value of e_{dk} to be non-negative. Since e_{dk} is jointly determined by the vehicle scheduling and dock scheduling, it is also used as the decision variable in the next section.

(2) Unloading Dock Scheduling

$$\min Z'' = \sum_{d=1}^{n}[\sum_{l=1}^{w} u_{dl} - (\sum\nolimits_{k=1}^{p} e_{dk} + T_d)] \tag{20}$$

s.t.

$$\sum_{r=0}^{n+1} b_{0rl} = 1, l \in \boldsymbol{U} \tag{21}$$

$$\sum_{d=0}^{n+1} b_{d,n+1,l} = 1, l \in \boldsymbol{U} \tag{22}$$

$$\sum_{d=0}^{n+1} b_{drl} = \sum_{d=0}^{n+1} b_{rdl}, r \in \boldsymbol{D}, l \in \boldsymbol{U} \tag{23}$$

$$\sum_{d=0}^{n+1}\sum_{l=1}^{w} b_{drl} = 1, r \in \boldsymbol{D} \tag{24}$$

$$u_{dl} + TU_l - M_{tw}(1 - b_{drl}) \leq u_{rl}, \{d, r\} \in \boldsymbol{D}, l \in \boldsymbol{U} \tag{25}$$

$$DE_l \sum\nolimits_{l=1}^{w} \sum_{r=0}^{n+1} b_{drl} \leq \sum\nolimits_{l=1}^{w} u_{dl} \leq UL_l \sum\nolimits_{l=1}^{w} \sum_{r=0}^{n+1} b_{drl}, d \in \boldsymbol{D} \tag{26}$$

$$UE_l \sum\nolimits_{r=0}^{n+1} b_{drl} \leq u_{dl} \leq (UL_l - TU_l) \sum\nolimits_{r=0}^{n+1} b_{drl}, r \in \boldsymbol{D}, l \in \boldsymbol{U} \tag{27}$$

$$e_{dk} + T_d + \sum\nolimits_{l=1}^{w} \sum\nolimits_{r=0}^{n+1} TU_l b_{drl} - M_{tw}(1 - a_{drk}) \leq e_{rk}, \{d, r\} \in \boldsymbol{D}, k \in \boldsymbol{V} \tag{28}$$

$$\sum\nolimits_{k=1}^{p} e_{dk} + T_d \leq \sum\nolimits_{l=1}^{w} u_{dl}, d \in \boldsymbol{D} \tag{29}$$

$$\sum\nolimits_{l=1}^{w} (u_{dl} + TU_l \sum\nolimits_{r=1}^{n} b_{drl}) \leq \sum\nolimits_{r=1}^{n} e_{rk} a_{drk} + M\left(1 - \sum\nolimits_{r=1}^{n} a_{brk}\right), d \in \boldsymbol{D}, k \in \boldsymbol{V} \tag{30}$$

$$b_{drl} = \begin{cases} 1\ if\ d \neq n+1, r \neq d, or\ r \neq 0 \\ 0 \qquad otherwise \end{cases}, \{d, r\} \in \boldsymbol{D_0}, k \in \boldsymbol{V} \tag{31}$$

$$u_{dl} \geq 0, d \in \boldsymbol{D_0}, l \in \boldsymbol{U} \tag{32}$$

Equation (20) describes the objective function of unloading docks scheduling, which is to minimize the waiting time of vehicles. The decision variables include b_{drl} and u_{dl}. Equations (21) and (22) express that the starting and ending tasks of each unloading dock are virtual tasks 0 and n+1. Equations (23) and (24) indicate that each cargo collection route can only be completed once by one dock. Equation (25) describes that if unloading dock l completes route *d* before route *r*, the start time of route *r* must be later than the completion time of route *d,* that is, one dock cannot unload cargoes from different routes at the same time. Equation (26) states that, for each route, the start time of unloading goods at dock *l* must be within the unloading time window of route *d*, and that if unloading dock l does not unload cargoes on route d, u_{dl}=0. Equation (27) indicates that, for each dock, the start time of unloading goods on route *d* at unloading dock l must be within the working time window of unloading dock l. Equation (28) indicates that if vehicle *k* finishes route *d* prior to route *r*, the start time of route *r* must be later than the unloading completion time of route *d*. Equation (29) states that the unloading will happen right after a route is finished, that is, the unloading start time of route *d* is the sum of its duration (T_d) and loading start time ($\sum_{k=1}^{p} e_{dk}$). Equation (30) describes that if route *d* is before route *r*, the loading start time of route *r* cannot be earlier than the unloading end time of route *d*. Equation (31) specifies the value of decision variables b_{drl}, which requires ① there is no route after n+1; ② dock l cannot unload cargoes from the same route ($r \neq d$); and ③ there is no other route before route *0*. Equation (32) defines the value of u_{dl} to be a non-negative real number.

4. Case Study

The LCL cargo collection problem in the Yangtze River Delta (YRD) region, the hinterland of Shanghai Port, is used as a case study. The cargo collection network, as shown in Figure 3, includes two levels: Two main routes marked by solid lines (Wuxi - Shanghai, Hangzhou - Shanghai) and three branch routes (Shanghai Branch, Jiangsu Branch and Zhejiang Branch). Shanghai Branch covers Suzhou, Jiaxing, and 18 districts in Shanghai; Zhejiang Branch covers Hangzhou and its surrounding areas; also, Jiangsu Branch covers Wuxi and its surrounding areas. In Figure 3, the dotted line stands for the Branch networks for Jiangsu. The RDC in Shanghai provides services for two main routes and the Shanghai branch network. It also consolidates all the LCL cargoes into full container loads.

In this model application, we focus on the cargo collection network of Jiangsu Branch. The RDC is located in Wuxi (H_0), and provides services for 25 major counties and cities (H_0, H_1, …, H_{25}), as shown in Figure 4. After the completion of unloading operations in the RDC, the LCL cargoes are grouped into five categories according to different destination ports and various shipping routes, such as Near-Sea Service, W/C America Service, E/C America Service, Europe Service and Mediterranean Service. As defined in Section 3, the LCL goods from city H_0 are stored directly in the RDC. The average daily transport demands for LCL cargoes at each CCP are shown in Table 1. The distances between each CCP are shown in Table 2, which contains the distance of the shortest route between each pair of CCPs. There are 3 unloading docks in the RDC, and their working time is from 500 min (8:20 a.m.) to 1100 min (18:20 p.m.). Earliest departure time of each vehicle is 300 min (5:00 a.m.).

Figure 3. LCL cargo collection network in Yangtze River Delta region

Figure 4. Distribution of CCPs

Table1. LCL daily shipping orders at each CCP

Cargo Collection Location (City)	H_0	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}
Transport Demand (Shipping order)	5	4	4	4	5	5	10	9	10	9	9	5	5
Cargo Collection Location (City)	H_{13}	H_{14}	H_{15}	H_{16}	H_{17}	H_{18}	H_{19}	H_{20}	H_{21}	H_{22}	H_{23}	H_{24}	H_{25}
Transport Demand (Shipping order)	5	5	5	5	5	6	6	5	5	6	5	6	6

Source: (Liu, 2017)

Table 2. Distance between each pair of CCPs

km	H_0	H_1	H_2	H_3	H_4	H_5	H_6	H_7	H_8	H_9	H_{10}	H_{11}	H_{12}	H_{13}	H_{14}	H_{15}	H_{16}	H_{17}	H_{18}	H_{19}	H_{20}	H_{21}	H_{22}	H_{23}	H_{24}
H_1	45																								
H_2	54	27																							
H_3	103	67	94																						
H_4	43	59	55	116																					
H_5	61	75	72	134	50																				
H_6	175	140	127	110	158	192																			
H_7	157	123	109	124	145	175	79																		
H_8	198	167	153	143	174	200	68	50																	
H_9	164	148	166	108	194	212	99	145	140																
H_{10}	147	103	121	77	149	167	58	98	93	57															
H_{11}	123	90	76	103	107	141	84	38	80	153	107														
H_{12}	114	81	67	137	84	109	116	90	133	186	139	62													
H_{13}	140	107	93	77	124	158	63	73	70	115	86	60	83												
H_{14}	96	62	48	99	79	113	102	85	107	143	96	51	43	68											
H_{15}	120	87	72	91	103	138	94	59	81	141	95	31	55	60	53										
H_{16}	118	107	93	164	79	105	156	99	124	206	169	97	57	116	76	77									
H_{17}	57	73	68	129	38	43	189	142	167	211	164	114	74	155	109	114	72								
H_{18}	88	104	86	161	49	74	142	108	134	212	165	70	59	108	88	90	39	51							
H_{19}	110	91	77	148	72	98	133	92	117	203	156	71	40	119	79	81	40	65	43						
H_{20}	176	163	150	224	138	163	197	131	165	255	228	138	93	174	132	138	66	130	94	95					
H_{21}	125	155	150	212	100	97	240	195	220	232	246	168	127	206	166	168	126	87	105	119	179				
H_{22}	189	217	212	273	185	159	313	282	307	307	308	255	214	279	253	255	213	164	192	206	257	96			
H_{23}	111	136	131	192	81	106	226	160	194	274	227	154	113	183	142	134	88	80	90	95	117	66	144		
H_{24}	129	156	151	213	124	99	272	230	255	259	247	193	162	219	193	203	161	112	130	154	205	54	62	94	
H_{25}	131	164	150	201	112	118	207	142	175	266	219	134	103	184	132	148	76	96	92	92	99	86	164	54	112

Source: (Liu, 2017)

The vehicles are assumed to be identical 9.6 m vans, with size and weight limit being 60 m^3 and 25 tons, respectively. The average transport cost is 1.2 yuan / km. From the Route Optimization Model in Stage 1, we can obtain 15 major cargo collection routes, as shown in Table 3.

Table 3. Optimized cargo collection routes

Route d	Collection Locations	Distance (km)	Vehicle Utilization Rate (%)
1	$H_0 – H_1 – H_3 – H_0$	215	68.0
2	$H_0 – H_{17} – H_{18} – H_0$	196	89.1
3	$H_0 – H_{12} – H_{19} – H_0$	264	86.3
4	$H_0 – H_{11} – H_{15} – H_0$	274	83.3
5	$H_0 – H_2 – H_4 – H_0$	152	76.3
6	$H_0 – H_5 – H_{24} – H_0$	289	93.6
7	$H_0 – H_{23} – H_{25} – H_0$	296	95.9
8	$H_0 – H_{10} – H_0$	294	75.4
9	$H_0 – H_{13} – H_{14} – H_0$	304	83.3
10	$H_0 – H_7 – H_0$	314	75.0
11	$H_0 – H_{21} – H_{22} – H_0$	410	97.5
12	$H_0 – H_{16} – H_{20} – H_0$	360	87.6
13	$H_0 – H_9 – H_0$	328	75.2
14	$H_0 – H_6 – H_0$	350	83.3
15	$H_0 – H_8 – H_0$	396	83.3

In the first stage, the total mileage is 4442 km. Compared with making direct deliveries from each CCP to the RDC, the total mileage saving is 1506 km, which is about one quarter. Of course, this only accounts for the savings from each CCP to the RDC. The total trucking distance saved will be much greater when compared with direct delivery from each shipper's location to the cargo consolidation warehouse in Shanghai.

In the second stage, the unloading time window for each route is also different. In this case, we assume that the average speed of the vehicle is 80 km/h, that the average loading speed is 5 minutes per shipment, that the cargo collection routes are as shown in Table 3, and that the working hours and unloading time for 3 docks are as shown in Table 4. The collection vehicle-dispatching plan and unloading dock scheduling arrangements are shown in Figures 5 and 6. In Figure 5, only the actual routes are plotted; for clarity, the virtual routes are not included.

Table 3. Duration and time window of each route

Route d	T_d	DE	DL
1	201	500	560
2	202	540	600
3	253	750	810

4	256	780	810
5	159	720	780
6	272	540	600
7	277	570	630
8	266	810	870
9	278	810	870
10	281	840	900
11	363	870	930
12	320	930	990
13	291	960	1020
14	313	990	1050
15	347	1020	1080

Table 4. Duration and time window of each unloading dock

Dock l	TU_l	BE	BL
1	50	500	1100
2	45	500	1100
3	40	500	1100

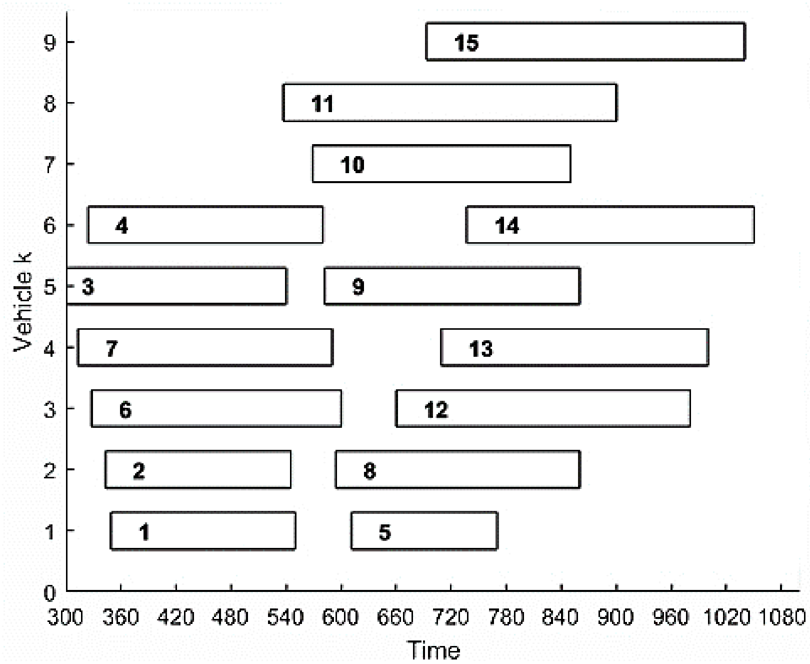

Figure 5. Collection vehicle schedule

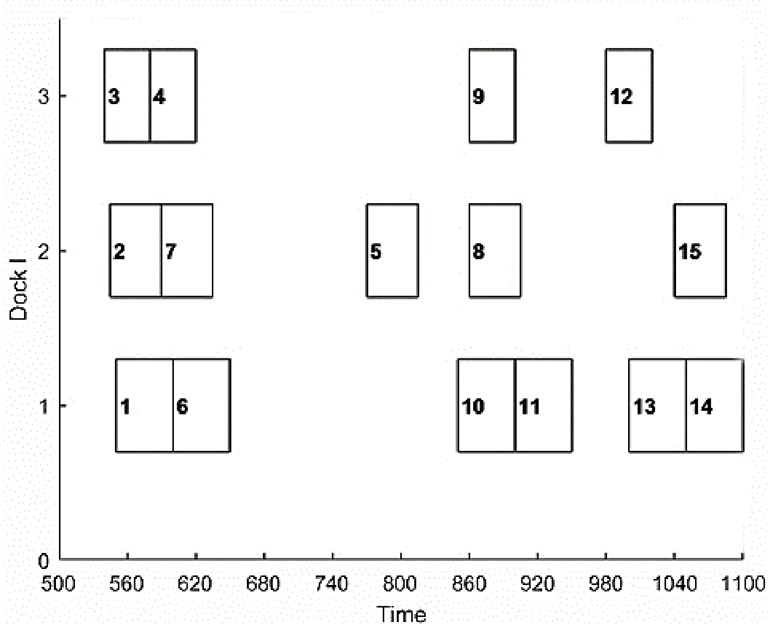

Figure 6. Unloading dock scheduling

5. Conclusions

In this paper, we studied the LCL cargo collection problem by integrating route optimization with vehicle and unloading dock scheduling. Through the establishment of CPPs and RDCs, the LCL goods are collected from each of the CCPs and taken to the RDCs for sorting according to different destination ports and various shipping routes, then re-loaded onto different trucks and transferred to the port city for consolidation into full containers.

Such LCL cargo collection networks can significantly reduce road traffic in the hinterland of a major port, which is especially important for a major container port surrounded by a large population center, such as Shanghai Port. As shown from the case study, calculating only the savings from the CCPs to the RDC in Jiangsu Province shows that a quarter of the total trucking mileage can be saved. If this system were to be implemented throughout the whole hinterland area, the percentage of savings should be much higher. This demonstrates the potential that an LCL cargo collection network has for reducing road traffic, which would also contribute to the reduction of air pollution in the YRD area. Finally, this study only considered the collection of export shipments. Such a system could also serve for the delivery of imported consolidated containers, which would further reduce trucking activities in the metropolitan area.

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