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A two-phase method for multi-echelon location-routing problems in supply chains

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ABSTRACT

The multi-echelon location-routing problems (LRPs) arise from transportation applications such as distribution systems of supply chains in city logistics. The literature review shows that most of the previous studies on location-routing in supply chains involve two-echelon LRPs. The main objective of this study is to develop a two-phase method based on improved Clarke and Wright savings algorithm for three-echelon and four-echelon LRPs. Computational experiments show that compared with other methods, the proposed method can obtain the solution for two LRPs in a shorter time. Moreover, computational experiments show this method can solve three and four location-routing problems in reasonable time. The study also provides managerial insights on the proposed models and method. Finally, the limitations on models and method as well as future research directions are given.

1. Introduction

With the development of economy, the competition among enterprises has changed into competition among supply chains. Distribution (logistics) system is an important aspect of supply chain management. A suitable distribution system can reduce transportation cost and the price of products (Ahmadizar, Zeynivand, & Arkat, 2015). Thus, the competitiveness of enterprises is enhanced. In a distribution or logistics system, the suppliers deliver the raw materials to the plants and the plants transport the products to the customers through the transit facilities. Transit facilities include regional centers or distribution centers which perform the consolidation and break-bulk operation (Dondo, Méndez, & Cerdá, 2011). In short, in this paper, distribution system of supply chains is composed of suppliers, plants, distribution centers, regional centers, and customers.

A multi-echelon distribution or logistics system does not allow for direct flow of goods from plants to customers. Instead, suppliers, plants, distribution centers, regional centers, and customers are organized into echelons and only the transportation of products in the different echelons is allowed (Santos, da Cunha, & Mateus, 2013). An example of multi-echelon system is city logistics. Many cities do not allow large vehicles to enter the urban area due to traffic and environmental considerations by building transit facilities (e.g., regional or distribution centers) where smaller and environment-friendly vehicles are allowed to go downtown (Nguyen, Prins, & Prodhon, 2012). The products from remote plants may be unloaded at these regional centers or distribution centers instead of shipping to the end-customers. Multi-echelon logistics system has four advantages. First, multi-echelon logistics system can bring economic benefits. As vehicles with different volumes at different echelons are used, the transportation cost is reduced. Specially, vehicles with large capacity are used from raw materials suppliers to plants, whereas vehicles with small capacity may be used from distribution centers or regional centers to customers. Second, multi-echelon logistics can reduce the negative impact of transport system on urban traffic. Cities in some countries stipulate linehaul vehicles can not enter the cities to avoid traffic congestion (Soysal, Bloemhof-Ruwaard, & Bektaş, 2015). Third, the multi-echelon logistics system reduces noise and air pollution through using small capacity and environmentally friendly vehicles (Breunig, Schmid, Hartl, & Vidal, 2016). Fourth, the multi-echelon system can meet the constraints of labor hours from laws and regulations. The multi-echelon logistics system has many applications including postal and parcel delivery distribution, press distribution, logistic systems for urban freight distribution, multimodal transportation, grocery distribution, and transportation sharing approaches (Gonzalez-Feliu, 2012).

In this paper, four location-routing problems (LRPs) are considerd: one-echelon LRP, two-echelon LRP, three-echelon LRP, and

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four-echelon LRP. One-echelon LRP includes one vehicle tour: from regional centers to customers. Two-echelon LRP includes two vehicle tours: the first tour is from regional centers to customers; the second tour is from distribution centers to regional centers. Three-echelon LRP includes three vehicle tours: the first tour is from regional centers to customers; the second tour is from distribution centers to regional centers; the third tour is from plants to distribution centers. Four-echelon LRP includes four vehicle tours: the first tour is from regional centers to customers; the second tour is from distribution centers to regional centers; the third tour is from plants to distribution centers; the fourth tour is from suppliers to plants.

LRP is NP-hard because both facility location problem and vehicle routing problem are NP-hard. This makes it difficult to solve LRP regular methods. In this case, intelligent search algorithms can be used. For example, Prins, Prodhon, and Calvo (2006a) used a Memetic Algorithm with Population Management to solve one-echelon LRP. In another study, the authors used GRASP (greedy randomized adaptive search procedure) to deal with one-echelon Capacitated LRP (Prins, Prodhon, & Calvo, 2006b). In recent years, some researchers have begun to solve the two-echelon LRP by different methods. For example, in order to solve two-echelon LRP, a multi-start iterated local search (Nguyen et al., 2012), a multi-start iterated local search (Hemmelmayr, Cordeau, & Crainic, 2012), and Branch-and-price algorithms (Santos et al., 2013) are employed, respectively. However, few published studies involved three or more echelon LRPs. In this paper, a two-phase method for multi-echelon LRPs is introduced and validated by computational experiments.

There are three motivations in this paper. The first motivation is to establish the models for four LRPs. The second motivation is to develop a two-phase method based on improved Clarke and Wright savings algorithm. The third motivation is to demonstrate the proposed method is not inferior to previous methods and may solve multi-echelon LRPs that can not be solved by previous methods through computational experiments.

Based on the above discussion, the main contributions that differentiate this paper from the existing literature are as follows. First, we formulate three-echelon and four-echelon location-routing mathematical models. Most published studies discuss one-echelon or two-echelon LRPs. Second, tour length constraint of vehicles is considered. In previous studies, only capacity constraints of facilities and vehicles are taken into account. Finally, a two-phase method is provided. This method is faster than other methods and it is easy to be used and can be extended. Furthermore, this method can be used without adjusting the parameters.

The rest of this paper is organized as follows. A review of the related literature is discussed in Section 2. The problem formulations are presented in Section 3. Section 4 describes the proposed two-phase method. Section 5 provides the computational experiments. Finally, Section 6 concludes this paper and provides future research directions.

2. Literature review

Literature is briefly reviewed in this section. We classify the literature in terms of problem variations and solution approaches. Literature may be divided into three categories according to problem variations: literature on routing problem, literature on LRP, and multi-echelon problem in supply chains. In terms of solution approaches, literature can be classified into exact solution methods and heuristic solution methods.

2.1. Literature review on problem variations

2.1.1. Routing problem

Anily and Federgruen (1993) developed distribution systems with a single depot and many retailers to obtain lower bounds for systems by extending earlier methods. Baldacci et al. (2013) formulated a two-echelon capacitated Vehicle Routing model and obtained valid lower bounds using an exact algorithm. Perboli, Tadei, and Vigo (2011) proposed a Two-Echelon Capacitated Vehicle Routing Problem and presented two math-heuristics to deal with this problem. Experimental results show this method is effective. Santos et al. (2013) proposed a two-echelon capacitated Vehicle Routing Problem and solved it using two branch-and-price algorithms. Grangier, Gendreau, Lehuédé, and Rousseau (2016) addressed a two-echelon multiple-trip routing problem with time window and synchronization constraints. An adaptive large neighborhood search was proposed to solve this problem. Li, Zhang, Lv, and Chang (2016) introduced a two-echelon time-constrained routing problem in linehaul-delivery systems. The improved Clarke and Wright savings algorithm is adopted to settle this problem. The computational results showed that this method is effective. The above literature studied the one-echelon or two-echelon vehicle routing problem from the point of view of operation. Nevertheless, the strategic problem, i.e., the location problem was not considered. Moreover, location problem and routing problem should be investigated together to avoid sub-optimal solutions.

2.1.2. Location-routing problem (LRP)

Most previous studies focused on solving one-echelon LRP. For instance, Wu, Low, and Bai (2002) presented a method with simulated annealing algorithm for solving one-echelon LRP. Prins, Prodhon, Ruiz, Soriano, and Wolfler Calvo (2007) developed a Cooperative Lagrangean Relaxation-Granular Tabu Search Heuristic to solve the one-echelon LRP with capacitated routes and depots. Recent studies focuses on solving two-echelon LRP. For example, Hemmelmayr et al. (2012) proposed an adaptive large neighborhood search algorithm to deal with two-echelon LRP in the context of city logistics. Computational experiments showed that this algorithm outperforms the existing methods. Contardo, Hemmelmayr, and Crainic (2012) introduced branch-and-cut algorithm and adaptive large-neighbourhood search to address the two-echelon capacitated LRP. Vienna et al. (2013) applied hybrid genetic algorithm and simulated annealing to solve a two-echelon LRP with vehicle capacity and route length constraints. These two algorithms were evaluated by numerical experiments. Govindan, Jafarian, Khodaverdi, and Devika (2014) developed a multi-objective perishable food supply chain network optimization model for a two-echelon location–routing problem with time-windows. A multi-objective hybrid approach which combines multi-objective particle swarm optimization and adapted multi-objective variable neighbor-hood search was used to solve this model. Winkenbach, Kleindorfer, and Spinler (2015) presented a large-scale static and deterministic model for a two-echelon capacitated LRP. Vidović, Ratković, Bjelić, and Popović (2016) formulated a two-echelon location-routing mathematical model for non-hazardous recyclables collection and proposed heuristics to obtain good solutions in reasonable time. For three-echelon LRP, only a limited number of studies have discussed this problem. For example, Wu, Nie, and Xu (2017) investigated a three-echelon LRP with time windows and time budget constraints and solved it using hybrid cross entropy algorithm. The above literature focused on solving LRPs by different methods. In this paper, besides one-echelon LRP and two-echelon LRP, three-echelon LRP and four-echelon LRPs with tour length constraints and capacity constraints of facilities and vehicles are developed and solved by two-phase method.

2.1.3. Multi-echelon problem in supply chains

Some researchers studied the multi-echelon routing problem in supply chains. For example, Shen and Honda (2009) developed a routing and replenishment plan taking into consideration lateral transfers for a three-echelon supply chain system, which includes one plant, distribution centers and retailers. Dondo et al. (2011) presented an N-echelon routing problem with cross-docking in supply chain management. The purpose of this study was to satisfy customer demands with the minimum cost. Ahmadizar et al. (2015) presented a two-lay routing problem with cross-docking in a three-echelon supply chain and solved it using a genetic algorithm to minimize the sum of the transportation, holding, and purchasing cost. In recent years, some scholars have begun to study the multi-echelon LRP in supply chains. For instance, Mousavi and Tavakkoli-Moghaddam (2013) proposed location and routing scheduling problems with cross-docking in the supply chain and settle these problems using a two-stage hybrid simulated annealing. Small-scale and large-scale problems are tested to validate this algorithm. Govindan et al. (2014) presented a two-layer location–routing problem for perishable food in multi-echelon supply chain network to optimize the transportation quantity of products at each echelon by multi-objective hybrid method.

Furthermore, some researchers extended multi-echelon problem to maintenance management and spare parts supply. For example, Ruan et al. (2012) established availability models for multi-echelon maintenance supply according to multi-echelon technique for recoverable item control theory and the characteristics of cannibalization. The results of the proposed model were verified by VMETRIC simulation. Duran and Perez (2014) presented and solved multi-echelon of repairable spare parts supply problem by employing Particle Swarm Optimization with local search procedures. Patriarca et al. (2016a) considered maintenance time and different skills in a multi-echelon single-indenture system with unidirectional lateral transshipment based on METRIC. A case study of a European airline showed the relevance and reproducibility of this system under different industrial contexts. Patriarca et al. (2016b) modeled a multi-echelon, multi-item, single-indenture, multi-transportation network in the context of airline company to minimize the spare parts supply cost by an innovative two-steps algorithm. Zhou, Peng, Li, and Ruan (2017) developed a model for maintenance and transportation supply of spare parts on the basis of the extended theory of multi-echelon technique for recoverable item control of repairable spare parts. The results of the case study showed that the model is an effective decision-making tool for decision makers. The above researchers studied the multi-echelon problem in supply chains. However, literature on multi-echelon LRP in supply chains is limited, especially three-echelon and four-echelon LRPs. In this paper, we establish and solve multi-echelon LRPs in supply chains.

2.2. Literature review on solution methods

2.2.1. Exact solution methods for LP, RP, or, LRP

The first exact algorithm for LRP was proposed by Laporte and Nobert (1981). This study used a branch-and-bound algorithm to minimize the operating and routing costs in depot location. Laporte, Nobert, and Arpin (1986) applied a branching procedure to solve a capacitated LRP that introduce chain barring and sub-tour elimination constraints. Averbakh and Berman (1994) used polynomial-time algorithms to find the home base of one or several delivery or sales-delivery men. Averbakh and Berman (2002) employed graph theoretical to solve min-max p-travelling salesmen location problem by minimizing the length of vehicle tour. Labbé, Rodríguezmartin, and Salazargonzález (2004) put forward a branch-and-cut algorithm to settle plant-cycle location problem with a number of valid constraints. Al-E-Hashem and Rekik (2014) established a multi-product inventory routing model considering greenhouse gas emission level and transportation cost. CPLEX was used to solve this model to show the validity of this model. Exact solution methods can solve LP, RP, or, LRP. However, these methods can only tackle small instances or successfully solve special cases of LRP due to the complexity of problems. For large-scale instances or general LP, RP, or LRP, heuristic solution methods are better alternatives.

2.2.2. Heuristic solution methods for LP, RP, or LRP

Barreto, Ferreira, Paixào, and Sousa Santos (2007) used clustering analysis for a capacitated LRP. Albareda-Sambola, DıÁz, and Fernández (2005) dealt with LRP by employing a new algorithm that includes diversification and intensification phases and is in a tabu search structure. Zarandi, Hemmati, and Davari (2011) proposed a simulation-embedded Simulated Annealing procedure to solve Capacitated LRP and justified this method using a standard test instance. Derbel, Jarboui, Hanafi, and Chabchoub (2012) presented a genetic algorithm with an iterative local search to determine the location and routing simultaneously. Computational experiments show that this method is more efficient than tabu search heuristic. Zhang, Qi, Lin, and Miao (2015) designed a metaheuristic algorithm in the basis of simulated annealing, a maximum-likelihood sampling method, two-stage neighborhood search, and route- reallocation improvement to settle a reliable capacitated LRP. Numerical examples demonstrate the applicability of this method. Marinakis (2015) developed a new particle swarm optimization for location routing problem with stochastic demands. This algorithm is tested by three benchmark instance and is compared with classical PSO and some nature inspired algorithms. Torfi, Farahani, and Mahdavi (2016)) put forward a two phase heuristic simulated annealing to solve three-echelon LRP, which is composed of depots, plants, and customers. And this developed method is tested by instances. Koç (2016) used Neighborhood Search metaheuristic for three variants of the Periodic LRP. Numerical examples on benchmark instances demonstrate this proposed algorithm outperforms previous methods. Wu et al. (2017) designed a hybrid cross entropy algorithm (HCEA) is proposed to settle the three-echelon LRP with time budget and windows. Computational experiments demonstrate HCEA is better than exhaustive enumeration algorithm in computational time. A case study verifies the applicability of the proposed algorithm. Though approximate solutions can only be obtained by using heuristic solution methods, these methods can be used to solve large-scale and general problems. Therefore, heuristic solution methods, specially, a two-phase method is used in this paper.

3. Problem formulations

In this section, mathematical formulations for four LRPs are presented. In particular these problems involve three different decisions: (1) location decisions: determining the number and locations of suppliers, plants, distribution centers, and regional centers, (2) allocation decisions: assigning customers to each open regional center, each open regional center to each open distribution center, each open distribution center to each open plant, and each open plant to each open supplier, (3) vehicle size and routing decisions: number of vehicles to use for transportation in each echelon and related routes.

3.1. Assumptions of study

In order to develop the location-routing models, we assume the following:

- Each customer demand is known and deterministic and vehicle capacity constraints are considered.

- Freight cannot be managed by direct shipping from suppliers or plants to customers, but must be handled by regional center or distribution center. In particular: the first echelon routes start from regional center, serve one or more customers and end to the same regional center; the second echelon routes start from a distribution center, serve one or more regional centers and end to the same distribution center; the third echelon routes start from a plant, serve one or more distribution centers and end to the same plant; the fourth echelon routes start from a supplier, serve one or more plants and end to the same supplier.
- The capacities of suppliers, plants, distribution centers, and regional centers are limited. Supplier's capacity is higher than plant's capacity. Plant's capacity is higher than distribution center's capacity. Distribution center's capacity is higher than regional center's capacity. Regional center's capacity is higher than the customer demand. Facilities that belong to the same echelon have different capacities.
- Each plant has to be served by a single supplier and by a single vehicle; each distribution center has to be served by a single plant and by a single vehicle; each regional center has to be served by a single distribution center and by a single vehicle; each customer has to be served by a single regional center and by a single vehicle.
- Vehicles operating in the same echelon have the same capacity value. Capacity of each vehicle for the first echelon is higher than customer demand. Capacity of each vehicle for the second echelon is higher than capacity of each vehicle for the first echelon.
- The tour length constraint of each vehicle for the same echelon is same and twice the maximum distance between nodes of the same echelon. In particular: the tour length constraint of each vehicle for the first echelon is same and twice the maximum distance between regional centers and customers; the tour length constraint of each vehicle for the second echelon is same and twice the maximum distance between distribution centers and regional centers; the tour length constraint of each vehicle for the third echelon is same and twice the maximum distance between plants and distribution centers; the tour length constraint of each vehicle for the fourth echelon is same and twice the maximum distance between suppliers and plants.
- The suppliers supply raw materials, which are processed by the plants and shipped to the distribution centers. Conversion ratio of raw materials to products is one and the products have no loss in transit.

In this paper, four problems are one-echelon LRP, two-echelon LRP, three-echelon LRP, and four-echelon LRP, respectively. These are deterministic problems with capacity and tour length constraints.

3.2. Sets, indices, parameters, and decision variables

3.2.1. Sets

S	set of the possible suppliers
P	set of the possible plants
D	set of the possible distribution centers
R	set of the possible regional centers
C	set of the customers
W	set of vehicles for the first echelon route
V	set of vehicles for the second echelon route
U	set of vehicles for the third echelon route
T	set of vehicles for the fourth echelon route

3.2.2. Indices

s	index for the possible suppliers
p	index for the possible plants
d	index for the possible distribution centers
r	index for the possible regional centers
c	index for the customers
w	index for vehicles of the first echelon route
v	index for vehicles of the second echelon route
u	index for vehicles of the third echelon route
t	index for vehicles of the fourth echelon route

3.2.3. Parameters

K_i	the capacity of facilities, $i \in S \cup P \cup D \cup R$. For supplier $i \in S$; for plant $i \in P$; for distribution center $i \in D$; for regional center $i \in R$.
k_i	the capacity of vehicles, $i \in T \cup U \cup V \cup W$. For the vehicle of the first echelon $i \in W$; for the vehicle of the second echelon $i \in V$; for the vehicle of the third echelon $i \in U$; For the vehicle of the fourth echelon $i \in T$.
F_i	the fixed cost for opening facilities, $i \in S \cup P \cup D \cup R$
f_i	the fixed cost for using vehicles, $i \in T \cup U \cup V \cup W$
d_c	the demand of customers, $c \in C$
Z_{ij}^t	the transportation cost for a vehicle from i to j. $i \in S \cup P$, $j \in S \cup P$
Z_{ij}^u	the transportation cost for a vehicle from i to j. $i \in P \cup D$, $j \in P \cup D$
Z_{ij}^v	the transportation cost for a vehicle from i to j. $i \in D \cup R$, $j \in D \cup R$
Z_{ij}^w	the transportation cost for a vehicle from i to j. $i \in R \cup C$, $j \in R \cup C$
ct_{ij}^w	per-unit transportation cost from i to j by vehicle w in the first echelon route. $i \in R \cup C$, $j \in R \cup C$, $w \in W$.
ct_{ij}^v	per-unit transportation cost from i to j by vehicle v in the second echelon route. $i \in D \cup R$, $j \in D \cup R$, $v \in V$.
ct_{ij}^u	per-unit transportation cost from i to j by vehicle u in the third echelon route. $i \in P \cup D$, $j \in P \cup D$, $u \in U$.
ct_{ij}^t	per-unit transportation cost from i to j by vehicle t in the fourth echelon route. $i \in S \cup P$, $j \in S \cup P$, $t \in T$.
cj_{sp}	per-unit transportation cost from s to p. $s \in S$, $p \in P$
cj_{pd}	per-unit transportation cost from p to d. $p \in P$, $d \in D$
cj_{dr}	per-unit transportation cost from d to r. $d \in D$, $r \in R$
cj_{rc}	per-unit transportation cost from r to c. $r \in R$, $c \in C$
tl_1	the maximum tour length of the fourth echelon
tl_2	the maximum tour length of the third echelon
tl_3	the maximum tour length of the second echelon
tl_4	the maximum tour length of the first echelon
jl_{ij}^t	the distance from i to j. $i \in S \cup P$, $j \in S \cup P$
jl_{ij}^u	the distance from i to j. $i \in P \cup D$, $j \in P \cup D$
jl_{ij}^v	the distance from i to j. $i \in D \cup R$, $j \in D \cup R$
jl_{ij}^w	the distance from i to j. $i \in R \cup C$, $j \in R \cup C$
td_{sp}	the distance from supplier s to plant p.
td_{pd}	the distance from plant p to distribution center d.
td_{dr}	the distance from distribution center d to regional center r.
td_{rc}	the distance from regional center r to customer c.
CF_{sp}	the transportation cost for a vehicle from supplier s to plant p. $s \in S$, $p \in P$
CF_{pd}	the transportation cost for a vehicle from plant $p$to distribution center d. $p \in P$, $d \in D$
CF_{dr}	the transportation cost for a vehicle from distribution center d to regional center r. $d \in D$, $r \in R$
CF_{rc}	the transportation cost for a vehicle from regional center r to customer c. $r \in R$, $c \in C$

3.2.4. Decision variables

d_i	the demand to facilities i, $i \in D \cup R$
y_i	binary variable for opening facility i, take value 1 if a facility is open at node i, 0 otherwise. $i \in S \cup P \cup D \cup R$.
n_{ij}^w	binary variable for vehicle w travel from i to j in the first echelon route, take value 1 if i precedes j in the first echelon route by a vehicle w, take value 0 otherwise. $i \in R \cup C$, $j \in R \cup C$, $w \in W$.

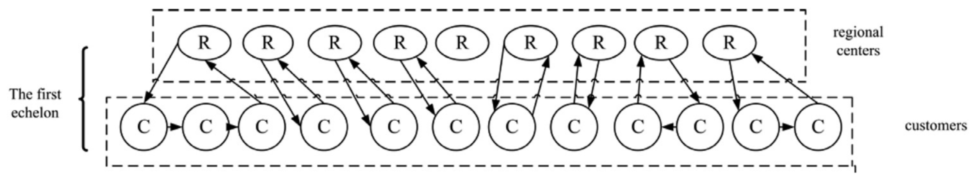

Fig. 1. One-echelon location-routing model.

m_{ij}^{v} binary variable for vehicle v travel from i to j in the second echelon route, take value 1 if i precedes j in the second echelon route by a vehicle v, take value 0 otherwise. $i \in D\cup R$, $j \in D\cup R$, $v \in V$.

h_{ij}^{u} binary variable for vehicle u travel from i to j in the third echelon route, take value 1 if i precedes j in the third echelon route by a vehicle u, take value 0 otherwise. $i \in P\cup D$, $j \in P\cup D$, $u \in U$.

g_{ij}^{t} binary variable for vehicle t travel from i to j in the fourth echelon route, take value 1 if i precedes j in the fourth echelon route by a vehicle t, take value 0 otherwise. $i \in S\cup P$, $j \in S\cup P$, $t \in T$.

L_{sp} binary variable for assigning plant p to supplier s, take value 1 if plant p is assigned to supplier s, take value 0 otherwise. $s \in S$,$p \in P$.

L_{pd} binary variable for assigning distribution center d to plant p, take value 1 if distribution center d is assigned to plant p, take value 0 otherwise. $p \in P$, $d \in D$.

L_{dr} binary variable for assigning regional center r to distribution center d, take value 1 if regional center r is assigned to distribution center d, take value 0 otherwise. $d \in D$, $r \in R$.

L_{rc} binary variable for assigning customer c to regional center r, take value 1 if customer c is assigned to regional center r, take value 0 otherwise. $r \in R$, $c \in C$.

q_i binary variable for used vehicle i in a route, take value 1 if a vehicle i is used in a route, take value 0 otherwise. $i \in T\cup U\cup V\cup W$

o_{sp}^{t} flow from supplier s to plant p by vehicle t. $s \in S$, $p \in P$, $t \in T$

o_{pd}^{u} flow from plant p to distribution center d by vehicle u. $p \in P$, $d \in D$, $u \in U$

o_{dr}^{v} flow from distribution center d to regional center r by vehicle v. $d \in D$, $r \in R$, $v \in V$

o_{rc}^{w} flow from regional center r to customer c by vehicle w. $r \in R$, $c \in C$, $w \in W$

3.3. The formulation of models

3.3.1. The one-echelon location-routing model

The one-echelon location-routing model is composed of retailers and regional centers (see Fig. 1). Demand of each customer is known and deterministic, and must be satisfied by only one regional center and one vehicle. The capacities and the maximum tour lengths of vehicles for the first echelon are predetermined. The routes start from regional center, serve one or more customers and end to the same regional center.

The objective of the one-echelon model is to minimize the total costs of the first echelon. Based on the above description, the one-echelon model can be formulated as follows.

$$\min \sum_{r\in R} F_r y_r + \sum_{w\in W} f_w q_w + \sum_{w\in W}\sum_{i\in R\cup C}\sum_{j\in R\cup C} jl_{ij}^{w} ct_{ij}^{w} n_{ij}^{w} \tag{1}$$

Subject to:

$$\sum_{r\in R} L_{rc} = 1 \forall c \in C \tag{2}$$

$$\sum_{c\in C} L_{rc} d_c \le K_r y_r \forall r \in R \tag{3}$$

$$\sum_{w\in W}\sum_{j\in C\cup R} n_{cj}^{w} = 1 \forall c \in C \tag{4}$$

$$\sum_{l\in C\cup R} n_{lj}^{w} - \sum_{l\in C\cup R} n_{jl}^{w} = 0 \forall j \in C\cup R, \forall w \in W \tag{5}$$

$$\sum_{i\in C'}\sum_{j\in C'} n_{ij}^{w} \le \left|C'\right| - 1 \forall w \in W, C' \subseteq C, \left|C'\right| \ge 2 \tag{6}$$

$$\sum_{i\in R}\sum_{j\in C} n_{ij}^{w} \le 1 \forall w \in W \tag{7}$$

$$\sum_{o\in R\cup C} n_{co}^{w} + \sum_{o\in R\cup C} n_{ro}^{w} - L_{rc} \le 1 \forall r \in R, \forall c \in C, \forall w \in W \tag{8}$$

$$\sum_{c\in C}\sum_{j\in R\cup C} d_c n_{cj}^{w} \le k_w q_w w \in W \tag{9}$$

$$\sum_{i\in C\cup R}\sum_{j\in C\cup R} n_{ij}^{w} jl_{ij}^{w} \le tl_1 w \in W \tag{10}$$

$$y_r \in \{0,1\} \forall r \in R \tag{11}$$

$$n_{ij}^{w} \in \{0,1\} \forall i \in R\cup C, \forall j \in R\cup C, \forall w \in W \tag{12}$$

$$L_{rc} \in \{0,1\} \forall r \in R, \forall c \in C \tag{13}$$

$$q_w \in \{0,1\} \forall w \in W \tag{14}$$

The objective function minimizes the sum of the fixed costs of opening regional centers, the fixed costs of using vehicles for one echelon, and the transportation costs for the first echelon. Constraint (2) imposes that each customer c is assigned by exactly one regional center. Constraint (3) imposes that the total demand of customers cannot exceed the capacity regional center. Constraint (4) imposes that each customer is served by exactly one vehicle. Constraint (5) imposes that a vehicle returns to its regional center of origin. Constraint (6) is sub-tour elimination constraint. Constraint (7) imposes that each vehicle has to be assigned to at most one regional center. Constraint (8) ensures that regional center r serves customer c if there exists one vehicle w leaving r and arriving at c. Constraint (9) imposes that demand satisfied by vehicle has to be less than its own capacity if the vehicle is used. Constraint (10) limits the length of each tour for the first echelon. Constraints (11)-(14) express binary integer constraints and non-negative constraints.

3.3.2. The two-echelon model

The two-echelon location-routing model is composed of retailers, regional centers, and distribution center (see Fig. 2). In addition to the above description on one-echelon model, the routes start from distribution center, serve one or more regional center and end to the same distribution center. Regional center is served by only one distribution center and one vehicle. The capacities and the maximum tour lengths of vehicles for the second echelon are predetermined.

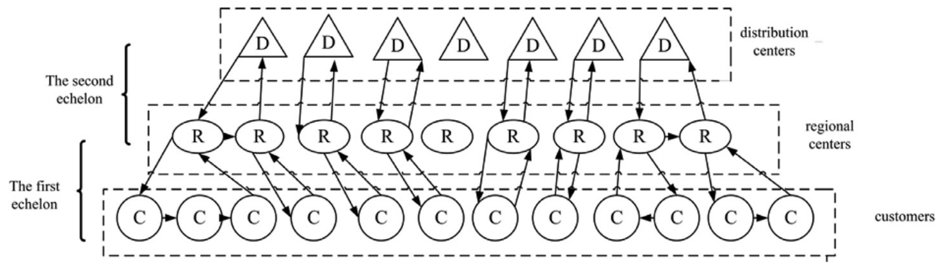

Fig. 2. Two-echelon location-routing model.

The objective of this model is to minimize the total costs of the first and the second echelon. Based on the above description, the two-echelon model can be formulated as follows.

$$\min \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r + \sum_{v\in V} f_v q_v + \sum_{w\in W} f_w q_w + \sum_{v\in V}\sum_{i\in D\cup R}\sum_{j\in D\cup R} jl_{ij}^v ct_{ij}^v m_{ij}^v + \sum_{w\in W}\sum_{i\in R\cup C}\sum_{j\in R\cup C} jl_{ij}^w ct_{ij}^w n_{ij}^w \tag{15}$$

Subject to:
Eq. (2)-(14)

$$\sum_{d\in D} L_{dr} = y_r \forall \mathrm{r} \in R \tag{16}$$

$$\sum_{r\in R} L_{dr} K_r \le K_d y_d \forall \mathrm{d} \in D \tag{17}$$

$$\sum_{l\in D\cup R} m_{lh}^v - \sum_{l\in D\cup R} m_{hl}^v = 0 \forall \mathrm{h} \in \mathrm{D}\cup\mathrm{R}, \forall v \in V \tag{18}$$

$$\sum_{i\in R'}\sum_{j\in R'} m_{ij}^v \le \left|R'\right| - 1 \forall v \in V, \mathrm{R}' \subseteq \mathrm{R}, \left|R'\right| \ge 2 \tag{19}$$

$$\sum_{i\in D}\sum_{j\in R} m_{ij}^v \le 1 \forall v \in V \tag{20}$$

$$\sum_{d\in D}\sum_{v\in V} o_{dr}^v - \sum_{c\in C} d_c L_{rc} = 0 \forall \mathrm{r} \in R \tag{21}$$

$$k_v \sum_{h\in R\cup D} m_{rh}^v - o_{dr}^v \ge 0 \forall v \in V, \forall d \in D, \forall r \in R \tag{22}$$

$$k_v \sum_{h\in R\cup D} m_{dh}^v - o_{dr}^v \ge 0 \forall v \in V, \forall d \in D, \forall r \in R \tag{23}$$

$$\sum_{d\in D}\sum_{r\in R} o_{dr}^v \le k_v q_v \forall \mathrm{v} \in \mathrm{V} \tag{24}$$

$$\sum_{i\in D\cup R}\sum_{j\in D\cup R} m_{ij}^v jl_{ij}^v \le tl_2 \mathrm{v} \in \mathrm{V} \tag{25}$$

$$y_d \in \{0, 1\} \forall d \in D \tag{26}$$

$$m_{ij}^v \in \{0, 1\} \forall i \in D\cup R, \forall j \in D\cup R, \forall v \in V \tag{27}$$

$$L_{dr} \in \{0, 1\} \forall \mathrm{d} \in \mathrm{D}, \forall \mathrm{r} \in R \tag{28}$$

$$q_v \in \{0, 1\} \forall v \in V \tag{29}$$

$$o_{dr}^v \ge 0 \forall d \in D, \forall r \in R, \forall v \in V \tag{30}$$

The objective function minimizes the sum of the fixed costs of opening facilities, the fixed costs of using vehicles for two echelons, and the transportation costs of two echelons. Constraint (16) ensures regional center r must be assigned to distribution center d if the regional center r is opened. Constraint (17) is the capacity limitation of distribution center. Constraint (18) imposes that a vehicle returns to its distribution center of origin. Constraint (19) is sub-tour elimination constraint. Constraint (20) imposes that each vehicle has to be assigned to at most one distribution center. Constraint (21) is flow conservation constraints at regional center. Constraints (22) and (23) guarantee that amount of flow on a vehicle v, from distribution center d to a regional center r is positive if and only if both distribution center and regional center are visited by the same vehicle t. Constraint (24) is the capacity limitation of vehicle. Constraint (25) limits the length of each tour for the second echelon. Constraints (26)-(30) express binary integer constraints and non-negative constraints.

3.3.3. The three-echelon model

The three-echelon location-routing model is composed of retailers, regional centers, distribution center, and plants (see Fig. 3). In addition to the above description on two-echelon model, the routes start from plant, serve one or more distribution center and end to the same plant. Distribution center is served by only one plant and one vehicle. The capacities and the maximum tour lengths of vehicles for the third echelon are predetermined.

The objective of this model is to minimize the total costs of the first, the second, and the third echelon. Based on the above description, the three-echelon model can be formulated as follows.

$$\min \sum_{p\in P} F_p y_p + \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r + \sum_{u\in U} f_u q_u + \sum_{v\in V} f_v q_v + \sum_{w\in W} f_w q_w + \sum_{u\in U}\sum_{i\in P\cup D}\sum_{j\in P\cup D} jl_{ij}^u ct_{ij}^u h_{ij}^u + \sum_{v\in V}\sum_{i\in D\cup R}\sum_{j\in D\cup R} jl_{ij}^v ct_{ij}^v m_{ij}^v + \sum_{w\in W}\sum_{i\in R\cup C}\sum_{j\in R\cup C} jl_{ij}^w ct_{ij}^w n_{ij}^w \tag{31}$$

Subject to:
Eq. (2)-(14) and (16)-(30)

$$\sum_{p\in P} L_{pd} = y_d \forall d \in D \tag{32}$$

$$\sum_{d\in D} L_{pd} K_d \le K_p y_p \forall \mathrm{p} \in P \tag{33}$$

$$d_r = \sum_{c\in C} d_c L_{rc} \forall \mathrm{r} \in \mathrm{R} \tag{34}$$

$$\sum_{l\in D\cup P} h_{la}^u - \sum_{l\in D\cup P} h_{al}^u = 0 \forall a \in \mathrm{D}\cup P, \forall u \in U \tag{35}$$

$$\sum_{i\in D'}\sum_{j\in D'} h_{ij}^u \le \left|D'\right| - 1 \forall u \in U, \mathrm{D}' \subseteq \mathrm{D}, \left|D'\right| \ge 2 \tag{36}$$

$$\sum_{i\in P}\sum_{j\in D} h_{ij}^u \le 1 \forall u \in U \tag{37}$$

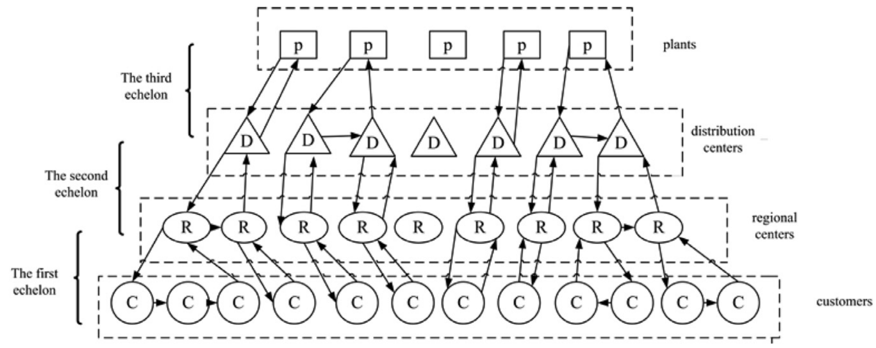

Fig. 3. Three-echelon location-routing model.

$$\sum_{p\in P}\sum_{u\in U} o^u_{pd} - \sum_{r\in R} d_r L_{dr} = 0 \forall d \in D \tag{38}$$

$$k_u \sum_{a\in P\cup D} h^u_{da} - o^u_{pd} \geq 0 \forall u \in U, \forall p \in P, \forall d \in D \tag{39}$$

$$k_u \sum_{a\in P\cup D} h^u_{pa} - o^u_{pd} \geq 0 \forall u \in U, \forall p \in P, \forall d \in D \tag{40}$$

$$\sum_{p\in P}\sum_{d\in D} o^u_{pd} \leq k_u q_u \forall \mathrm{u} \in \mathrm{U} \tag{41}$$

$$\sum_{i\in D\cup P}\sum_{j\in D\cup P} h^u_{ij} jl^u_{ij} \leq tl_3 \mathrm{u} \in \mathrm{U} \tag{42}$$

$$y_p \in \{0,1\} \forall p \in P \tag{43}$$

$$h^u_{ij} \in \{0,1\} \forall i \in D\cup P, \forall j \in D\cup P, \forall u \in U \tag{44}$$

$$L_{pd} \in \{0,1\} \forall \mathrm{p} \in \mathrm{P}, \forall d \in \mathrm{D} \tag{45}$$

$$q_u \in \{0,1\} \forall u \in U \tag{46}$$

$$d_r \geq 0, r \in R \tag{47}$$

$$o^u_{pd} \geq 0 \forall p \in P, \forall d \in D, \forall u \in U \tag{48}$$

The objective function minimizes the sum of the fixed costs of opening facilities, the fixed costs of using vehicles for three echelons, and the transportation costs for three echelons. Constraints (32) and (33) are location and allocation constraints imposing on the third echelon the same conditions that constraints (16) and (17) impose on second echelon. Constraint (34) ensures the demand to each regional center is equal to the sum of customers' demand. Constraints (35)-(42) are vehicle size and routing constraints imposing on the third echelon the same conditions that constraints (18)-(25) impose on second echelon. Constraints (43)-(48) express binary integer constraints and non-negative constraints.

3.3.4. The four-echelon model

The four-echelon location-routing model is composed of retailers, regional centers, distribution centers, and plants (see Fig. 4). In addition to the above description on three-echelon model, the routes start from supplier, serve one or more plant and end to the same supplier. Plant is served by only one supplier and one vehicle. The capacities and the maximum tour lengths of vehicles for the fourth echelon are predetermined.

The objective of this model is to minimize the total costs of the first, the second, the third echelon, and the fourth echelon. Based on the above description, the four-echelon model can be formulated as follows.

$$\begin{aligned}&\sum_{s\in S} F_s y_s + \sum_{p\in P} F_p y_p + \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r \\ &+ \sum_{t\in T} f_t q_t + \sum_{u\in U} f_u q_u + \sum_{v\in V} f_v q_v + \sum_{w\in W} f_w q_w \\ &+ \sum_{t\in T}\sum_{i\in S\cup P}\sum_{j\in S\cup P} jl^t_{ij} ct^t_{ij} g^t_{ij} + \sum_{u\in U}\sum_{i\in P\cup D}\sum_{j\in P\cup D} jl^u_{ij} ct^u_{ij} h^u_{ij} \\ &+ \sum_{v\in V}\sum_{i\in D\cup R}\sum_{j\in D\cup R} jl^v_{ij} ct^v_{ij} m^v_{ij} + \sum_{w\in W}\sum_{i\in R\cup C}\sum_{j\in R\cup C} jl^w_{ij} ct^w_{ij} n^w_{ij}\end{aligned} \tag{49}$$

Subject to:
Eq. (2)–(14), 16)–(30), and (32)–((48)

$$\sum_{s\in S} L_{sp} = y_p \forall p \in P \tag{50}$$

$$\sum_{p\in P} L_{sp} K_p \leq K_s y_s \forall s \in S \tag{51}$$

$$d_d = \sum_{r\in R} d_r L_{dr} \forall \mathrm{d} \in \mathrm{D} \tag{52}$$

$$\sum_{l\in S\cup P} g^t_{la} - \sum_{l\in S\cup P} g^t_{al} = 0 \forall a \in S\cup P, \forall t \in T \tag{53}$$

$$\sum_{i\in P'}\sum_{j\in P'} g^t_{ij} \leq \left|P'\right| - 1 \forall t \in T, \mathrm{P}' \subseteq \mathrm{P}, \left|P'\right| \geq 2 \tag{54}$$

$$\sum_{i\in S}\sum_{j\in P} g^t_{ij} \leq 1 \forall t \in T \tag{55}$$

$$\sum_{s\in S}\sum_{t\in T} o^t_{sp} - \sum_{d\in D} d_d L_{pd} = 0 \forall p \in P \tag{56}$$

$$k_t \sum_{a\in P\cup S} g^t_{sa} - o^t_{sp} \geq 0 \forall t \in T, \forall s \in S, \forall p \in P \tag{57}$$

$$k_t \sum_{a\in P\cup S} g^t_{pa} - o^t_{sp} \geq 0 \forall t \in T, \forall s \in S, \forall p \in P \tag{58}$$

$$\sum_{s\in S}\sum_{p\in P} g^t_{pa} \leq k_t q_t \forall \mathrm{t} \in \mathrm{T} \tag{59}$$

$$\sum_{i\in S\cup P}\sum_{j\in S\cup P} g^t_{ij} jl^t_{ij} \leq tl_4 \mathrm{t} \in \mathrm{T} \tag{60}$$

$$y_s \in \{0,1\} \forall s \in S \tag{61}$$

$$g^t_{ij} \in \{0,1\} \forall i \in S\cup P, \forall j \in S\cup P, \forall t \in T \tag{62}$$

$$L_{sp} \in \{0,1\} \forall \mathrm{s} \in \mathrm{S}, \forall \mathrm{p} \in \mathrm{P} \tag{63}$$

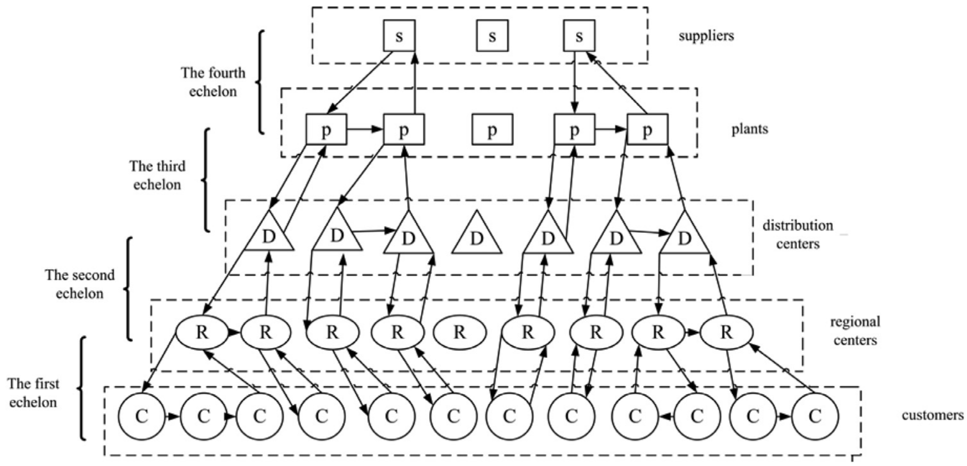

Fig. 4. Four-echelon location-routing model.

$$q_t \in \{0, 1\} \forall t \in T \tag{64}$$

$$d_d \geq 0 d \in D \tag{65}$$

$$o^t_{sp} \geq 0 \forall s \in S, \forall p \in P, \forall t \in T \tag{66}$$

The objective function is the sum of the fixed costs of opening facilities, the fixed costs of using vehicles for four echelons, and the transportation costs of four echelons. Constraints (50) and (51) are location and allocation constraints imposing on the fourth echelon the same conditions that constraints (32) and (33) impose on third echelon. Constraint (52) ensures the demand to each distribution center is equal to the sum of demand to regional centers. Constraints (53)-(60) are vehicle size and routing constraints imposing on the fourth echelon the same conditions that constraints (35)-(42) impose on third echelon. Constraints (61)-(66) express binary integer constraints and non-negative constraints.

4. Two-phase method (TPM)

These LRPs are NP problems. Furthermore, the problems mentioned in Section 3 are more complex than the common LRPs in two aspects. First, capacity and tour length constraints of vehicles are considered. Second, multi-echelon LRPs, i.e., two-echelon, three-echelon and four-echelon problems are considered. Therefore, it is difficult to obtain global optimal solutions for large-scale problems in reasonable time. Thus, the local optimal solutions are accepted when the difference of local and global optimal solutions is not large. In this paper, a two-phase method (TPM) based on improved Clarke Wright savings algorithm is proposed. Compared to other methods, this method has faster speed and is easier to be used and expanded (see Section 5.2.1 for detail).

This method includes two principal phases. The purpose of the first one is to solve location problem. Specially, the number and locations of suppliers, plants, distribution centers, and regional centers is determined. In addition, assign each customer to each open regional center, each open regional center to each open distribution center, each open distribution center to each open plant, and each open plant to each open supplier are also completed in this phase. The second phase aims to solve routing problems. Specially, the size of vehicle and routing decisions are made in this phase. The diagram of two-phase method is presented in Fig. 5. In the following subsection, we illustrate this method with four specific problems.

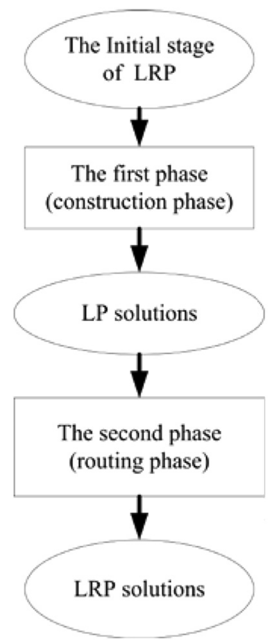

Fig. 5. The diagram of two-phase method.

4.1. A two-phase method for one-echelon location-routing problem

4.1.1. Construction phase

In this phase, we solve the following MILP problem using Cplex 12.6 to determine the construction of one-echelon LRP.

$$\min \sum_{r\in R} F_r y_r + \sum_{r\in R}\sum_{c\in C} t d_{rc} c j_{rc} L_{rc} \tag{67}$$

Subject to:

Eq. (2), (3), (11) and (13)

We can obtain LP solutions, which include location decisions and allocation decisions. These solutions will be used in routing phase.

4.1.2. Routing phase

In this phase, we use improved Clarke Wright saving algorithm to make fleet size and routing decisions based on the results of construction phase. According to Clarke and Wright (1964), the steps of improved Clarke Wright saving algorithm are summarized as follows.

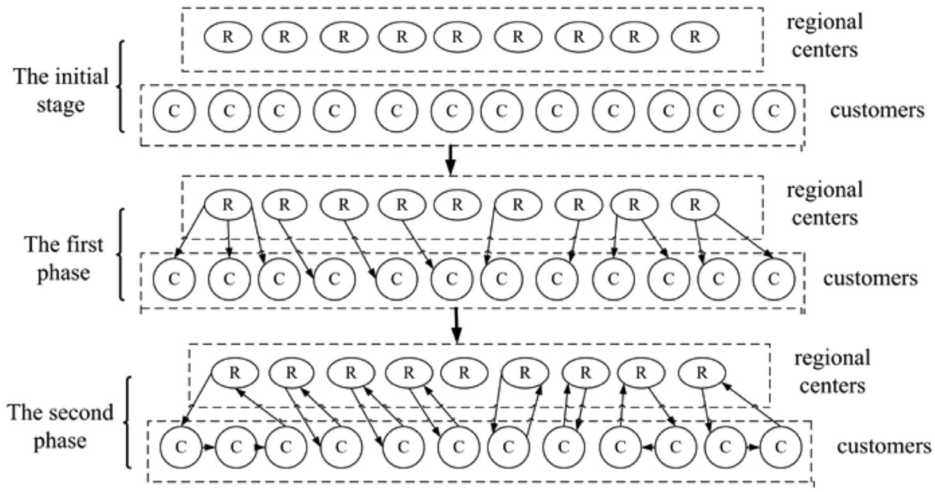

Fig. 6. An illustrative example for one-echelon location-routing problem.

Step 1. Calculate the savings $s(i, j)$. Savings refer to shorten distance after merging two paths into one path. If point r deliver goods to point i and point j using two vehicles, the total distance is $jl1 = 2(jl(r, i) + jl(r, j))$. If point r deliver goods to point i and point j using one vehicle, the total distance is $jl2 = jl(r, i) + jl(r, j) + jl(i, j)$. Thus, $s(i, j) = jl1 - ji2 = jl(r, i) + jl(r, j) - jl(i, j)$, where $jl(r, i)$ is the distance between the point r and point i; $jl(r, j)$ is the distance between the point r and point j;$jl(i, j)$ is the distance from the point i to the point j.

Step 2. Rank the savings $s(i, j)$ in descending order and create the savings list. Process the savings list beginning with the largest $s(i, j)$.

Step 3. For the saving $s(i, j)$ under consideration, include link (i, j) in a route if no route constraints will be violated through the inclusion of (i, j) in a route, and if:

- Case 1: If neither i nor j have already been assigned to a route and constraints of capacity and tour length are not violated, then a new route is initiated including both i and j.
- Case 2: If exactly one of the two points (i or j) has already been included in an existing route and that point is not interior to that route (a point is interior to a route if it is not adjacent to the point r in the order of traversal of points), and constraints of capacity and tour length are not violated, then the link (i,j) is added to that same route.
- Case 3: If both i and j have already been included in two different existing routes and neither point is interior to its route, and constraints of capacity and tour length are not violated, then the two routes are merged by connecting i and j.

Step 4. If the savings list $s(i, j)$ has not been exhausted, return to Step 3, processing the next entry in the list; otherwise, stop. The solution to the VRP (Vehicle Routing Problem) consists of the routes created during Step 3. Any points that have not been assigned to a route during Step 3 must each be served by a vehicle route that begins at the point r, visits the unassigned point, and returns to the point r.

As the classical Clarke Wright saving algorithm is improved by incorporated into constraints of capacity and tour length, we call this algorithm as improved Clarke Wright savings algorithm.

4.1.3. An illustrative example for one-echelon location-routing problems

Fig. 6 presents an illustrative example for one-echelon LRP. The example consists of 12 customers and 9 regional centers. As we can see from Fig. 6, the initial stage shows the geographic distribution of the customers and regional centers. The first phase (i.e., construction phase) represents the solutions to one-echelon location problem. The second phase (i.e., routing phase) shows the solutions to one-echelon LRP.

4.2. A two-phase method for ..two-echelon location-routing problem

For two-echelon LRP, we also use a two-phase method to deal with it. In construction phase, the following location problem is solved to determine the construction of two-echelon LRP.

$$\min \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r + \sum_{d\in D}\sum_{r\in R} td_{dr} cj_{dr} L_{dr} + \sum_{r\in R}\sum_{c\in C} td_{rc} cj_{rc} L_{rc} \tag{68}$$

Subject to:
Eqs. (2), (3), (11), (13), (16), (17), (26), and (28)

LP solutions including location decisions and allocation decisions will be used in routing phase. In routing phase, an improved Clarke Wright saving algorithm mentioned in Section 4.1.2 is employed to determine the fleet size and routing.

An illustrative example for two-echelon LRPs is presented in Fig. 7. The example consists of 12 customers, 9 regional centers, and 7 distribution centers. As shown in Fig. 7, the initial stage shows the geographic distribution of the customers, regional centers, and distribution centers. The first phase (i.e., construction phase) shows the solutions to two-echelon location problem. The second phase (i.e., routing phase) presents the solutions to two-echelon LRP.

4.3. A two-phase method for three-echelon location-routing problem

For three-echelon LRP, we also use a two-phase method to solve it. In construction phase, the following location problem is solved to determine the construction of three-echelon LRP.

$$\min \sum_{p\in P} F_p y_p + \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r + \sum_{p\in P}\sum_{d\in D} td_{pd} cj_{pd} L_{pd} + \sum_{d\in D}\sum_{r\in R} td_{dr} cj_{dr} L_{dr} + \sum_{r\in R}\sum_{c\in C} td_{rc} cj_{rc} L_{rc}$$

Subject to:
Eq. (2), (3), (11), (13), (16), (17), (26), (28), (32), (33), (43), and (45)

In routing phase, an improved Clarke Wright saving algorithm mentioned in subsection 4.1.2 is employed to determine the fleet

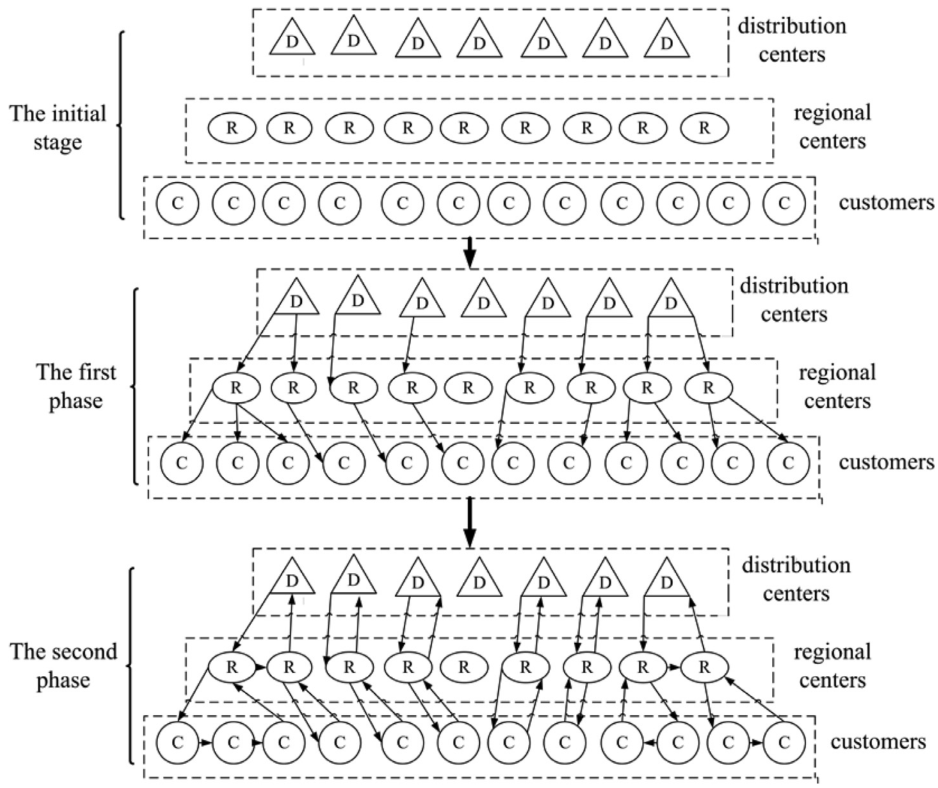

Fig. 7. An illustrative example for two-echelon location-routing problem.

size and routing based on the solutions obtained from construction phase. An illustrative example for three-echelon LRPs is presented in Fig. 8. The example consists of 12 customers, 9 regional centers, 7 distribution centers, and 5 plants.

4.4. A two-phase method for four-echelon location-routing problem

In construction phase, we solve the following location problem to determine the construction of four-echelon LRP.

$$\min \sum_{s\in S} F_s y_s + \sum_{p\in P} F_p y_p + \sum_{d\in D} F_d y_d + \sum_{r\in R} F_r y_r + \sum_{s\in S}\sum_{p\in P} td_{sp} cj_{sp} L_{sp} + \sum_{p\in P}\sum_{d\in D} td_{pd} cj_{pd} L_{pd} + \sum_{d\in D}\sum_{r\in R} td_{dr} cj_{dr} L_{dr} + \sum_{r\in R}\sum_{c\in C} td_{rc} cj_{rc} L_{rc}$$

Subject to:

Eq. (2), (3), (11), (13), (16), (17), (26), (28), (32), (33), (43), (45), (50), (51), (61), and (63)

In routing phase, the fleet size and routing is determined by the improved Clarke Wright saving algorithm. Fig. 9 presents an illustrative example for four-echelon LRP. The example consists of 12 customers, 9 regional centers, 7 distribution centers, 5 plants, and 3 suppliers.

5. Computational experiments

In this section, the data needed in computational experiments are presented. The four LRPs were implemented in Matlab 7.6 and run on a PC with a Pentium (R) Processor (2 GHz) and 2 GB memory.

5.1. Data of computational experiments

For the LRP, there are 200 customers, 10 regional centers, 8 distribution centers, 5 plants, and 3 suppliers. The data on customers and regional centers is taken from Prins et al. (2006a). The difference is that depots are replaced by regional centers. The data is available at http://prodhonc.free.fr/. Table 1 presents the coordinates, capacities, and fixed costs of the distribution centers, plants, and suppliers. These data were generated randomly according to the assumptions of the study. The first two rows are horizontal coordinates and longitudinal coordinates of distribution centers, plants, and suppliers, respectively. The third row is capacity of distribution centers, plants, and suppliers. The fourth row is the fixed cost of distribution centers, plants, and suppliers. Distance between two points is calculated by Euclidean distance. The per-unit transportation costs for the first echelon, the second echelon, the third echelon, and the fourth echelon are 100, 200, 300, and 400, respectively. In other words, $ct^w_{ij} = cj_{rc} = 100$, $ct^v_{ij} = cj_{dr} = 200$, $ct^u_{ij} = cj_{pd} = 300$, $ct^t_{ij} = cj_{sp} = 400$. The transportation costs are truncked to be stored in an integer variable. To ensure that each node has access to the service of vehicle, the maximum tour length for each echelon is twice as much as the maximum distance between facilities of each echelon. The fixed costs for using vehicle of the first, second, third, fourth echelon are 1000, 5000, 7000, and 8000, respectively. The capacities of vehicles are: $k_w \in \{70, 150\}$, $k_v \in \{1785, 1890\}$, $k_u \in \{2300, 3900\}$, $k_t \in \{3500, 5900\}$.

5.2. Computational results

5.2.1. Comparison with other methods

In order to test the performance of two-phase method (TPM), one-echelon and two-echelon LRP derived from Prodhon's CLRP benchmarks are solved using this method. We performed one run for each instance and recorded runtime and total cost. The results are presented in Tables 2 and 3. We also compare this method with GRASP (Prins et al., 2006b), GRASPxLP (Nguyen, Prins, & Prodhon, 2010), MAPM (Prins et al., 2006a), and LRGTS (Prins et al., 2007) for one-echelon LRP and compare this method with GRASPxLP (Nguyen et al., 2010), GRASPxPR (Nguyen et al., 2010), MS-ILS (Nguyen et al., 2010), and MS-ILSxPR

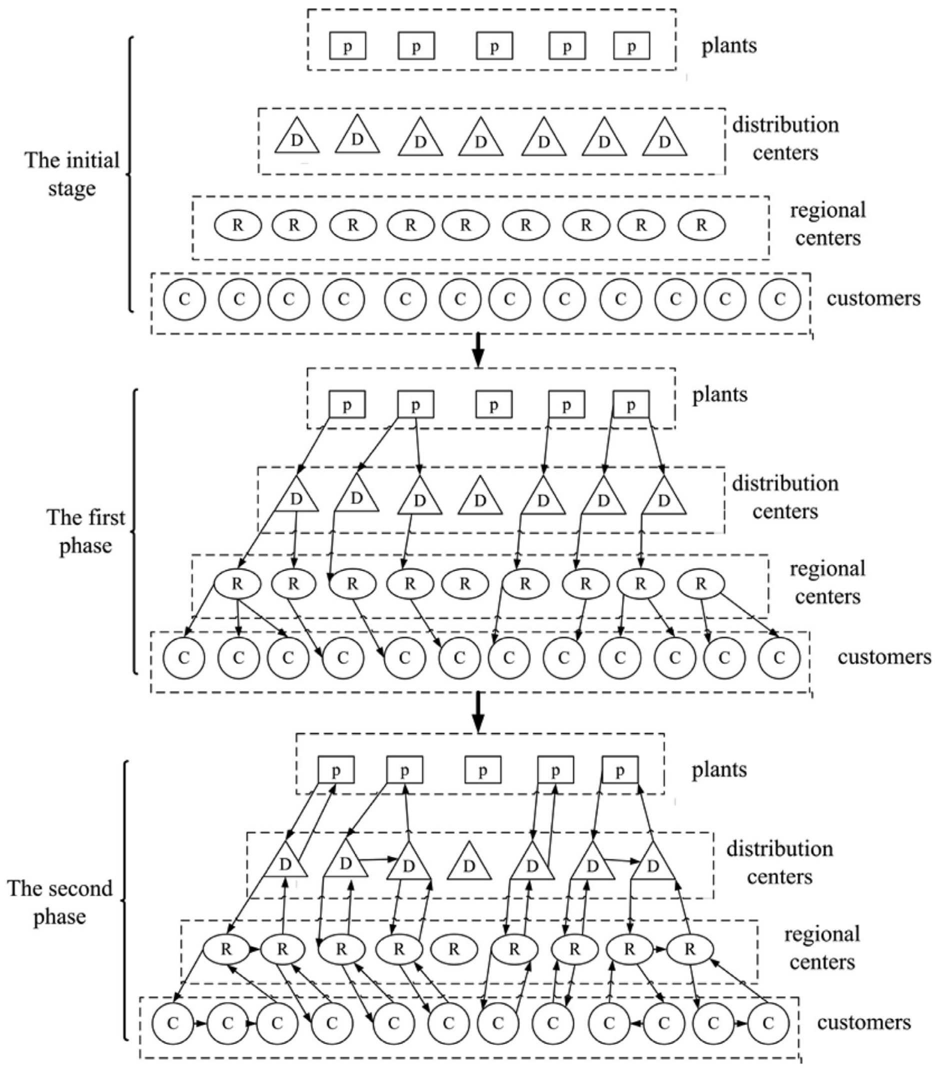

Fig. 8. An illustrative example for three-echelon location-routing problem.

Table 1
Coordinates, capacity, and fixed costs of distribution centers, plants, and suppliers.

	Distribution centers								Plants					Suppliers		
	1	2	3	4	5	6	7	8	1	2	3	4	5	1	2	3
x	0	1	33	58	31	6	13	32	3	10	17	30	6	4	29	8
y	0	53	60	2	22	10	12	5	8	48	43	4	41	46	3	2
K_i	3877	3750	4013	4125	3963	4375	4325	4488	4510	4620	4730	4840	4620	5000	5200	5100
F_i	165,000	175,000	179,000	182,000	176,000	173,000	131,000	151,000	223,000	222,000	216,000	226,000	206,000	332,000	352,000	345,000

(Nguyen et al., 2010) for two-echelon LRP with one distribution center (main depot). For comparison, the maximum tour length is set to infinite. In term of speed, we find TPM is the fastest in all methods for one-echelon LRP as the average CPU time of GRASP, MAPM, LRGTS, and TPM is 234 s, 18.5 s, 173.1 s, 40.6 s, and 5.2 s, respectively. For two-echelon LRP, TPM is also the fastest method since the average CPU time of GRASPxLP, GRASPxPR, MS-ILS, MS-ILSxPR, and TPM is 22.6 s, 40.8 s, 423.5 s, 485.3 s, and 7.54 s, respectively. Furthermore, we find with the increasing size of the problems, the CPU time increases rapidly (for detail, see Table 5 and Table 6 of Nguyen et al., 2010). Thus, if the scale of problem is very large, it is impossible to obtain a feasible solution in reasonable time. The price to pay for shorted CPU time is the reduction in quality of solutions. In term of quality of solutions (i.e. accuracy of solutions), TPM is better than GRASP and GRASPxLP since the average gap/BKS of GRASP, GRASPxLP, and TPM for the one-echelon LRP is 7.03%, 3.66%, and 3.06%, respectively. And TPM is worse than MAPM and LRGTS as the average gap/BKS of MAPM and LRGTS is 2.35%, and 0.69%, respectively. For two-echelon LRP, TPM is the worst in quality of solution since the average gap/BKS of GRASPxLP, GRASPxPR, MS-ILS, MS-ILSxPR, and TPM is 1.16%, 0.56%, 0.12%, 0.008%, and 2.63%, respectively. However, we also find the average gap/BKS obtained by TPM for one-echelon LRP and two-echelon LRP is no more than 3.1%. Therefore, if the requirement on the quality of solution is not very high, this method is acceptable. Besides fastest speed of calculation, another advantage of TPM is easy to use as the results can be obtained only one run and without tuning the parameters of algorithms.

Furthmore, we investigate the impact of vehicles capacities and maximum tour length on the total cost for the one-echelon model.

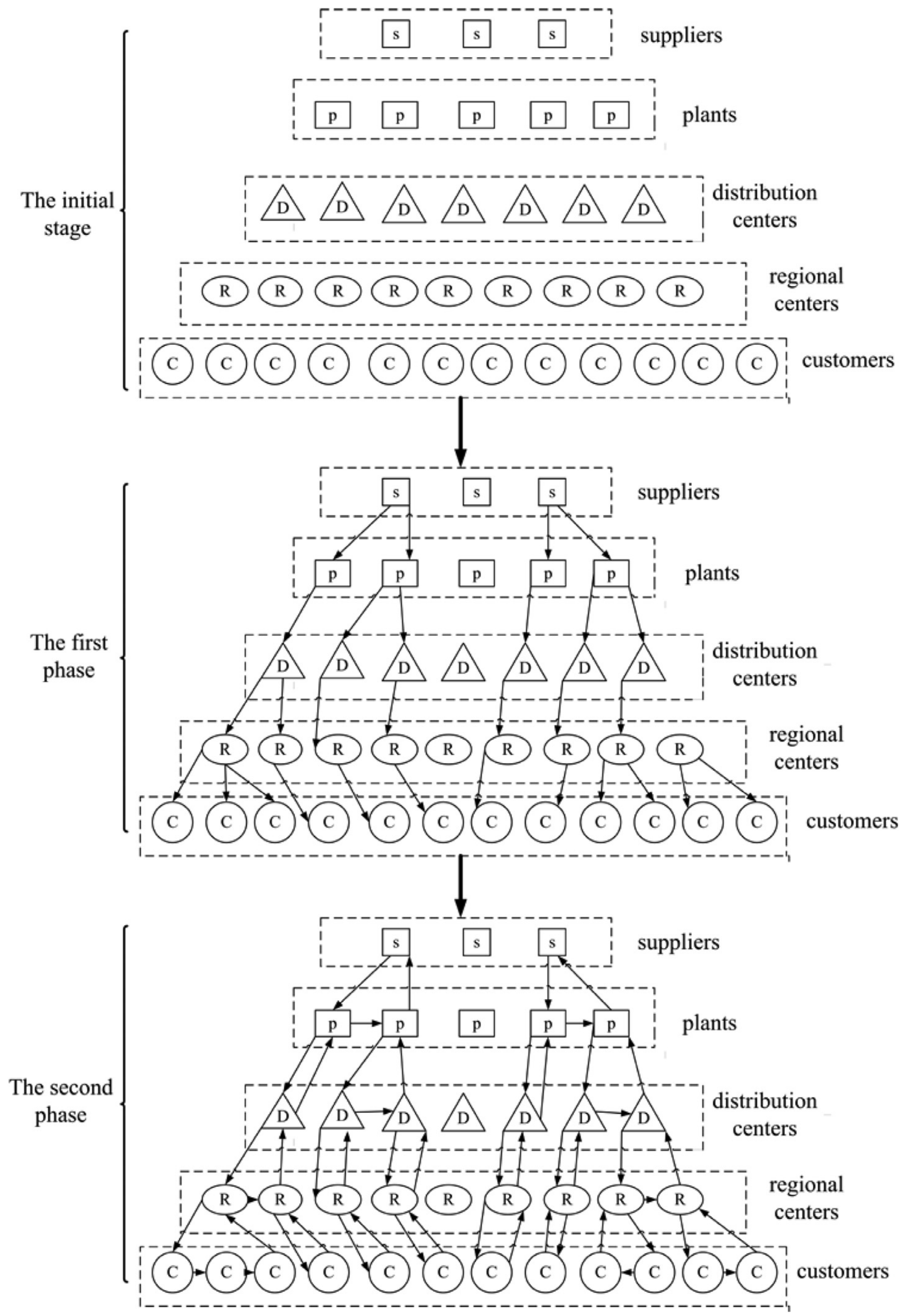

Fig. 9. An illustrative example for four-echelon location-routing problem.

We find when the capacities of vehicles become larger, the total cost become smaller. In other words, the capacities of vehicles have a negative impact on the total cost. For example, for 200-10-1a and 200-10-1b, when the capacities of vehicles for the first echelon increase from 75 to 1500, the total cost decrease from 490,768 to 395,216. The reason for this is that the same demand can be satisfied by a smaller number of vehicles because of the increasing capacities of vehicles. In order to investigate the impact of the maximum tour length on the total cost, we calculate the total cost when the maximum tour length for each echelon is four times as much as the maximum distance between facilities of each echelon. We find the total cost remain unchanged for each instance. It indicates the tour length constraint does not play a role due to the existence of vehicles capacities constraints.

5.2.2. Results for multi-echelon location-routing problems using TPM

In this subsection, we solve the two-echelon with 8 distribution centers, three-echelon, and four echelon LRPs using TPM. The instances are created by extending the data of Prins et al. (2006b). For details, see section 5.1.

5.2.2.1. Results for two-echelon location-routing problem with 8 distribution centers. The results for two-echelon LRP with 8 distribution centers are shown in Table A.1 of Appendix A. 200-10-8-1aa means 200 customers, 10 regional centers, and 8 distribution centers; the vehicle capacity for the first echelon is 75; the vehicle

Table 2
Results for one-echelon location-routing problem derived from Prodhon's CLRP benchmarks.

Instances	BKR	GRASP			GRASPxLP			MAPM			LRGTS			TPM		
		Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)
100-10-1a	290,429	323,171	37.4	11.27	321,700	12.5	10.77	316,575	24.7	9.00	291,887	14.1	0.50	297,072	3.1	2.29
100-10-1b	234,641	271,477	29.5	15.70	271,261	11.0	15.61	270,251	36.0	15.18	235,532	14.0	0.38	246,067	2.6	4.87
100-10-2a	244,265	254,087	39.1	4.02	248,229	11.7	1.62	245,123	24.6	0.35	246,708	14.4	1.00	251,488	2.2	2.96
100-10-2b	203,988	206,555	29.8	1.26	206,888	15.5	1.42	205,052	31.6	0.52	204,435	10.1	0.22	211,743	2.2	3.80
100-10-3a	253,344	270,826	35.4	6.90	258,428	11.2	2.01	253,669	29.0	0.13	258,656	13.3	2.10	256,075	2.8	1.08
100-10-3b	204,597	216,173	39.8	5.66	206,476	11.6	0.92	204,815	36.5	0.11	205,883	10.8	0.63	210,846	3.1	3.05
200-10-1a	479,425	490,820	571.5	2.38	494,615	24.1	3.17	483,497	345.1	0.85	481,676	62.0	0.47	490,768	8.7	2.37
200-10-1b	378,773	416,753	379.1	10.03	385,090	21.9	1.67	380,044	463.0	0.34	380,613	60.3	0.49	395,216	7.2	4.34
200-10-2a	450,468	512,679	554.3	13.81	458,143	27.0	1.70	451,840	280.6	0.30	452,353	60.3	0.64	456,880	7.3	1.42
200-10-2b	374,435	379,980	367.4	1.48	380,255	27.4	1.55	375,019	321.0	0.16	377,351	76.9	0.78	379,929	7.5	1.47
200-10-3a	472,898	496,694	434.8	5.03	485,562	28.7	2.68	478,132	212.9	1.11	476,684	77.2	0.80	484,156	7.1	2.38
200-10-3b	364,178	389,016	290.2	6.82	367,041	19.9	0.79	364,834	272.0	0.18	365,250	73.3	0.29	388,726	8.5	6.74
average			234	7.03		18.5	3.66		173.1	2.35		40.6	0.69		5.2	3.06

Table 3
Results for two-echelon location-routing problem with one distribution (main depot) center derived from Prodhon's CLRP benchmarks.

Instances	BKR	GRASPxLP			GRASPxPR			MS-ILS			MS-ILSxPR			TPM		
		Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)	Total cost	CPU (s)	Gap/BKS (%)
200-10-1a	557,099	570,210	26.5	2.35	561,103	39.7	0.72	559,428	553	0.42	557,099	700.9	0	561,840	8.15	0.85
200-10-1b	452,286	454,181	20.6	0.42	453,286	47.1	0.22	452,731	673	0.1	452,286	723.7	0	466,288	7.51	4.34
200-10-2a	502,333	508,450	22.4	1.22	506,345	41.9	0.8	502,400	211.1	0.01	502,333	220.2	0	505,700	7.52	0.67
200-10-2b	425,311	429,075	21.9	0.88	247,147	37.4	0.43	425,311	248.1	0	425,311	267.3	0	428,749	7.67	0.80
200-10-3a	533,732	541,754	26	1.5	538,821	43.2	0.95	533,732	632.9	0	533,993	676.3	0.05	546,708	7.31	2.38
200-10-3b	419,047	421,585	18.3	0.61	419,984	35.2	0.22	419,790	222.9	0.18	419,047	323.6	0	451,278	7.07	6.74
average			22.6	1.16		40.8	0.56		423.5	0.12		485.3	0.008		7.54	2.63

capacity for the second echelon is 1785. 200-10-8-1bb means 200 customers, 10 regional centers, and 8 distribution centers; the vehicle capacity for the first echelon is 150; the vehicle capacity for the second echelon is 1890. In short, the first a or b indicate the vehicle capacity for the first echelon is 75 or 150, respectively. The second a or b indicate the vehicle capacity for the second echelon is 1785 or 1890, respectively. TC, FCV, FCRC, FCDC represent transportation cost, fixed cost of vehicles, fixed cost of regional centers, fixed cost of distribution centers, respectively. The total cost is the sum of transportation cost, fixed cost of vehicles, and fixed cost of regional centers and distribution centers for the first and second echelon. For instance 200-10-8-1aa, the fixed cost of vehicles for the first and second echelon is 48,000, and 15,000, respectively. It means 48 vehicles and 3 vehicles are used in the first echelon route and the second echelon route, respectively. As the first, second, and fourth regional centers is opened, the fixed cost of regional centers is 266,151. The fixed cost of distribution centers is 131,000 since the seventh distribution center is opened. The total cost can be calculated by the following equation.

$$176{,}617 + 4800 + 266{,}151 + 38{,}566 + 1500 + 131{,}000 = 675{,}334.$$

The other instances are similar to this instance. We examine the impact of vehicles capacities and maximum tour length on the total cost for the two-echelon model. And the same findings and reason as the one-echelon model are obtained. Furthermore, we find the CPU time of all instances is no more than 8.96 s.

5.2.2.2. Results for three-echelon location-routing problem. We also solve the three-echelon LRPs using TPM. The results for three-echelon LRPs are presented in Table A.2 of Appendix A. 200-10-8-5-1aaa means 200 customers, 10 regional centers, 8 distribution centers, and 5 plants; the vehicle capacity for the first echelon is 75; the vehicle capacity for the second echelon is 1785; the vehicle capacity for the third echelon is 2300. 200-10-8-5-1bbb means 200 customers, 10 regional centers, 8 distribution centers, and 5 plants; the vehicle capacity for the first echelon is 150; the vehicle capacity for the second echelon is 1890; the vehicle capacity for the third echelon is 3900. In short, the third a or b indicate the vehicle capacity for the third echelon is 2300 or 3900, respectively. The meaning of FCP is the fixed cost of plants. The total cost is the sum of transportation cost, fixed cost of vehicles, fixed cost of regional centers, distribution centers, and plants for the first, second, and third echelon. For instance 200-10-8-5-1aaa, the fixed cost of vehicles for the third echelon is 7000. It means one vehicle is used in the third echelon route. As the fifth plant is opened, the fixed cost of plant is 206,000. The total cost can be calculated by the following equation.

$$176617 + 4800 + 26\ 6151 + 38566 + 1500 + 131000 + 17900 + 7000 + 206000 = 906234$$

The other instances are similar to this instance. We investigate the impact of vehicles capacities and maximum tour length on the total cost for the three-echelon model. And the same findings and reason as the one-echelon model are obtained. In addition, we can see the CPU time of all instances is no more than 11.52 s.

5.2.2.3. Results for four-echelon location-routing problem. Four-echelon LRPs is solved using TPM. The results for four-echelon LRPs are presented in Table A.3 of Appendix A. 200-10-8-5-3-1aaaa means 200 customers, 10 regional centers, 8 distribution centers, 5 plants, and 3 suppliers; the vehicle capacity for the first echelon is 75; the vehicle capacity for the second echelon is 1785; the vehicle capacity for the third echelon is 2300; the vehicle capacity for the fourth echelon is 3500. 200-10-8-5-3-1bbbb means 200 customers, 10 regional centers, 8 distribution centers, 5 plants, and 3 suppliers; the vehicle capacity for the first echelon is 150; the vehicle capacity for the second echelon is 1890; the vehicle capacity for the third echelon is 3900; the vehicle capacity for the fourth echelon is 5900. In short, the fourth a or b indicate the vehicle capacity for the third echelon is 3500 or 5900, respectively. The meaning of FCS is the fixed cost of suppliers. The total cost is the sum of transportation cost, fixed cost of vehicles, fixed cost of regional centers, distribution centers, plants, and suppliers for the first, second, third, fourth echelon. For instance 200-10-8-5-3-1aaaa, the fixed cost of vehicles for the third echelon is 8000. It means one vehicle are used in the fourth echelon route. Since the first supplier is opened, the fixed cost of suppliers is 332,000. The total cost can be calculated by the following equation.

$176{,}617 + 4800 + 266{,}151 + 38{,}566 + 1500 + 131{,}000 + 17{,}900 + 7000 + 206{,}000 + 4310 + 8000 + 332{,}000 = 1{,}250{,}544$. The other instances are similar to this instance. We also study the impact of vehicles capacities and maximum tour length on the total cost for four-echelon model. And the same findings and reasons as the one-echelon model are obtained. Besides, we can see the CPU time of all instances is no more than 12.22 s.

The above computational experiments prove that TPM can solve the one-echelon, two-echelon, three-echelon, and four-echelon location routing problems. We also see the CPU time does not rapidly increase with the increasing scale of problem since the maximum time is from 8.96 s to 12.22 s. It indicates that even for larger scale problems, TPM can still quickly obtain solutions. In computational experiments, one-echelon LRP, two-echelon LRP, three-echelon LRP, four-echelon LRP are all solved by TPM. It shows that this method is easy to be used and can be extend. We can use this method to solve more echelon LRPs, such as five-echelon, six-echelon LRPs.

5.3. Managerial insights

The managerial implications of the proposed model for the decision makers in supply chains include the following. First, the proposed model is an integration of location and routing problems and it considers the location of facilities, routing structures, and allocation of products for each echelon. This model helps decision makers to minimize the total cost on the premise of satisfying the customers' demand by making decisions in strategic and tactical/operational levels. Second, four mixed integer programming (MIP) models are developed to formulate four LRPs (i.e., one-echelon LRP, two-echelon LRP, three-echelon LRP, and four-echelon LRP). These models help the managers to connect the different echelons of a distribution system and deal with their interdependences in supply chains. Third, decision makers may investigate the impact of different parameters on the distribution system performance. Thus, the decision makers can select the parameters that need to be adjusted according to their preference while keeping the total cost unchanged or reducing the total cost. For example, if decision makers like new vehicles with higher fixed cost and lower per-unit transportation cost and using new vehicles does not lead to the increasing total cost according to computational results of these models, they may replace old vehicles with new vehicles.

The managerial insights of the proposed two-phase method include the following. First, this method can help decision-makers to solve the multi-echelon LRPs that are introduced by city logistics in short time. Most previous studies involve two-echelon LRPs and need a longer computational time to find the best solution. However, the two-phase method can solve three-echelon and four-echelon LRPs in a short period of time. Second, this method is easy to be used without tuning the parameters of the algorithms. The parameters of some heuristic solution methods need to be adjusted and they can impact on the computational results. Thus, these heuristic methods are not easy to be used, especially, for the beginners. Third, the two-phase method can be extended to solve more echelons LRPs, such as five echelon LRP or six echelon LRP. Furthermore, the computational time increases slowly with the increasing the scale of the problem.

6. Conclusions and future research directions

This study proposed four LRPs, i.e., one-echelon, two-echelon, three-echelon, and four-echelon LRPs. The objective is to minimize the total cost for the four problems. The total cost is composed of transportation cost, fixed cost of vehicles, and fixed cost of facilities. Solving these problems has an important significance to decision makers. These problems are NP problem and are difficult to solve by regular method. In order to deal with these four problems, a two-phase method based on improved Clarke Wright saving algorithm is developed. In computational experiments, this method is compared with other methods for one-echelon LRP and two-echelon LRP with one distribution center (main depot). It was found that though the quality of solutions obtained by the proposed method is not high, the computational speed of this method is faster than other methods discussed in the literature. And the computational time increases slowly as the scale of the problem increases. In addition, the proposed method may be used to solve three-echelon, and four-echelon LRPs, which can not be addressed by previous methods. We also believe this method is easy to be used and can be extended to solve more echelon LRPs, such as five-echelon or six-echelon LRPs.

There are some limitations of this research. In term of models, we assumed the demand of customers is deterministic rather than uncertain. Although uncertainty will make the models more complex, uncertain demand is more realistic. Furthermore, in order to validate the proposed method, we assume a facility of this echelon is served by a single facility of upper echelon and by a single vehicle. For example, it was assumed each plant has to be served by a single supplier and by a single vehicle. This assumption may be too strict. In addition, transshipment in the same echelon can be considered since the total cost can be reduced. In term of the method, though two-phase method is faster than most other methods, the quality of solutions obtained by this method is not high and there is room for improvement.

For future research directions, in the aspect of models, some assumptions can be relaxed to extend the application scope of the models. Some factors can also be considered into LRP such as time constraints, uncertain (fuzzy and stochastic) parameters, and inventory. Inventory control which involves the decision on the replenishment cycle and quantity is one of the important operational problems in supply chain management. How to integrate inventory control into location-routing problems is an interesting topic for future research. In addition, a multi-commodity, multi-sourcing, and dynamic (multi-period) LRP with synchronization constraints can be investigated. In term of methodology, some local search algorithms may be integrated into TPM to improve the quality of the solution. Furthermore, developing a new exact method on the basis of branch-and-bound or branch-and-cut for multi-echelon LRPs to shorten the computational tine is a promising research direction.

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Appendix A

Tables A1–A3.

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Table A.1
Results for two-echelon location-routing problem with 8 distribution centers using TPM.

Instance	The first echelon			The second echelon			Total cost	CPU(s)
	TC	FCV	FCRC	TC	FCV	FCDC		
200-10-8-1aa	176,617	48,000	266,151	38,566	15,000	131,000	675,334	8.96
200-10-8-1ba	106,065	23,000	266,151	38,566	15,000	131,000	579,782	7.87
200-10-8-1ab	176,617	48,000	266,151	38,566	15,000	131,000	675,334	8.06
200-10-8-1bb	106,065	23,000	266,151	38,566	15,000	131,000	579,782	7.73
200-10-8-2aa	126,510	50,000	280,370	27,098	15,000	131,000	629,978	8.06
200-10-8-2ba	76,559	23,000	280,370	27,098	15,000	131,000	553,027	8.11
200-10-8-2ab	126,510	50,000	280,370	25,724	10,000	131,000	623,604	7.97
200-10-8-2bb	76,559	23,000	280,370	25,724	10,000	131,000	546,653	8.12
200-10-8-3aa	162,628	49,000	272,528	29,734	15,000	131,000	659,890	7.80
200-10-8-3ba	93,198	23,000	272,528	29,734	15,000	131,000	564,460	6.98
200-10-8-3ab	162,628	49,000	272,528	29,734	15,000	131,000	659,890	7.70
200-10-8-3bb	93,198	23,000	272,528	29,734	15,000	131,000	564,460	6.98

Table A.2
Results for three echelon location-routing problem using TPM.

Instance	The first echelon			The second echelon			The third echelon			Total cost	CPU(s)
	TC	FCV	FCRC	TC	FCV	FCDC	TC	FCV	FCP		
200-10-8-5-1aaa	176617	48000	266151	38566	15000	131000	17900	7000	206000	906234	11.52
200-10-8-5-1baa	106065	23000	266151	38566	15000	131000	17900	7000	206000	810682	9.86
200-10-8-5-1aba	176617	48000	266151	38566	15000	131000	17900	7000	206000	906234	10.50
200-10-8-5-1bba	106065	23000	266151	38566	15000	131000	17900	7000	206000	810682	9.82
200-10-8-5-1aab	176617	48000	266151	38566	15000	131000	17900	7000	206000	906234	10.24
200-10-8-5-1bab	106065	23000	266151	38566	15000	131000	17900	7000	206000	810682	9.68
200-10-8-5-1abb	176617	48000	266151	38566	15000	131000	17900	7000	206000	906234	9.77
200-10-8-5-1bbb	106065	23000	266151	38566	15000	131000	17900	7000	206000	810682	10.02
200-10-8-5-2aaa	126510	50000	280370	27098	15000	131000	17900	7000	206000	860878	10.07
200-10-8-5-2baa	76559	23000	280370	27098	15000	131000	17900	7000	206000	783927	10.04
200-10-8-5-2aba	126510	50000	280370	25724	10000	131000	17900	7000	206000	854504	10.21
200-10-8-5-2bba	76559	23000	280370	25724	10000	131000	17900	7000	206000	777553	10.04
200-10-8-5-2aab	126510	50000	280370	27098	15000	131000	17900	7000	206000	860878	9.77
200-10-8-5-2bab	76559	23000	280370	27098	15000	131000	17900	7000	206000	783927	9.92
200-10-8-5-2abb	126510	50000	280370	25724	10000	131000	17900	7000	206000	854504	9.84
200-10-8-5-2bbb	76559	23000	280370	25724	10000	131000	17900	7000	206000	777553	9.65
200-10-8-5-3aaa	162628	49000	272528	29734	15000	131000	17900	7000	206000	890790	8.77
200-10-8-5-3baa	93198	23000	272528	29734	15000	131000	17900	7000	206000	795360	8.1
200-10-8-5-3aba	162628	49000	272528	29734	15000	131000	17900	7000	206000	890790	8.91
200-10-8-5-3bba	93198	23000	272528	29734	15000	131000	17900	7000	206000	795360	8.23
200-10-8-5-3aab	162628	49000	272528	29734	15000	131000	17900	7000	206000	890790	8.87
200-10-8-5-3bab	93198	23000	272528	29734	15000	131000	17900	7000	206000	795360	8.47
200-10-8-5-3abb	162628	49000	272528	29734	15000	131000	17900	7000	206000	890790	8.81
200-10-8-5-3bbb	93198	23000	272528	29734	15000	131000	17900	7000	206000	795360	7.74

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Table A.3
Results for four echelon location-routing problem using TPM.

Instance	The first echelon			The second echelon			The third echelon			The fourth echelon			Total cost	CPU(S)
	TC	FCV	FCRC	TC	FCV	FCDC	TC	FCV	FCP	TC	FCV	FCS		
200-10-8-5-3-1aaaa	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.64
200-10-8-5-3-1baaa	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.71
200-10-8-5-3-1abaa	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.93
200-10-8-5-3-1bbaa	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.26
200-10-8-5-3-1aaba	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.68
200-10-8-5-3-1baba	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.55
200-10-8-5-3-1abba	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.31
200-10-8-5-3-1bbba	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.07
200-10-8-5-3-1aaab	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.32
200-10-8-5-3-1baab	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.07
200-10-8-5-3-1abab	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.24
200-10-8-5-3-1bbab	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.10
200-10-8-5-3-1aabb	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.21
200-10-8-5-3-1babb	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.06
200-10-8-5-3-1abbb	176617	48000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1250544	11.27
200-10-8-5-3-bbbb	106065	23000	266151	38566	15000	131000	17900	7000	206000	4310	8000	332000	1154992	11.07
200-10-8-5-3-2aaaa	126510	50000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1205188	11.17
200-10-8-5-3-2baaa	76559	23000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1128237	11.65
200-10-8-5-3-2abaa	126510	50000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1198814	11.22
200-10-8-5-3-2bbaa	76559	23000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1121863	11.71
200-10-8-5-3-2aaba	126510	50000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1205188	11.28
200-10-8-5-3-2baba	76559	23000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1128237	11.7
200-10-8-5-3-2abba	126510	50000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1198814	11.19
200-10-8-5-3-2bbba	76559	23000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1121863	11.65
200-10-8-5-3-2aaab	126510	50000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1205188	11.18
200-10-8-5-3-2baab	76559	23000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1128237	11.67
200-10-8-5-3-2abab	126510	50000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1198814	11.21
200-10-8-5-3-2bbab	76559	23000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1121863	11.76
200-10-8-5-3-2aabb	126510	50000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1205188	11.16
200-10-8-5-3-2babb	76559	23000	280370	27098	15000	131000	17900	7000	206000	4310	8000	332000	1128237	11.71
200-10-8-5-3-2abbb	126510	50000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1198814	11.28
200-10-8-5-3-2bbbb	76559	23000	280370	25724	10000	131000	17900	7000	206000	4310	8000	332000	1121863	11.81
200-10-8-5-3-3aaaa	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.89
200-10-8-5-3-3baaa	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.15
200-10-8-5-3-3abaa	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.37
200-10-8-5-3-3bbaa	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.17
200-10-8-5-3-3aaba	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.88
200-10-8-5-3-3baba	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.17
200-10-8-5-3-3abba	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.16
200-10-8-5-3-3bbba	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.33
200-10-8-5-3-3aaab	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	12.22
200-10-8-5-3-3baab	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11
200-10-8-5-3-3abab	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.78
200-10-8-5-3-3bbab	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.51
200-10-8-5-3-3aabb	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.68
200-10-8-5-3-3babb	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.36
200-10-8-5-3-3abbb	162609	49000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1235081	11.31
200-10-8-5-3-3bbbb	94015	23000	272528	29734	15000	131000	17900	7000	206000	4310	8000	332000	1140487	11.31

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