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Research Article

A Location-Inventory-Routing Problem in Forward and Reverse Logistics Network Design

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We study a new problem of location-inventory-routing in forward and reverse logistic (LIRP-FRL) network design, which simultaneously integrates the location decisions of distribution centers (DCs), the inventory policies of opened DCs, and the vehicle routing decision in serving customers, in which new goods are produced and damaged goods are repaired by a manufacturer and then returned to the market to satisfy customers' demands as new ones. Our objective is to minimize the total costs of manufacturing and remanufacturing goods, building DCs, shipping goods (new or recovered) between the manufacturer and opened DCs, and distributing new or recovered goods to customers and ordering and storage costs of goods. A nonlinear integer programming model is proposed to formulate the LIRP-FRL. A new tabu search (NTS) algorithm is developed to achieve near optimal solution of the problem. Numerical experiments on the benchmark instances of a simplified version of the LIRP-FRL, the capacitated location routing problem, and the randomly generated LIRP-FRL instances demonstrate the effectiveness and efficiency of the proposed NTS algorithm in problem resolution.

1. Introduction

The need for designing distribution network to achieve a variety of the supply chain objects with the overall productivity has received considerable attentions and becomes more and more stronger in recent years. As Javid and Azad [1] said, location allocation problem, inventory control problem, and the vehicle routing problem are the most considered subproblems in designing a distribution network. Liu and Lee [2] showed that the routing and inventory decisions affect the location decision. Also, Viswanathan and Mathur [3] found that transportation costs will increase when the order quantity during each production runs decreases. Similar conclusions have also been found by Zhang et al. [4]; they pointed out that the above three subproblems are strongly correlated and mutually affect each other. Considering the three subproblems at the same time may provide a comprehensive estimation in constructing an efficient production-distribution network. This gives rise to the researches on the location-inventory-routing problem (LIRP).

Differing in inventory policies used, the types of facilities located, and the vehicle routing strategies adopted, lots of researches on LIRP in forward logistics network design have been reported. Liu and Lee [2] studied a LIRP using order up to level inventory policy. A route-first and location-allocation second heuristic method was proposed by them to solve LIRP. Ambrosino and Scutella [5] studied a LIRP with the consideration of customers service level. Using (Q, R) inventory policy, Shen and Qi [6] proposed a Lagrangian relaxation and a rank and search algorithm to solve the LIRP. Following the researches of [6], Javid and Azad [1] solved the same problem by using a tabu search and simulated annealing. Guerrero et al. [7] proposed a column generation, Lagrangian relaxation, and local search combined heuristic for a multiperiod LIRP.

As Ravi et al. [8] said, the forces of economic factors, legislation, corporate citizenship, and environmental protection problems are driving the increasing interests and investments of enterprises in reverse logistics. These motivate researchers to develop optimization models for reverse supply network design in the past decades (Vahdani and Naderi-Beni [9]).

Chen et al. [10] concluded that the consideration of reverse logistics in distribution network design can greatly reduce the logistics costs without interrupting the forward flows. Taking both the forward logistics and reverse logistics into account, many researches on facility location, vehicle routing, and inventory management had been presented.

Vahdani et al. [11] focused on a fuzzy facility location-allocation problem in closed loop logistics. Differing from [11], Vahdani et al. [12, 13] proposed a fuzzy possibility programming method to solve multiobjective facility problems in forward and reverse logistic.

Under the background of forward and reverse logistic, different inventory models had also been developed in the literature. Richter [14] proposed the first inventory model in a closed logistic using EOQ model. It assumed that customers' demands can be satisfied by newly made products or by repaired products. For a given fixed waste disposal rate, the optimal minimum cost expression was derived. Shi et al. [15] considered an inventory policy under uncertain customer demand. A Lagrangian relaxation based approach was proposed.

Vehicle routing decision is another important research subject in forward and reverse logistic management. Zachariadis and Kiranoudis [16] studied a VRP problem under the background of forward and reverse logistic. A tabu search method was proposed. For a similar VRP problem, Goksal et al. [17] developed a particle swarm optimization (PSO) based approach for its resolution, in which a variable neighborhood descent (VND) algorithm was used as a local search to explore solution space.

Different combination of facility location decision, inventory management decision, and vehicle routing decision gives rise to different research problems in forward and reverse logistics. For example, Liu et al. [18] proposed a hybrid particle swarm optimization to solve a location routing problem using grey systems theory in reverse logistics. Yu and Lin [19] presented a location routing problem with simultaneous pickup and delivery, which was solved via a multistart simulated annealing algorithm with multistart hill climbing. Modeling the problem as a bilevel programming problem, Wang et al. [20] studied realistic location-inventory problem in reverse logistic of a China B2C company. Li et al. [21] solved a location and inventory control problem by a two-stage heuristic algorithm that combined Lagrangian relaxation method with an ant colony algorithm.

Due to the intrinsic complexity of the problem in mathematics, to our best knowledge, only a few researches, except that of Li et al. [22], simultaneously considered the decisions of the facility location, the inventory management, and vehicle routing in forward and reverse logistics in the literature. In their model, they consider retrieving those products that customers dislike to the DCs. As these products are new or unused, they can be sold to customers directly with no need to be returned to manufacturer for repair.

However, as the work of Adler et al. [23] indicated, used (old or damaged) products (e.g., the engines of Caterpillar Company) can also be retrieved, recovered, and returned to the market to satisfy customers' demands as new ones. This realistic new feature motivates us to focus on goods production, distribution, and recycling.

A location-inventory-routing problem in forward and reverse logistic (LIRP-FRL) network design is studied in this paper. The LIRP-FRL simultaneously integrates the location decisions of distribution centers (DCs), the inventory policies of opened DCs, and the vehicle routing decision in serving customers, in which new goods are produced and damaged goods are repaired by a manufacturer and then transported to opened DCs. Vehicles that start from and end in the same DC distribute new or recovered goods to satisfy the demands of customers and retrieve damaged goods. Our objective is to minimize the total costs of manufacturing and remanufacturing goods, building DCs, shipping goods (new or recovered) between the manufacturer and opened DCs, distributing new or recovered goods to customers, and retrieving damaged goods from customers to DCs and the inventory costs of DCs including ordering new or recovered goods and holding these goods.

Without taking the inventory strategy of DCs into account, our problem is simplified to the classical *capacitated location routing problem* (CLRP) [24], which is NP-hard in strong sense. Consequently, our problem is also NP-hard. Further, the LIRP-FRL is a nonlinear problem as the EOQ inventory policy is adopted. Due to its complexity, we focus on finding near optimal solutions for the LIRP-FRL. A new tabu search (NTS) algorithm is proposed to find approximately optimal solutions. This algorithm probabilistically accepts a second best solution to change search direction to achieve this goal. Numerical experiments of the CLRP benchmarks demonstrate the effectiveness and the efficiency of the proposed NTS method in obtaining high quality solutions in a very reasonable time. Computational and sensitivity analysis results on randomly generated LIRP-FRL instances are also reported.

The rest of this paper is organized as follows. In Section 2, a mathematical model is developed to describe the studied LIRP-FRL. A tabu search that seeks to search near optimal solution for the LIRP-FRL is proposed in Section 3. Algorithm performance evaluations are conducted in Section 4. Finally, we conclude the paper in Section 5.

2. Mathematical Model

Given a set of potential sites of distribution centers (DCs), the studied location-inventory-routing problem in forward and reverse logistic (LIRP-FRL) network design is to optimally determine the locations of DCs and their order quantities from a manufacturer, the product flows (forward and reverse) between the manufacturer and the opened DCs, and the paths of vehicles in serving customers. We assume that each route starts from and ends in the same DC, by which new or recovered products are delivered to satisfy the demands of customers for each cycle, and damaged products are retrieved. The objective of the LIRP-FRL is to minimize the sum of the opening costs and the inventory costs of DCs, the setup costs of vehicles, and the transportation costs of (new, repaired, and damaged) products. An example of the studied LIRP-FRL is illustrated in Figure 1.

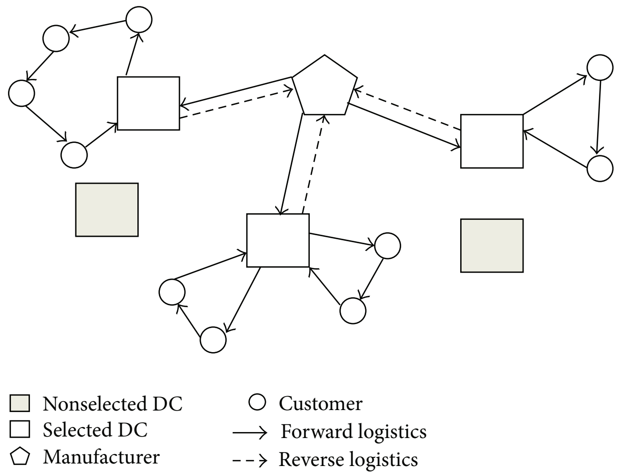

Figure 1: Location-inventory-routing problem in forward and reverse logistic.

2.1. Notations. The notations are described as follows:

I: the index set of customers,

J: the index set of potential distribution centers,

K: the index set of vehicles,

S: the merged set of customers and potential distribution centers ($I \cup J$),

V_j: the maximum capacity of the distribution center j, $j \in J$,

FC_j: the fixed opening cost of establishing distribution center j, $j \in J$,

Q: the maximum capacity of homogeneous vehicle,

c_{ij}: the transportation cost of a vehicle on arc(i, j), i, $j \in S$, $i \neq j$,

f_j: the setup cost of using a vehicle at distribution center j, $j \in J$,

c^j: the product unit transportation cost from the manufacturer to distribution center j, $j \in J$,

A^m: the order cost of new products of DCs per cycle,

A^r: the order cost of recovered or repaired products of DCs per cycle,

c^m: the cost of manufacturing a new product,

c^r: the cost of repairing a damaged product to a new product,

D_i: the demand of customers per cycle,

h_j: the unit holding cost of distribution center j, $j \in J$,

r: the rate of return in percentage,

c^d: the unit cost of disposal of useless retrieved products,

u: the percentage of reuse of retrieved products.

2.2. Decision Variables. The decision variables are described as follows:

Q_j^m is the order quantity of new products of DC $j \in J$ for each period,

Q_j^r is the order quantity of recovered products of DC $j \in J$ for each period,

M_j is the order times of new products from DC $j \in J$ during each period,

R_j is the order times of recovered products from DC $j \in J$ during each period,

$x_{ijk} = \{1$, if arc(i, j) is travelled by vehicle k; 0, otherwise$\}$ $(i, j \in S, k \in K)$,

$y_{ij} = \{1$, if customer $i \in I$ is served by distribution center $j \in J$; 0, otherwise$\}$,

$Z_j = \{1$, if distribution center $j \in J$ is established; 0, otherwise$\}$.

2.3. Cost Analysis. To simplify the presentation, we first abbreviate the costs related to the LIRP-FRL as follows:

(1) The total fixed cost of opening distribution centers is

$$\mathrm{FIXCOST} = \sum_{j \in J} \mathrm{FC}_j \cdot z_j. \tag{1}$$

(2) The total cost of ordering new and recovered products is

$$\mathrm{OC} = \sum_{j \in J} A^m \cdot \frac{\sum_{i \in I} D_i (1-u) y_{ij}}{Q_j^m} + A^r \cdot \frac{\sum_{i \in I} D_i u y_{ij}}{Q_j^r}. \tag{2}$$

(3) The total cost of producing new products and recovering retrieved products is

$$\mathrm{MR} = \sum_{j \in J} \sum_{i \in I} D_i \cdot \left((1-u) \cdot c^m + u \cdot c^r\right) \cdot y_{ij}. \tag{3}$$

(4) The total cost of disposal of useless retrieved products is

$$\mathrm{DISP} = \sum_{j \in J} \sum_{i \in I} D_i \cdot (r-u) \cdot c^d \cdot y_{ij}. \tag{4}$$

(5) The transportation cost between the manufacturer and distribution centers is

$$\mathrm{TRAN} = \sum_{j \in J} c^j \sum_{i \in I} D_i \cdot (1+u) \cdot y_{ij}. \tag{5}$$

(6) The transportation cost between distribution centers and customers is

$$\mathrm{TRC} = \sum_{k \in K} \sum_{j \in S} \sum_{i \in S} f_j \cdot x_{ijk} + \sum_{k \in K} \sum_{j \in S} \sum_{i \in I} c_{ij} \cdot x_{ijk}. \tag{6}$$

Given the locations of DCs and the routes of vehicles, the LIRP-FRL is reduced to the inventory model of Teunter [25]. Some of their valuable conclusions can be directly applied to our LIRP-FRL.

Proposition 1 (Teunter [25]). *"It is reasonable to restrict our attention to those policies with either $M = 1$ or $R = 1$."*

Teunter [25] concluded that the policies with either $M = 1$ or $R = 1$ can obtain near optimal solution with less computational time by comparing with that of achieving optimal solution. Since our problem is more complicated than that of Teunter [25], to simplify the resolution of LIRP-FRL, we consider only the two cases in our implementation. The two cases are as follows.

Case 1 $(1, M)$. That means $R = 1$; in this case the order times of recovered products for each DC are equal to one.

Case 2 $(R, 1)$. That means $M = 1$; in this case the order times of new products for each DC are equal to one.

For Case 1 $(1, M)$, the holding cost is

$$\mathrm{HM} = \sum_{j\in J} \frac{1}{2} h_j \left((1-u)\cdot Q_j^m + u\cdot Q_j^r + Q_j^r \cdot \frac{u}{r} \right)\cdot z_j. \quad (7)$$

Consequently, the total cost is denoted as

$$\begin{aligned}\mathrm{TCM} = {} & \mathrm{FIXCOST} + \mathrm{OC} + \mathrm{MR} + \mathrm{DISP} + \mathrm{TRAN} \\ & + \mathrm{TRC} + \mathrm{HM}.\end{aligned} \quad (8)$$

For Case 2 $(R, 1)$, the holding cost is

$$\begin{aligned}\mathrm{HR} = {} & \sum_{j\in J} \frac{1}{2} h_j \left((1-u)\cdot Q_j^m + u\cdot Q_j^r \right. \\ & \left. + \left(r\left(Q_j^m + Q_j^r\right) - (r-u)\cdot\left(Q_j^m + \frac{u}{1-u} Q_j^m\right)\right)\frac{u}{r}\right) \\ & \cdot z_j.\end{aligned} \quad (9)$$

The corresponding total cost is

$$\begin{aligned}\mathrm{TCR} = {} & \mathrm{FIXCOST} + \mathrm{OC} + \mathrm{MR} + \mathrm{DISP} + \mathrm{TRAN} \\ & + \mathrm{TRC} + \mathrm{HR}.\end{aligned} \quad (10)$$

2.4. Mathematical Model. The LIRP-FRL can be formulated as the following nonlinear mixed integer programming problem:

$$\min \quad \{\mathrm{TCM}, \mathrm{TCR}\}, \quad (11)$$

$$\text{s.t.} \quad \sum_{k\in K}\sum_{i\in S} x_{ijk} = 1, \quad j \in I \quad (12)$$

$$\sum_{j\in S} x_{ijk} - \sum_{j\in S} x_{jik} = 0, \quad i \in S,\ k \in K \quad (13)$$

$$\sum_{j\in J}\sum_{i\in I} x_{ijk} \le 1, \quad k \in K \quad (14)$$

$$\sum_{j\in J}\sum_{i\in I} D_i x_{ijk} \le Q, \quad k \in K \quad (15)$$

$$\sum_{i\in I} D_i y_{ij} - V_j \cdot z_j \le 0, \quad j \in J \quad (16)$$

$$y_{ij} + 1 \ge \sum_{g\in I} x_{igk} + \sum_{g\in S\setminus\{j\}} x_{gjk}, \quad i \in J,\ j \in I,\ k \in K \quad (17)$$

$$\sum_{j\in W}\sum_{i\in W} x_{ijk} \le |W| - 1, \quad W \subseteq I,\ k \in K \quad (18)$$

$$x_{ijk} \in \{0,1\}, \quad i \in S,\ j \in S,\ k \in K \quad (19)$$

$$y_{ij} \in \{0,1\}, \quad i \in I,\ j \in J \quad (20)$$

$$z_j \in \{0,1\}, \quad j \in J. \quad (21)$$

Constraints (12) state that each customer is exactly served by one vehicle. Constraints (13) are the equilibrium constraints of vehicle routes on nodes. Constraints (14) ensure that each vehicle can be used by at most one DC. Constraints (15) guarantee that the capacity of vehicle cannot be exceeded. Constraints (16) are the capacity constraints of distribution centers. Constraints (17) make sure that a customer can only be served by the vehicle which originates from the DC it is assigned to. Constraints (18) are the subtours elimination constraints of vehicle routes.

Proposition 2. *For any distribution center, $j \in J$, its order quantities Q_j^m and Q_j^r can be represented as a function of customers' demands, respectively.*

We have $Q_j^m = \sqrt{2A^m \sum_{i\in I} D_i \cdot y_{ij}/h_j}$ and $Q_j^r = \sqrt{2A^r \cdot r \cdot \sum_{i\in I} D_i \cdot y_{ij}/(r+1)h_j}$ for any $j \in J$.

Proof. It can be observed that, no matter case $(1, M)$ or case $(R, 1)$, decision variables Q_j^m and Q_j^r appear only in the objective function. For the case $(R, 1)$, the optimal value of Q_j^m and Q_j^r can be obtained by checking the extreme conditions: $\partial\mathrm{TCM}/\partial Q_j^m = 0$ and $\partial\mathrm{TCM}/\partial Q_j^r = 0$.

Since $\partial^2\mathrm{TCM}/\partial(Q_j^m)^2 = (2A^m \cdot (1-u)\sum_{i\in I} D_i \cdot y_{ij})/(Q_j^m)^3 \ge 0$ and $\partial^2\mathrm{TCM}/\partial(Q_j^r)^2 = (2A^r \cdot u \sum_{i\in I} D_i \cdot y_{ij})/(Q_j^r)^3 \ge 0$, consequently the extreme point is a minimum point. We obtain the optimal order quantities $Q_j^m = \sqrt{(2A^m \sum_{i\in I} D_i \cdot (1-u) y_{ij})/h_j(1 - ((r-u)/(1-u))\cdot(u/r))}$ and $Q_j^r = \sqrt{(A^r \cdot \sum_{i\in I} D_i \cdot y_{ij})/h_j}$ and the corresponding order time $R_j = (u \cdot Q_j^m)/(1 - u \cdot Q_j^r)$.

For the same reason, for the case $(1, M)$, we can derive that the order quantities $Q_j^m = \sqrt{(2A^m \sum_{i\in I} D_i \cdot y_{ij})/h_j}$ and $Q_j^r = \sqrt{(2A^r \cdot r \cdot \sum_{i\in I} D_i \cdot y_{ij})/(r+1)h_j}$ and the corresponding order time $M_j = (1 - u \cdot Q_j^r)/(u \cdot Q_j^m)$.

Observe that, without considering the inventory strategy of these two cases, Cases 1 and 2, the LIRP-FRL is reduced to the classical capacitated location routing problem (CLRP), which is NP-hard in the strong sense. As a result, the LIRP-FRL is also NP-hard. As Belenguer et al. [24] reported, to

21	23	19	16	15	14	8	11	6	22	4	1	12	18	20	13	5	7	3	24	25	2	17	9	10

Figure 2: An example of solution representation.

find CLRP optimal solution, even for the median size CLRP instances (with 50 customers and 5 potential distribution centers), significant research efforts need to be expensed. Thus, in this paper, we focus on finding near optimal solutions for the LIRP-FRL. □

3. New Tabu Search

Using tabu list to avoid visited solutions to be revisited, the tabu search proposed by Glover [26] is one of the most effective approaches for solving mixed integer programming problems, which has been successfully applied to a variety of distribution network design problems. For the detailed introduction and application of the tabu search, we refer readers to Glover [27] and Habet [28].

In this section, a tabu search (NTS) algorithm that probabilistically accepts the second best solution in search process when a local optimum is reached is proposed to effectively solve the LIRP-FRL. The key components of the NTS, including a solution representation technique, an initial solution generation method, neighbourhood structures, and the general framework of the new tabu search, are presented in detail as follows.

3.1. Solution Representation. A good solution representation can not only describe the problem solutions clearly but also improve the performance of heuristics adopted. Similar to that of Yu et al. [29], in our implementation, solution $\{x_1, x_2, \ldots, x_n, x_{n+1}, \ldots, x_{n+m}\}$ is represented by a permutation of number $\{1, 2, \ldots, n, n+1, n+2, \ldots, n+m\}$, where $x_j \in \{1, 2, \ldots, n\}$ indexes customer x_j and $x_i \in \{n+1, n+2, \ldots, n+m\}$ denotes potential DC x_i.

An example was given in Figure 2. In this example, the first number is distribution center 21, followed by distribution center 23. Since there are no customers between distribution center 21 and distribution center 23, distribution center 21 is closed. Customers (19, 16, 15, 14, 8, 11, and 6) between distribution center 23 and distribution center 22 are real customers; thus distribution center 23 is opened to service these customers. The first route of distribution center 23 services customers 19, 16, 15, and 14. Because adding customer 8 exceeds the vehicle capacity, the second route services customers 8, 11, and 6. Customer 6 is followed by distribution center 22, so the second route is terminated. For a similar reason as mentioned above, distribution centers 22 and 25 are open with two routes and one route, respectively.

This representation has determined which distribution center is open and the customers on each route. With that decided, we can easily calculate the objective function value, because the inventory cost is related to LRP, which means when LRP is solved the inventory cost can be uniquely determined by Proposition 2. Note that the capacity of distribution center is not taken into consideration. So during the decoding process, a per unit penalty cost M with a big value is added to the objective function value when the total demand serviced by a distribution center exceeds its capacity.

To simplify the presentation of the algorithms proposed in following subsections, we say that an element x_i of the solution is *before* another element x_j or element x_j is *after* element x_i if and only if $i < j$. Further, with the smallest value $|i-j|$, if DC x_i is *before* DC x_j, we say that DC x_i is *nearest before* DC x_j, or DC x_j is *nearest after DC* x_i.

3.2. Constructing Initial Solution. A greedy nearest neighbor method is proposed to construct an initial feasible solution of the LIRP-FRL, which is used as an input for the tabu search. Details of the greedy algorithm are given as follows.

Algorithm 3 (greedy nearest neighbour method).

Step 0. Initialize $\Omega^0 := J$, $\Omega^1 := \varnothing$, $\Phi^0 := I$, and $\Phi^1 := \varnothing$.

Step 1. Assign each customer in Φ^0 to its closest DCs in Ω^0.

Step 2. Open the DC in Ω^0 with the largest number of customers assigned to say DC j^*.

Step 3. Sort the customers of set Φ^0 in nondecreasing order of the distance between it and the DC j^*.

Step 4. With the order, let $\Phi = \{s_1, s_2, \ldots, s_{|\Phi^0|}\}$ be the subset of customers of Φ^0 with the largest $|\Phi|$ and $\sum_{i=1}^{|\Phi|} d_{s_i} \le V_{j^*}$. Renew $\Omega^1 := \Omega^1 \cup \{j^*\}$, $\Omega^0 := J/\Omega^1$, $\Phi^1 := \Phi^1 \cup \Phi$, and $\Phi^0 := I/\Phi^1$.

Step 5. If $\Phi^0 \neq \varnothing$, then return to Step 1; Otherwise, open the DCs in Ω^1 and assign each customer to a DC according to the customer-DC assignments determined in Step 4.

Step 6. For each opened DC, sort the customers assigned to it into sequence by using a nearest neighbor heuristic (refer to Rosenkrantz et al. [30]). Split the sequence into several feasible routes so that vehicle capacity constraints are satisfied.

Step 7. Output feasible solution.

In our implementation of Step 2, if more than one DC has the largest number of customers assigned to, we select the DC with the highest capacity.

3.3. Neighborhoods. Given a solution

$$X = \left(x_1, x_2, \ldots, x_{i-1}, x_i, x_{i+1}, \ldots, x_{j-1}, x_j, x_{j+1}, \ldots, x_n\right), \quad (22)$$

a permutation of $\{1, 2, \ldots, n, n+1, \ldots, n+m\}$, three kinds of neighbourhoods are considered in our tabu search.

3.3.1. Insertion Neighbourhood. The insertion neighborhood is defined as the set of solutions that can be reached by insertion move, which deletes one element of the solution X and then inserts it to another place. For example, delete element x_i and insert it into the jth place; we obtain a new solution:

$$X' = \left(x_1, x_2, \ldots, x_{i-1}, x_{i+1}, \ldots, x_{j-1}, x_j, x_i, x_{j+1}, \ldots, x_n\right). \quad (23)$$

According to the element selected (customer or depot) and the position it is inserted in, there are four cases:

(a) If x_i and x_j are both customers, then customer x_i is reassigned to the DC that customer x_j is assigned to.

(b) If x_i and x_j are both DCs, then reassign the customers previously assigned to the DC nearest before it. Close DC x_j and assign its customers to DC x_i.

(c) If x_i is a customer and x_j is a DC, then customer x_i is reassigned to DC x_j.

(d) If x_i is a DC and x_j is a customer, reassign customers that are nearest after customer x_j to DC x_i. All customers assigned to DC x_i are reassigned to the DC nearest before it.

3.3.2. Swap Neighbourhood. The swap neighbourhood, a set of solutions, contains the solutions that can be reached by performing a swap move, which exchanges the places of two different elements of solution X. For example, exchange element x_i and element x_j of X; the resulting new solution is

$$X' = \left(x_1, x_2, \ldots, x_{i-1}, x_j, x_{i+1}, \ldots, x_{j-1}, x_i, x_{j+1}, \ldots, x_n\right). \quad (24)$$

Similar to the insert move, the swap move has also four cases:

(e) If x_i and x_j are both customers, then we exchange the two DCs they are currently assigned to and obtain two new customer-DC assignments.

(f) If x_i and x_j are both DCs, then we exchange all the customers currently assigned to them.

(g) If x_i is a customer and x_j is a DC, then the customers after x_i assigned to the same DC are reassigned to DC x_j, and customer x_i is reassigned to the DC nearest before DC x_j. All customers previously assigned to DC x_j will be reassigned to the DC nearest before it.

(h) If x_i is a DC and x_j is a customer, this case is similar to case g.

3.3.3. 2-Opt Neighbourhood. With the consideration of vehicle capacity, in our definition, the 2-opt neighbourhood contains the solutions that can be obtained by selecting two customers of X (e.g., x_i and x_j) and then reversing the substring in the solution representation between them, the so-called 2-opt move. For example, applying 2-opt move to elements x_i and x_j, we obtain

$$X' = \left(x_1, x_2, \ldots, x_{i-1}, x_j, x_{j-1}, \ldots, x_{i+1}, x_i, x_{j+1}, \ldots, x_n\right). \quad (25)$$

3.4. Tabu Search Framework. To increase the probability of obtaining high quality solutions, a diversification strategy is implemented. This strategy probabilistically accepts the second best solution in the search process while no better solution can be found in the neighborhoods of the current solution. By doing so, we can effectively diversify the search direction and thus more solution space will be explored. Consequently, better solution may be found. The computation results in Section 4 prove this strategy. The proposed tabu search can be summarized as follows.

Algorithm 4 (new tabu search).

Step 0. Input an initial feasible solution X_0 (see Section 3.2) and initialize Iter $:= 0$, $X_{\text{curr}} := X_0$, and $\text{Obj}^* := \text{Obj}(X_0)$.

Step 1. Explore the neighborhoods of X_{curr} and denote the best solution in the neighborhoods, the best nontabu solution, and the second best nontabu solution as X_{best}, $X_{\text{tabu-best}}$, and $X_{\text{tabu-2nd}}$, respectively.

Step 2. If $\text{Obj}(X_{\text{best}}) < \text{Obj}^*$, then set $X_{\text{curr}} := X_{\text{best}}$ and add the corresponding move to tabu list; otherwise,

if $\text{Obj}(X_{\text{tabu-best}}) < \text{Obj}(X_{\text{curr}})$, then $X_{\text{curr}} := X_{\text{tabu-best}}$ and add the corresponding move to tabu list;

otherwise, probabilistically move to $X_{\text{tabu-best}}$ or $X_{\text{tabu-2nd}}$, $X_{\text{curr}} := \text{Prob}\{X_{\text{tabu-best}}, X_{\text{tabu-2nd}}\}$, and add the corresponding move to tabu list.

Step 3. Iter $:=$ Iter + 1; If no stopping criterion is reached, return to Step 1.

Step 4. Output the best solution objective function value Obj^*.

In the proposed tabu search algorithm, Iter counts the number of iterations and X_0 represents the initial solution obtained by greedy nearest neighbour method (Section 3.2). X_{curr} denotes the current solution. Obj^* is the objective function value corresponding to the best solution found so far. The function $\text{Obj}(X)$ represents the objective function value of solution X.

In Step 2, comparing with the current solution X_{curr} if no better solution can be found in its neighbourhood, we need to probabilistically move X_{curr} to $X_{\text{tabu-best}}$ or $X_{\text{tabu-2nd}}$. In implementation, we randomly generate a value β in interval $[0, 1]$. If $\beta \geq \lambda$, then X_{curr} is moved to $X_{\text{tabu-best}}$; and otherwise X_{curr} is moved to $X_{\text{tabu-2nd}}$, where λ is a given parameter.

At each iteration of the tabu search procedure, the best admissible nontabu insertion, swap or 2-opt move is performed. The two elements of solution X_{curr} involved in such move are declared as tabu-active, which is forbidden to be removed in the next t iterations. t is the tabu-tenure parameter selected randomly from a range $[T_{\min}, T_{\max}]$.

The tabu search iteration is terminated if the maximum number of iterations maxIter is reached or if the best solution found so far has been improved in successive SucIter iteration.

Table 1: Computational results on CLRP benchmarks.

Problem	$\|I\|$	$\|J\|$	Q	BKS	TS UB	TS Gap	TS Time	NTS UB	NTS Gap	NTS Time	DEV
P1	20	5	70	54793	54793	0.00	0.12	54793	0.00	0.49	0.00
P2	20	5	150	39104	39104	0.00	0.12	39104	0.00	0.69	0.00
P3	20	5	70	48908	48908	0.00	0.50	48908	0.00	0.53	0.00
P4	20	5	150	37542	37611	0.18	0.37	37611	0.18	0.74	0.00
P5	50	5	70	90111	90806	0.77	2.58	90461	0.39	3.35	−0.38
P6	50	5	150	63242	65010	2.80	10.43	63242	0.00	11.73	−2.80
P7	50	5	70	88298	89688	1.57	22.07	88643	0.39	23.94	−1.18
P8	50	5	150	67340	68071	1.09	7.48	67340	0.00	11.16	−1.09
P9	50	5	70	84055	84227	0.20	14.13	84110	0.07	16.96	−0.13
P10	50	5	150	51822	51902	0.15	10.21	51883	0.12	13.49	−0.03
P11	50	5	70	86203	86223	0.02	9.20	86203	0.00	14.71	−0.02
P12	50	5	150	61830	61978	0.24	19.54	61830	0.00	21.49	−0.24
P13	100	5	70	275993	281229	1.90	11.51	278926	1.05	38.41	−0.85
P14	100	5	150	214392	218886	2.10	9.52	216802	1.11	29.74	−0.99
P15	100	5	70	194598	196587	1.02	145.25	196436	0.94	95.16	−0.08
P16	100	5	150	157173	159244	1.32	180.38	158720	0.97	124.63	−0.35
P17	100	5	70	200246	203297	1.52	126.12	202682	1.20	110.85	−0.32
P18	100	5	150	152586	157859	3.46	122.47	156049	2.22	105.26	−1.24
P19	100	10	70	290429	334486	15.17	97.80	294774	1.47	143.2	−13.70
P20	100	10	150	234641	285303	21.59	75.87	236217	0.67	113.6	−20.92
P21	100	10	70	244265	257455	5.40	103.49	248003	1.51	139.85	−3.89
P22	100	10	150	203988	216253	6.01	69.65	208455	2.14	107	−3.87
P23	100	10	70	253344	291153	14.92	169.98	258221	1.89	153.53	−13.03
P24	100	10	150	204597	220528	7.79	67.06	209390	2.29	131.52	−5.50
P25	200	10	70	479425	518815	8.22	347.64	491097	2.43	554.88	−5.79
P26	200	10	150	378773	408401	7.82	469.61	384126	1.39	799.75	−6.43
P27	200	10	70	450468	494247	9.72	491.36	461810	2.46	1101.8	−7.26
P28	200	10	150	374435	396998	6.03	339.17	380004	1.47	775.62	−4.56
P29	200	10	70	472898	485672	2.70	397.96	479708	1.42	776.73	−1.28
P30	200	10	150	364178	374923	2.95	358.23	372971	2.36	919.82	−0.59
	Average					4.22	122.66		1.00	211.35	−3.22

4. Computational Results

The proposed tabu search algorithm was coded in the C program and ran on a computer with Intel(R) Core(TM) CPU (3.2 GHz) with 4 GB of RAM under the Microsoft Windows 7 operation system.

4.1. Test Beds. Two test beds were used to evaluate the performance of the proposed tabu search algorithms:

(1) The benchmarks of CLRP (Prins et al. [31]), which contains 30 instances: two potential distribution center sizes $|J| = 5$ or 10 are considered. The number of customers is $|I| = 20$, 50, 100, and 200. The customers and DCs are uniformly distributed in a $[1, 50] \times [1, 50]$ square. The fixed opening costs of DCs are randomly generated from interval [5000, 125000]. The traveling cost between two nodes equals their Euclidean distance multiplied by 100 and rounded up to the next integer. The setup cost of a vehicle is 1000. The vehicle capacity Q equals 70 or 150. Customers' demands are randomly selected from interval [11, 20].

(2) Randomly generated LIRP-FRL instances: based on the data of CLRP benchmarks and using the setting of [25] for the parameters, such as the order cost of new products of DCs A^m (=200), the order cost of recovered products of DCs A^r (=100), the cost of manufacturing c^m (=60), recovering c^r (=50), disposal c^d (−10), and the return rate of product, we randomly generate the LIRP-FRL instances as follows:

   (i) The holding cost for each distribution center is uniformly distributed in $U\ [5, 10]$.

   (ii) The transportation cost per unit product of the distribution center at site j, $j \in J$, is uniformly distributed in $U\ [1, 10]$.

4.2. Parameter Settings. The maximum number of iterations for NTS maxIter is set to 10000 and the search iteration is terminated if the best upper bound has not been improved in successive 800 iteration (SusIter = 800). Parameter λ is uniformly distributed in $U\ [0.01, 0.8]$. The lower and upper bound of tabu-tenure $T_{\min}$ and $T_{\max}$ are set to 5 and 12, respectively.

4.3. Numerical Results. To evaluate the performance of the proposed new tabu search (NTS), we compare it with the classical tabu search algorithm (denoted as TS in following discussion) in terms of the best upper bound (UB) found so far and the corresponding computational time in CPU seconds (time). Moreover, the parameter settings of TS is the same as NTS's except parameter λ that TS did not have. Computational results on CLRP benchmarks are listed in Table 1. The column BKS is the best known solution objective function value reported in the literature. Gap is calculated by the following formula: Gap $= 100 * (\text{UB} - \text{BKS})/\text{UB}$. DEV is the deviation of the gap of NTS from the gap of TS; that is, DEV $= \text{Gap}_{\text{NTS}} - \text{Gap}_{\text{TS}}$.

Using the diversification strategy of probabilistically accepting the second best solution, the NTS increases the probability of exploring more solution space. As a result, the NTS takes more computational time than the TS. However, from Table 1, we can observe that although the average computational time of NTS is about two times that of TS, it is still in a very acceptable range. The NTS provides more competitive upper bound than the TS. The average gap between the best upper bound found so far by NTS and the best known upper bound in the literature is about 1.00%, compared to the 4.22% of the TS. The NTS outperforms the TS in the quality of solutions obtained with the average deviation of the gap DEV = −3.22%.

Table 2 reports the computational results on test bed of randomly generated LIRP-FRL instances. From the table, we can also find that the NTS performs better than the classic TS with an average gap between the best upper bound of NTS and that of TS, about −2.79%. The average computational time of NTS is slightly bigger than that of TS.

Table 2: Computational results on LIRP-FRL instances.

Prob. ID	$\lvert I\rvert$	$\lvert J\rvert$	Q	TS		NTS		*Gap 1 (%)
				UB	Time	UB	Time	
P1	20	5	70	67528	0.50	67528	0.53	0.00
P2	20	5	150	42867	0.55	42867	0.61	0.00
P3	20	5	70	60021	0.46	60021	0.65	0.00
P4	20	5	150	40255	0.57	40255	0.62	0.00
P5	50	5	70	115984	22.56	115534	22.95	−0.39
P6	50	5	150	84468	36.43	84401	34.18	−0.08
P7	50	5	70	117828	22.56	117530	24.06	−0.25
P8	50	5	150	96633	21.61	96161	21.64	−0.49
P9	50	5	70	112493	24.31	111625	24.51	−0.78
P10	50	5	150	82667	23.01	82392	24.66	−0.33
P11	50	5	70	108639	21.28	108568	20.32	−0.07
P12	50	5	150	82938	21.58	82804	22.07	−0.16
P13	100	5	70	342786	139.24	342309	139.97	−0.14
P14	100	5	150	276104	137.64	273409	138.72	−1.37
P15	100	5	70	239544	143.75	238937	158.07	−0.25
P16	100	5	150	201533	125.58	200708	135.06	−0.41
P17	100	5	70	250239	121.28	249565	124.88	−0.27
P18	100	5	150	198842	126.84	197310	128.30	−0.78
P19	100	10	70	406342	138.30	396469	161.50	−2.49
P20	100	10	150	368668	138.84	339644	157.86	−8.55
P21	100	10	70	328174	121.59	320363	151.15	−2.44
P22	100	10	150	278729	128.50	274026	134.76	−1.72
P23	100	10	70	388259	113.47	320651	143.94	−21.08
P24	100	10	150	339851	120.77	283008	136.13	−20.09
P25	200	10	70	645014	393.75	629604	525.43	−2.45
P26	200	10	150	558189	368.91	528721	510.52	−5.57
P27	200	10	70	627737	427.91	611151	542.92	−2.71
P28	200	10	150	543988	379.41	517132	432.50	−5.19
P29	200	10	70	607894	419.25	598889	428.33	−1.50
P30	200	10	150	530675	422.72	509796	563.14	−4.10
Average					138.77		163.67	−2.79

*Gap 1 (%) = 100 ∗ (H2 solution value − H1 solution value)/H2 solution value.

4.4. Sensitivity Analysis. Sensitivity analysis is also conducted to investigate the effects on the total costs when the input parameters such as the return rate(r) or the rate between the unit producing cost of new products and recovered products ($c^m : c^r$) changes.

Table 3 reports the computational results when the product return rate is changed for each randomly generated instance. To manifest the trend more clearly, for each return rate value, we calculate the arithmetic average objective function values of all tested instances. The results are shown in Figure 3. From the figure, we can find that the total costs decrease with the increase of return rate r. Focusing on those products with high return rate can effectively reduce the system costs.

Table 4 shows the numerical results when the rate between the cost of producing a new product and that of recovering a damaged or old product varies. For each rate, we average the best upper bound obtained for all tested instances. The results are depicted in Figure 4. From the figure, we can observe that the total costs decrease with the increase of the rate. That means reducing the unit recovering cost of product can effectively reduce the total costs, which indicates us to retrieve those subnew products or to improve repairing technique so as to reduce recovering cost.

5. Conclusions and Future Works

We study a location-inventory-routing problem in forward and reverse logistics (LIRP-FRL) in this paper. A nonlinear mixed integer programming model is proposed to formulate the LIRP-FRL. Based on this model, a new tabu search that probabilistically accepts the second best solution in its neighborhoods is proposed to find near optimal solution for the problem. Numerical experiments on CLRP benchmarks

Table 3: Results of different return rates.

Prob. ID	r	$\vert I\vert$	$\vert J\vert$	Q	TS UB	TS Time	NTS UB	NTS Time	Gap 1 (%)
P1	0.1	20	5	70	67617	3.22	67617	2.66	0.00
	0.2				67522	3.38	67522	3.48	0.00
	0.3				67423	3.64	67423	3.14	0.00
	0.4				67568	2.73	67320	3.28	−0.37
	0.5				67293	4.69	67211	3.22	−0.12
	0.6				67094	3.26	67094	2.95	0.00
	0.7				66966	3.19	66966	2.77	0.00
	0.8				66904	3.15	66822	3.67	−0.12
	0.9				66646	2.68	66646	3.15	0.00
P2	0.1	20	5	150	42972	2.54	42972	2.87	0.00
	0.2				42969	2.43	42969	2.96	0.00
	0.3				42965	3.07	42965	2.57	0.00
	0.4				42961	3.40	42961	2.66	0.00
	0.5				42955	3.00	42955	3.18	0.00
	0.6				42948	2.63	42948	2.92	0.00
	0.7				42939	2.68	42939	3.08	0.00
	0.8				42927	2.66	42927	3.02	0.00
	0.9				42908	2.47	42908	3.04	0.00
P3	0.1	20	5	70	61544	2.70	61296	2.68	−0.40
	0.2				61175	3.14	61175	3.40	0.00
	0.3				61050	2.68	61050	2.99	0.00
	0.4				61011	3.16	60921	2.91	−0.15
	0.5				60786	2.62	60786	2.98	0.00
	0.6				60733	2.55	60644	2.81	−0.15
	0.7				60492	2.99	60492	3.23	0.00
	0.8				60325	2.87	60325	3.10	0.00
	0.9				60308	3.18	60127	3.19	−0.30
P4	0.1	20	5	150	40396	2.56	40396	2.71	0.00
	0.2				40395	2.58	40395	2.63	0.00
	0.3				40393	2.64	40393	2.94	0.00
	0.4				40390	2.68	40390	2.41	0.00
	0.5				40386	2.66	40386	3.12	0.00
	0.6				40381	2.53	40381	2.46	0.00
	0.7				40373	2.68	40373	2.66	0.00
	0.8				40363	2.46	40363	2.63	0.00
	0.9				40346	2.88	40346	2.61	0.00
P5	0.1	50	5	70	117680	36.19	116409	34.62	−1.08
	0.2				115813	32.65	115115	31.58	−0.60
	0.3				114965	30.64	114542	31.43	−0.37
	0.4				115279	30.7	114927	31.34	−0.31
	0.5				116446	26.22	115078	30.92	−1.17
	0.6				114151	30.48	114039	31.18	−0.10
	0.7				114504	31.34	114190	32.04	−0.27
	0.8				115578	28.66	114239	26.56	−1.16
	0.9				112326	31.31	112310	33.62	−0.01
P6	0.1	50	5	150	87885	20.30	87678	24.04	−0.24
	0.2				87289	23.82	86748	27.87	−0.62
	0.3				88191	23.95	87140	24.59	−1.19
	0.4				89497	20.47	86970	23.87	−2.82
	0.5				87240	21.81	86955	24.84	−0.33
	0.6				87233	24.34	86283	24.26	−1.09
	0.7				86366	24.17	86173	21.05	−0.22
	0.8				85494	22.81	84771	24.78	−0.85
	0.9				84673	23.93	84358	24.24	−0.37

Table 3: Continued.

Prob. ID	r	$\|I\|$	$\|J\|$	Q	TS UB	TS Time	NTS UB	NTS Time	Gap 1 (%)
P7	0.1	50	5	70	122232	26.84	121605	22.23	−0.51
	0.2				121038	26.14	120826	26.16	−0.18
	0.3				121147	26.17	120530	26.66	−0.51
	0.4				120239	26.41	119945	26.86	−0.24
	0.5				120223	26.11	119788	26.03	−0.36
	0.6				119636	26.05	119545	28.81	−0.08
	0.7				119795	25.50	119440	32.04	−0.30
	0.8				119994	26.05	119100	27.80	−0.75
	0.9				119728	25.72	118222	27.31	−1.26
P8	0.1	50	5	150	99470	26.38	99178	27.75	−0.29
	0.2				99455	25.21	99319	25.61	−0.14
	0.3				100163	28.65	98682	21.78	−1.48
	0.4				98722	25.14	98642	25.32	−0.08
	0.5				98930	25.27	98617	27.10	−0.32
	0.6				98131	24.90	98056	26.23	−0.08
	0.7				98723	25.60	97815	23.55	−0.92
	0.8				97633	25.78	97296	33.13	−0.35
	0.9				97752	25.43	96882	26.07	−0.89
P9	0.1	50	5	70	86438	25.22	86398	29.74	−0.05
	0.2				86031	22.20	85926	28.47	−0.12
	0.3				86300	25.01	85635	21.50	−0.77
	0.4				85292	21.61	85283	22.87	−0.01
	0.5				85084	24.46	84834	28.05	−0.29
	0.6				84628	23.10	84495	28.72	−0.16
	0.7				84358	24.98	84116	22.87	−0.29
	0.8				83239	21.88	83103	21.64	−0.16
	0.9				83386	22.48	82806	25.97	−0.70
P10	0.1	50	5	150	115321	25.76	115143	28.26	−0.15
	0.2				114968	26.16	114609	21.55	−0.31
	0.3				114628	27.12	114347	24.59	−0.25
	0.4				114620	26.62	113993	27.86	−0.55
	0.5				114243	25.93	113821	27.95	−0.37
	0.6				113720	26.05	113461	29.29	−0.23
	0.7				113367	22.95	113204	28.36	−0.14
	0.8				113157	26.73	112657	28.41	−0.44
	0.9				112518	32.52	111908	26.90	−0.54
P11	0.1	50	5	70	112376	26.82	111843	32.35	−0.47
	0.2				111582	25.94	111286	27.18	−0.27
	0.3				111920	23.13	111054	29.51	−0.77
	0.4				111642	24.91	110986	28.05	−0.59
	0.5				111345	23.08	110891	27.75	−0.41
	0.6				110712	26.11	110203	28.93	−0.46
	0.7				110789	25.79	109949	29.03	−0.76
	0.8				110232	25.79	109923	28.18	−0.28
	0.9				109797	24.80	109042	32.89	−0.69
P12	0.1	50	5	150	85505	24.69	85246	27.45	−0.30
	0.2				85187	24.25	85019	23.92	−0.20
	0.3				84879	24.73	84757	24.78	−0.14
	0.4				84797	28.33	84337	30.83	−0.54
	0.5				84312	25.84	83955	28.38	−0.42
	0.6				84053	26.65	83933	21.82	−0.14
	0.7				83933	26.31	83358	31.33	−0.69
	0.8				83651	26.92	82897	29.92	−0.90
	0.9				82655	23.22	82439	26.95	−0.26

Table 3: Continued.

Prob. ID	r	$\|I\|$	$\|J\|$	Q	TS		NTS		Gap 1 (%)
					UB	Time	UB	Time	
	0.1				343359	189.12	341812	146.89	−0.45
	0.2				346569	187.44	343870	187.75	−0.78
	0.3				345210	169.49	342124	141.65	−0.89
	0.4				348100	180.08	345668	190.9	−0.70
P13	0.5	100	5	70	349269	159.25	343318	184.88	−1.70
	0.6				347719	182.23	343891	162.19	−1.10
	0.7				349525	182.84	342643	169.88	−1.97
	0.8				349171	160.17	341151	158.68	−2.30
	0.9				351251	182.08	349382	186.92	−0.53
	0.1				282054	135.84	281389	190.02	−0.24
	0.2				281199	128.94	279541	151.39	−0.59
	0.3				279903	155.98	279153	160.32	−0.27
	0.4				278748	161.52	277988	130.87	−0.27
P14	0.5	100	5	150	279806	152.32	278460	162.29	−0.48
	0.6				280003	188.32	279155	127.99	−0.30
	0.7				280823	126.66	278542	171.61	−0.81
	0.8				276206	136.94	275974	138.12	−0.08
	0.9				276528	157.65	275917	163.14	−0.22
	0.1				246010	156.28	245337	148.54	−0.27
	0.2				245120	175.84	244537	172.42	−0.24
	0.3				244563	154.52	243754	154.32	−0.33
	0.4				243537	154.53	243124	133.88	−0.17
P15	0.5	100	5	70	242570	120.21	241529	192.88	−0.43
	0.6				241778	171.75	241435	150.70	−0.14
	0.7				240726	153.04	240237	138.58	−0.20
	0.8				239819	149.01	239716	153.79	−0.04
	0.9				238793	145.75	238624	144.34	−0.07
	0.1				209027	131.28	208711	153.17	−0.15
	0.2				208060	149.78	207229	157.39	−0.40
	0.3				206328	167.99	205454	200.44	−0.42
	0.4				207220	154.39	205877	195.70	−0.65
P16	0.5	100	5	150	206676	163.29	205654	172.25	−0.49
	0.6				204833	137.78	204547	168.87	−0.14
	0.7				204402	137.86	204284	153.95	−0.06
	0.8				203509	173.04	203068	191.72	−0.22
	0.9				203695	153.95	201648	146.62	−1.00
	0.1				259816	195.04	258025	149.48	−0.69
	0.2				258004	164.99	256937	193.31	−0.41
	0.3				256120	124.51	256057	123.60	−0.02
	0.4				254658	130.21	254594	150.79	−0.03
P17	0.5	100	5	70	254764	133.42	253722	165.32	−0.41
	0.6				255047	155.20	252587	151.01	−0.96
	0.7				250732	153.72	249812	149.22	−0.37
	0.8				253732	182.23	249612	167.72	−1.62
	0.9				252906	168.49	249337	157.79	−1.41
	0.1				204826	145.28	204678	191.50	−0.07
	0.2				205474	172.75	204621	193.28	−0.42
	0.3				203254	167.53	202691	155.11	−0.28
	0.4				203120	148.82	201380	121.34	−0.86
P18	0.5	100	5	150	202003	122.00	201329	145.70	−0.33
	0.6				200401	145.62	199858	151.80	−0.27
	0.7				199032	147.58	198618	155.51	−0.21
	0.8				198858	153.76	197776	145.95	−0.54
	0.9				199502	134.57	197513	150.85	−1.00

Table 3: Continued.

Prob. ID	r	$\|I\|$	$\|J\|$	Q	TS UB	TS Time	NTS UB	NTS Time	Gap 1 (%)
P19	0.1	100	10	70	414613	171.01	401365	198.5	−3.20
	0.2				413680	164.18	400546	204.34	−3.17
	0.3				420538	167.47	399896	195.42	−4.91
	0.4				414460	154.11	394054	202.68	−4.92
	0.5				411688	158.96	395828	211.36	−3.85
	0.6				412339	162.17	394750	213.73	−4.27
	0.7				410641	163.97	394617	210.72	−3.90
	0.8				409561	181.48	394513	218.27	−3.67
	0.9				408967	178.1	394294	201.13	−3.59
P20	0.1	100	10	150	365982	113.65	362144	114.33	−1.05
	0.2				365164	111.79	361157	142.29	−1.10
	0.3				365868	117.97	349578	113.22	−4.45
	0.4				365307	145.30	349277	144.62	−4.39
	0.5				366266	115.01	348378	158.55	−4.88
	0.6				363989	151.05	348198	117.37	−4.34
	0.7				113367	22.95	113204	28.36	−0.14
	0.8				113157	26.73	112657	28.41	−0.44
	0.9				112518	32.52	111908	26.90	−0.54
P21	0.1	100	10	70	330001	132.05	323564	131.91	−1.95
	0.2				329657	155.75	322848	178.39	−2.07
	0.3				329303	166.30	322162	176.31	−2.17
	0.4				328939	160.91	321756	167.07	−2.18
	0.5				328561	167.71	321589	152.01	−2.12
	0.6				328166	166.06	321183	182.85	−2.13
	0.7				327744	132.12	321102	174.83	−2.03
	0.8				327281	133.30	320160	179.93	−2.18
	0.9				326742	134.59	319244	188.47	−2.29
P22	0.1	100	10	150	281700	140.71	278464	129.13	−1.15
	0.2				285498	140.01	278181	179.95	−2.56
	0.3				285035	128.87	277760	184.58	−2.55
	0.4				282821	157.09	277349	159.42	−1.93
	0.5				284563	129.31	277133	181.07	−2.61
	0.6				284057	152.07	276776	183.34	−2.56
	0.7				280960	129.57	276530	172.01	−1.58
	0.8				282955	157.32	276208	181.27	−2.38
	0.9				278306	132.02	273261	178.52	−1.81
P23	0.1	100	10	70	399113	125.10	375576	164.77	−5.90
	0.2				396761	146.84	371533	160.97	−6.36
	0.3				397280	168.97	360348	155.58	−9.30
	0.4				396341	139.25	347788	175.99	−12.25
	0.5				393942	143.91	346723	183.96	−11.99
	0.6				392957	153.30	344273	145.58	−12.39
	0.7				393378	159.10	325508	172.95	−17.25
	0.8				390858	130.43	325392	172.15	−16.75
	0.9				391111	140.30	322910	167.81	−17.44
P24	0.1	100	10	150	297873	126.28	296530	138.04	−0.45
	0.2				295735	139.68	294394	164.50	−0.45
	0.3				334584	138.60	292118	173.75	−12.69
	0.4				334011	152.64	288251	183.57	−13.70
	0.5				345871	130.23	287245	142.65	−16.95
	0.6				343622	150.07	286258	149.21	−16.69
	0.7				344063	132.18	285833	132.30	−16.92
	0.8				343388	151.00	285505	145.31	−16.86
	0.9				342624	161.02	276622	165.18	−19.26

Table 3: Continued.

Prob. ID	r	$\|I\|$	$\|J\|$	Q	TS		NTS		Gap 1 (%)
					UB	Time	UB	Time	
P25	0.1	200	10	70	665405	1003.37	646837	1358.56	−2.79
	0.2				663368	1022.24	646011	1275.81	−2.62
	0.3				662357	840.78	645933	1052.16	−2.48
	0.4				660795	819.73	643790	900.59	−2.57
	0.5				660155	819.55	641200	1170.31	−2.87
	0.6				657577	835.74	640619	1172.54	−2.58
	0.7				655423	831.23	640582	851.98	−2.26
	0.8				654409	830.95	637338	858.12	−2.61
	0.9				653286	792.33	622908	836.45	−4.65
P26	0.1	200	10	150	573667	753.47	553421	1069.24	−3.53
	0.2				570023	765.06	551891	1297.82	−3.18
	0.3				569666	776.15	537807	1069.80	−5.59
	0.4				567939	797.95	535782	1163.39	−5.66
	0.5				564777	900.56	535225	1108.99	−5.23
	0.6				564413	887.18	535083	1195.13	−5.20
	0.7				562167	849.13	531505	1236.66	−5.45
	0.8				560098	799.95	514584	1157.03	−8.13
	0.9				557554	864.90	513652	1023.90	−7.87
P27	0.1	200	10	70	661785	1384.45	631700	1228.42	−4.55
	0.2				662602	1317.90	630853	969.39	−4.79
	0.3				647333	1144.41	630036	1119.12	−2.67
	0.4				647377	1238.22	625782	1060.19	−3.34
	0.5				647837	955.81	625659	1159.76	−3.42
	0.6				651234	972.11	624175	1104.26	−4.16
	0.7				643657	994.18	623635	1203.08	−3.11
	0.8				648507	1007.51	618926	1251.66	−4.56
	0.9				640631	974.55	617253	1352.17	−3.65
P28	0.1	200	10	150	560151	1039.68	554838	901.12	−0.95
	0.2				567066	805.96	552250	1205.61	−2.61
	0.3				565177	1107.27	551150	1429.66	−2.48
	0.4				551554	1150.46	546455	1283.46	−0.92
	0.5				550006	845.09	546211	901.12	−0.69
	0.6				548151	679.59	543161	850.63	−0.91
	0.7				546181	835.08	539990	965.50	−1.13
	0.8				545049	869.30	538293	1444.22	−1.24
	0.9				543203	937.76	522946	1065.27	−3.73
P29	0.1	200	10	70	621423	1031.98	619749	810.58	−0.27
	0.2				624921	755.35	618833	817.09	−0.97
	0.3				620040	711.57	617782	991.29	−0.36
	0.4				617601	867.88	615738	958.45	−0.30
	0.5				623408	1135.24	614301	1168.53	−1.46
	0.6				614480	799.56	612048	1337.13	−0.40
	0.7				612960	1095.73	611365	948.58	−0.26
	0.8				611261	1126.74	609791	969.75	−0.24
	0.9				609581	846.60	608927	712.33	−0.11
P30	0.1	200	10	150	522946	935.56	520709	1214.20	−0.43
	0.2				521952	696.92	518710	871.10	−0.62
	0.3				520505	730.31	516812	1182.22	−0.71
	0.4				519262	780.89	516352	1289.81	−0.56
	0.5				517999	707.29	516019	1335.97	−0.38
	0.6				516930	1052.88	515388	1212.71	−0.30
	0.7				515604	954.61	513938	1054.47	−0.32
	0.8				514221	687.26	511705	1073.18	−0.49
	0.9				497335	1020.75	492080	1113.48	−1.06

Table 4: Results of different rate between the cost of recovered products and the cost of new products.

Prob. ID	$c^m : c^r$	$\|I\|$	$\|J\|$	Q	TS UB	TS Time	NTS UB	NTS Time	Gap 1 (%)
P1	1	20	5	70	68142	3.00	68142	2.78	0.00
	1.25				67402	2.68	67402	2.39	0.00
	1.5				67211	2.14	66964	2.61	−0.37
	1.75				66898	3.15	66649	2.54	−0.37
	2				66496	2.76	66414	2.79	−0.12
P2	1	20	5	150	43008	3.33	43008	2.35	0.00
	1.25				42964	3.11	42964	2.54	0.00
	1.5				42934	2.49	42934	2.22	0.00
	1.75				42913	2.40	42913	3.15	0.00
	2				42897	3.55	42897	3.19	0.00
P3	1	20	5	70	61680	2.72	61680	2.82	0.00
	1.25				61028	2.46	61028	2.81	0.00
	1.5				60595	2.47	60595	2.54	0.00
	1.75				60367	2.59	60285	2.71	−0.14
	2				60132	2.52	60052	2.50	−0.13
P4	1	20	5	150	40458	2.45	40458	2.05	0.00
	1.25				40391	2.18	40391	2.36	0.00
	1.5				40346	2.86	40346	2.96	0.00
	1.75				40314	2.69	40314	2.32	0.00
	2				40290	1.92	40290	2.28	0.00
P5	1	50	5	70	117832	26.39	116378	25.98	−1.23
	1.25				117029	25.68	114692	26.63	−2.00
	1.5				115617	26.14	114374	25.88	−1.08
	1.75				115126	26.70	114022	26.30	−0.96
	2				113413	25.84	112590	25.75	−0.73
P6	1	50	5	150	90053	22.94	87484	20.19	−2.85
	1.25				88307	24.22	86991	20.15	−1.49
	1.5				87796	23.82	86910	23.21	−1.01
	1.75				86976	20.81	86535	22.24	−0.51
	2				86703	22.88	86394	17.23	−0.36
P7	1	50	5	70	123939	18.23	122295	21.88	−1.33
	1.25				121637	19.25	120958	16.91	−0.56
	1.5				120474	18.75	119532	20.84	−0.78
	1.75				119790	21.88	118308	21.61	−1.24
	2				118183	16.95	117858	21.77	−0.27
P8	1	50	5	150	100524	17.41	100439	25.51	−0.08
	1.25				99371	28.59	99067	29.73	−0.31
	1.5				98231	24.37	97807	29.53	−0.43
	1.75				97514	24.48	96608	22.80	−0.93
	2				96942	25.15	96560	17.95	−0.39
P9	1	50	5	70	117880	27.00	115956	22.17	−1.63
	1.25				116053	30.39	114876	35.22	−1.01
	1.5				114690	24.03	113420	28.06	−1.11
	1.75				113128	19.20	112769	28.95	−0.32
	2				112006	28.62	111756	26.96	−0.22
P10	1	50	5	150	88057	23.26	87883	31.21	−0.20
	1.25				86485	25.83	86222	31.48	−0.30
	1.5				85367	31.62	84589	19.58	−0.91
	1.75				83386	26.10	83478	22.37	0.11
	2				83455	25.45	83235	21.90	−0.26

Table 4: Continued.

Prob. ID	$c^m : c^r$	$\|I\|$	$\|J\|$	Q	TS		NTS		Gap 1 (%)
					UB	Time	UB	Time	
P11	1	50	5	70	114793	20.04	112544	25.68	−1.96
	1.25				112136	19.99	111395	27.60	−0.66
	1.5				111087	20.16	111062	29.96	−0.02
	1.75				110640	27.13	109472	22.12	−1.06
	2				110405	22.60	108934	26.43	−1.33
P12	1	50	5	150	87232	24.63	86433	29.55	−0.04
	1.25				86410	22.09	86199	18.89	−0.57
	1.5				85173	27.98	83868	19.14	−1.94
	1.75				84523	21.53	83656	15.63	−2.18
	2				83027	18.38	82912	20.22	−1.46
P13	1	100	5	70	364895	155.68	361755	159.32	−0.86
	1.25				363309	160.69	360230	160.93	−0.85
	1.5				362096	163.84	359999	168.78	−0.58
	1.75				359974	157.96	356857	141.78	−0.87
	2				355624	156.57	339404	161.89	−4.56
P14	1	100	5	150	305053	164.11	300033	139.62	−1.65
	1.25				303135	141.89	296364	121.95	−2.23
	1.5				301834	139.24	295118	121.68	−2.23
	1.75				298777	139.76	294442	133.88	−1.45
	2				291740	133.99	276706	135.66	−5.15
P15	1	100	5	70	296619	124.99	258199	125.21	−12.95
	1.25				260317	137.47	254461	128.82	−2.25
	1.5				249922	115.05	247152	183.34	−1.11
	1.75				249195	132.22	244535	154.43	−1.87
	2				247529	149.44	241351	171.13	−2.50
P16	1	100	5	150	233346	120.31	223398	126.11	−4.26
	1.25				229687	129.75	220760	114.91	−3.89
	1.5				226932	127.63	218861	117.39	−3.56
	1.75				216624	137.42	214174	115.09	−1.13
	2				211223	128.79	205238	122.39	−2.83
P17	1	100	5	70	267713	134.93	265309	110.60	−0.90
	1.25				266067	132.17	262547	122.34	−1.32
	1.5				263994	130.92	260267	110.49	−1.41
	1.75				261711	116.78	259735	150.61	−0.76
	2				260804	170.99	252673	124.40	−3.12
P18	1	100	5	150	226178	124.86	224348	139.70	−0.81
	1.25				223053	127.08	219578	134.79	−1.56
	1.5				220970	115.28	218823	184.85	−0.97
	1.75				219154	158.19	216341	129.00	−1.28
	2				217751	159.37	209257	182.73	−3.90
P19	1	100	10	70	412240	135.46	409643	141.11	−0.63
	1.25				406518	139.13	403969	173.98	−0.63
	1.5				404199	137.06	401006	167.12	−0.79
	1.75				403475	136.64	400046	178.88	−0.85
	2				401608	136.54	394231	149.81	−1.84
P20	1	100	10	150	366576	105.10	364188	166.50	−0.65
	1.25				364342	123.15	362564	100.25	−0.49
	1.5				360397	153.27	358732	143.08	−0.46
	1.75				357502	158.04	356178	114.59	−0.37
	2				350419	100.43	345948	154.21	−1.28

Table 4: Continued.

Prob. ID	$c^m : c^r$	$\lvert I\rvert$	$\lvert J\rvert$	Q	TS		NTS		Gap 1 (%)
					UB	Time	UB	Time	
P21	1	100	10	70	337749	113.31	334240	100.11	−1.04
	1.25				333248	114.45	330768	112.04	−0.74
	1.5				330981	127.66	329900	133.01	−0.33
	1.75				329982	143.46	325218	139.32	−1.44
	2				327911	189.02	322382	150.34	−1.69
P22	1	100	10	150	300245	112.22	297406	94.24	−0.95
	1.25				293642	127.66	291212	119.95	−0.83
	1.5				290938	186.05	287471	192.95	−1.19
	1.75				288716	183.72	285885	127.07	−0.98
	2				286473	132.29	281933	125.07	−1.58
P23	1	100	10	70	369343	127.38	364871	132.22	−1.21
	1.25				364871	152.70	359677	141.96	−1.42
	1.5				359613	147.70	355286	152.78	−1.20
	1.75				358094	155.05	354980	142.97	−0.87
	2				341610	146.96	320343	172.26	−6.23
P24	1	100	10	150	328663	124.91	299018	132.71	−9.02
	1.25				325042	125.13	295553	137.29	−9.07
	1.5				323847	156.83	291860	135.43	−9.88
	1.75				299214	135.60	288433	157.16	−3.60
	2				294706	121.22	281938	168.67	−4.33
P25	1	200	10	70	665281	829.11	653633	1026.07	−1.75
	1.25				657935	834.27	652114	1061.26	−0.88
	1.5				655818	823.79	651574	984.23	−0.65
	1.75				649604	820.10	646761	1055.81	−0.44
	2				642489	820.87	641864	1139.61	−0.10
P26	1	200	10	150	581623	611.52	580270	618.26	−0.23
	1.25				579961	608.25	569283	626.20	−1.84
	1.5				574684	604.60	536008	613.79	−6.73
	1.75				556955	621.66	535570	623.55	−3.84
	2				554052	621.92	528999	622.53	−4.52
P27	1	200	10	70	773781	793.09	662523	778.08	−14.38
	1.25				713012	819.64	655573	803.25	−8.06
	1.5				681260	804.27	642081	739.51	−5.75
	1.75				635834	770.17	632602	723.11	−0.51
	2				632061	739.14	623493	704.85	−1.36
P28	1	200	10	150	576983	666.69	555923	987.24	−3.65
	1.25				568736	675.82	546433	859.83	−3.92
	1.5				564064	674.70	543330	859.83	−3.68
	1.75				560726	914.60	535818	761.02	−4.44
	2				534830	977.03	522356	795.76	−2.33
P29	1	200	10	70	666957	790.82	636582	820.80	−4.55
	1.25				658832	832.47	633813	1119.70	−3.80
	1.5				653454	1149.63	621988	965.82	−4.82
	1.75				622078	801.89	619907	825.17	−0.35
	2				616051	863.47	608644	1080.37	−1.20
P30	1	200	10	150	542071	734.01	540384	705.36	−0.31
	1.25				525159	727.55	524172	786.56	−0.19
	1.5				521758	716.37	510933	763.03	−2.07
	1.75				518474	787.04	506479	752.31	−2.31
	2				515142	755.66	502884	698.85	−2.38

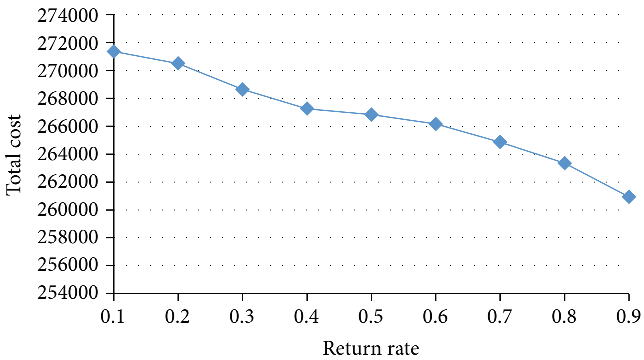

Figure 3: Results of different return rates.

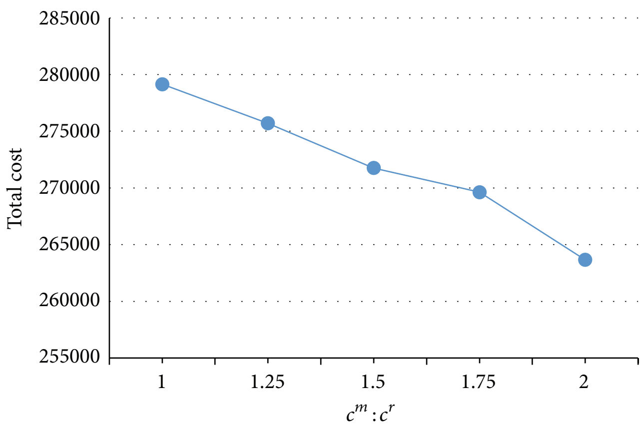

Figure 4: Results of different rate between the cost of recovered products and the cost of new products.

and randomly generated instances of LIRP-FRL with various problem sizes demonstrate the effectiveness and the efficiency of the new tabu search, which can find high quality solution with a reasonable time. Sensitivity analyses are also conducted to investigate the intrinsic management insights of the problems.

For future research, to be more close to the reality, the stochastic demand of customer should also be considered in the LIRP-FRL.

Competing Interests

The authors declare that they have no competing interests.

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