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Facility location model for a remanufacturing logistics network

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Abstract: First a remanufacturing logistics network is constructed, in which the structure of both the forward logistics and the reverse logistics are of two levels and all the logistics facilities are capacitated. Both the remanufacturing products and the new products can be used to meet the demands of customers. Moreover, it is assumed that homogeneous facilities can be designed together into integrated ones, based on which a mixed integer nonlinear programming (MINLP) facility location model of the remanufacturing logistics network with six types of facilities to be sited is built. Then an algorithm based on enumeration for the model is given. The feasible combinations of binary variables are searched by enumeration, and the remaining sub-problems are solved by the LP solver. Finally, the validities of the model and the algorithm are illustrated by means of an example. The result of the sensitivity analysis of parameters indicates that the integration of homogeneous facilities may influence the optimal solution of the problem to a certain degree.
Key words: reverse logistics; remanufacturing logistics network; facility location

Facility location is an important issue in reverse logistics network design. A reasonable facility location can bring down costs, raise recovery efficiency and improve the degree of customer satisfaction, and even it is of great significance in the whole reverse logistics system operation.

Based on the classification of return-objects proposed by Fleischmann et al. [1] and the main recovery options categorized by Thierry et al. [2], four kinds of basic reverse logistics networks can be identified: the directly reusable network, the remanufacturing network, the repair service network and the recycling network. In this paper, we focus on the remanufacturing logistics network. The process of remanufacturing usually includes several activities as follows: collection, checking, sorting, disassembly, remanufacturing, disposal and redistribution[2].

Several works of literature researched the facility location problem in the remanufacturing logistics network. Thierry[3] and Krikke et al. [4] built a linear programming (LP) model and a mixed integer linear programming (MILP) model to design distribution and product recovery networks for copying machines, respectively. Jayaraman et al. [5] proposed an MILP model to solve the problem of the location of remanufacturing/distribution facilities and to optimize the corresponding flows of remanufactured products. Shih[6] proposed an MILP model to design a recycling network of electrical appliances and computers. Min et al. [7] researched the problem of determining the number and location of centralized return centers (CRCs), based on which they proposed a mixed integer nonlinear programming (MINLP) model and a genetic algorithm to solve the model. But Shih[6] and Min et al. [7] did not consider the mutual interactions and the integration of the forward logistics and the reverse logistics. Moreover, a review of the quantitative models of remanufacturing reverse logistics can be found in Ref. [1].

Lu et al. [8] presented a two-level location problem with three types of facilities to be located in a remanufacturing logistics network. They proposed an MILP model, in which they simultaneously considered forward and reverse flows and their mutual interactions. Based on Lagrangian heuristics they developed an algorithm to solve the model. But in their model they did not consider some forward logistics facilities such as distribution centers (DCs). They also did not consider the integration of some homogeneous facilities, which can contribute to the reduction in the total costs. Moreover, they assumed that all the logistics facilities were uncapacitated. Aiming at the above deficiencies, we improve on their models in this paper by adding more logistics participants, and restricting the capacity of various logistics facilities. Furthermore, we consider the integration of homogeneous facilities and introduce the parameters of the saving rates of fixed costs, which can make the objective function nonlinear, so the original MILP model is converted to the one of an MINLP.

1 Problem Definition

Consider such a remanufacturing logistics network as follows: the network includes several logistics participants, such as customer zones, DCs, CRCs, producers, remanufacturing factories and so on (see Fig. 1). We assume that a producer and a remanufacturing factory can be designed together into an integrated factory; a DC and a CRC can be designed together into an integrated center as well.

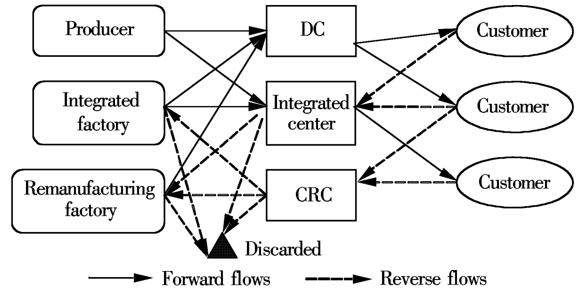

Fig. 1 The structure of a remanufacturing logistics network

The entire operation process is as follows: First, used products are recovered by CRCs (or integrated centers), which are responsible for some essential activities, such as cleaning, disassembly, checking and sorting. Secondly, the repairable products are shipped back to the remanufacturing

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factories(or integrated factories). Thirdly, the remanufacturing factories accept the checked returns and are responsible for the process of remanufacturing. In addition, as a member of the forward channel, producers are in charge of making new products. Finally the two parts of the products are transported to customer zones together by DCs(or integrated centers).

2 Condition Assumptions

Prior to developing the model for reverse logistics network design, we make the following underlying assumptions and simplifications:

① The model considers a remanufacturing logistics network, which has only one kind of production during a single period. The period begins with reverse logistics activities.

② The positions of customer zones are known and deterministic, whereas the positions of other logistics facilities will be chosen from their respective potential location sites.

③ The quantity of product demands and available returns at the customer zones are known and deterministic.

④ Used products of poor quality are discarded at both CRC(or integrated centers) and remanufacturing factories(or integrated factories).

⑤ The product demands at the customer zones can be met by both new products and remanufactured products. It means that the remanufactured products from remanufacturing factories are considered the same as the new products from traditional producers in terms of satisfying the customer zones.

⑥ Without loss of generality, for the case of a remanufacturing activity, we suppose that the total demand for products in the whole logistics system is greater than the quantity of products that can be obtained by remanufacturing.

⑦ It is assumed that all the remanufactured products that can be obtained in the system must be fully used to meet the product demands of customer zones.

⑧ The distances and the freights between different types of facilities are known and the transportation costs have simple linear relationships with the volumes.

⑨ All kinds of logistics facilities are capacitated.

It can be seen that the closed-loop remanufacturing logistics system includes not only the forward logistics but also the reverse logistics. In this location problem, the structure of both the forward logistics and the reverse logistics are of two levels and the number of locations of possible facilities to be decided on is of six different types: producers, remanufacturing factories, integrated factories, DCs, CRCs and integrated centers. Based on the above assumptions and analysis, we develop an MINLP model.

3 Model

Objective function:

$$\min f=\sum_{j\in J}F_j^{\mathrm{m}}Y_j^{\mathrm{m}}+\sum_{j\in J}F_j^{\mathrm{rm}}Y_j^{\mathrm{rm}}+\sum_{k\in K}F_k^{\mathrm{p}}Y_k^{\mathrm{p}}+\sum_{k\in K}F_k^{\mathrm{h}}Y_k^{\mathrm{h}}-\sum_{j\in J}\alpha_jY_j^{\mathrm{m}}Y_j^{\mathrm{rm}}(F_j^{\mathrm{m}}+F_j^{\mathrm{rm}})-\sum_{k\in K}\alpha_kY_k^{\mathrm{p}}Y_k^{\mathrm{h}}(F_k^{\mathrm{p}}+F_k^{\mathrm{h}})+\sum_{j\in J}\sum_{k\in K}\sum_{i\in I}c'_{ikj}d_i^fX_{ikj}^f+\sum_{i\in I}\sum_{k\in K}\sum_{j\in J}cr'_{ikj}d_i^{\mathrm{r}}X_{ikj}^{\mathrm{r}} \quad (1)$$

s. t.

$$\sum_{j\in J}\sum_{k\in K}X_{ikj}^{\mathrm{f}}=1 \quad \forall i\in I \quad (2)$$

$$\sum_{j\in J}\sum_{k\in K}X_{ikj}^{\mathrm{r}}=1 \quad \forall i\in I \quad (3)$$

$$\sum_{k\in K}\sum_{i\in I}d_i^{\mathrm{f}}X_{ikj}^{\mathrm{f}}\geqslant(1-\gamma)(1-\beta)\sum_{k\in K}\sum_{i\in I}d_i^{\mathrm{r}}X_{ikj}^{\mathrm{r}} \quad \forall j\in J \quad (4)$$

$$\sum_{k\in K}\sum_{i\in I}d_i^{\mathrm{f}}X_{ikj}^{\mathrm{f}}-(1-\gamma)(1-\beta)\sum_{k\in K}\sum_{i\in I}d_i^{\mathrm{r}}X_{ikj}^{\mathrm{r}}\leqslant Y_j^{\mathrm{m}}M_j^{\mathrm{m}} \quad \forall j\in J \quad (5)$$

$$(1-\beta)X_{ikj}^{\mathrm{r}}<Y_j^{\mathrm{rm}} \quad \forall i\in I,\forall j\in J,\forall k\in K \quad (6)$$

$$X_{ikj}^{\mathrm{f}}\leqslant Y_k^{\mathrm{p}} \quad \forall i\in I,\forall j\in J,\forall k\in K \quad (7)$$

$$X_{ikj}^{\mathrm{r}}\leqslant Y_k^{\mathrm{h}} \quad \forall i\in I,\forall j\in J,\forall k\in K \quad (8)$$

$$\sum_{j\in J}\sum_{i\in I}d_i^{\mathrm{f}}X_{ikj}^{\mathrm{f}}\leqslant Y_k^{\mathrm{p}}M_k^{\mathrm{p}} \quad \forall k\in K \quad (9)$$

$$\sum_{j\in J}\sum_{i\in I}d_i^{\mathrm{r}}X_{ikj}^{\mathrm{r}}\leqslant Y_k^{\mathrm{h}}M_k^{\mathrm{h}} \quad \forall k\in K \quad (10)$$

$$\sum_{k\in K}\sum_{i\in I}(1-\beta)d_i^{\mathrm{r}}X_{ikj}^{\mathrm{r}}\leqslant Y_j^{\mathrm{rm}}M_j^{\mathrm{rm}} \quad \forall j\in J \quad (11)$$

$$Y_j^{\mathrm{m}},Y_j^{\mathrm{rm}},Y_k^{\mathrm{p}},Y_k^{\mathrm{h}}=0,1 \quad \forall j\in J,\forall k\in K \quad (12)$$

$$X_{ikj}^{\mathrm{f}},X_{ikj}^{\mathrm{r}}\geqslant 0 \quad \forall i\in I,\forall j\in J,\forall k\in K \quad (13)$$

$$c'_{ikj}=E_1l_{jk}+c_j^{\mathrm{m}}+c_k^{\mathrm{p}}+E_1l_{ik} \quad (14)$$

$$c''_{ikj}=E_2l_{ik}+c_k^{\mathrm{h}}(1-\beta)+c_k^{\mathrm{d}}\beta+E_2l_{kj}(1-\beta)+c_j^{\mathrm{rm}}(1-\gamma)(1-\beta)+c_j^{\mathrm{d}}\gamma(1-\beta)-(1-\gamma)(1-\beta)c_j^{\mathrm{m}} \quad (15)$$

where $j\in J=\{1,2,\ldots,M\}$ and $k\in K=\{1,2,\ldots,P\}$ denote the index of potential location sites for factories (producers, remanufacturing factories and integrated factories) and the index of potential location sites for intermediate facilities (DCs, CRCs and integrated centers), respectively; $i\in I=\{1,2,\ldots,N\}$ denotes the index of customer zones; F_j^{m} and F_j^{rm} are the fixed costs of setting a producer and a remanufacturing factory at site j, respectively; F_k^{p} and F_k^{h} are the fixed costs of setting up a DC and a CRC at site k, respectively; M_j^{m} and M_j^{rm} are the maximum production capacity and the maximum collection/remanufacturing capacity at site j, respectively; M_k^{p} and M_k^{h} are the maximum distribution capacity and the maximum collection capacity at site k, respectively; c_j^{m} is the unit production cost at producer j; c_j^{rm} is the unit remanufacturing cost at remanufacturing factory j; c_k^{p} is the unit variable cost at DC k in forward logistics(including packing, sorting and storage in general); c_k^{h} is the unit variable cost at CRC k in reverse logistics (including collection, checking, storage, sorting and disassembly in general); c_k^{d} is the unit discarded cost at CRC k or integrated center k; c_j^{d} is the unit disposal cost at remanufacturing factory j or integrated factory j; d_i^{f} is the product demand at customer site i; d_i^{r} is the available quantity of return-products ready for recovery at customer site i; l_{kj} is the distance from factory j to intermediate facility k; l_{ik} is the distance from intermediate facility k to customer site i; E_1 is the freight per demand-distance for forward flows; E_2 is the freight per recovery-distance for reverse flows; β is the percentage at which the return-products will be discarded at CRC k or integrated center $k(\beta<1)$; γ is the percentage at which the return-products will be discarded at remanufacturing factory j or integrated factory $j(\gamma < 1)$; α_j is the saving rate of the fixed costs in building an integrated factory at site $j(0 \leqslant \alpha_j \leqslant 1)$; α_k is the saving rate of the fixed costs in building an integrated center at site $k(0 \leqslant \alpha_k \leqslant 1)$. α_j and α_k reflect the degree of the integration of homogeneous facilities. The larger α_j and α_k are, the higher the degree of the integration is.

Y_j^{m} and Y_j^{rm} are the binary variables for the potential site j. $Y_j^{\mathrm{m}} = 1$, if a producer is located at potential site j; $Y_j^{\mathrm{m}} = 0$, otherwise. $Y_j^{\mathrm{rm}} = 1$, if a remanufacturing factory is located at potential site j; $Y_j^{\mathrm{rm}} = 0$, otherwise. If $Y_j^{\mathrm{m}} = 1$ and $Y_j^{\mathrm{rm}} = 1$, an integrated factory is located at potential site j; Y_k^{p} and Y_k^{h} are the binary variables for the potential site k. $Y_k^{\mathrm{p}} = 1$, if a DC is located at potential site k; $Y_k^{\mathrm{p}} = 0$, otherwise. $Y_k^{\mathrm{h}} = 1$, if a CRC is located at potential site k; $Y_k^{\mathrm{p}} = 0$, otherwise. If $Y_k^{\mathrm{p}} = 1$ and $Y_k^{\mathrm{h}} = 1$, an integrated center is located at potential site k; X_{ikj}^{f} is the fraction of product demand at customer site i which is met by producer j or remanufacturing factory j or integrated factory j through DC k or integrated center k; X_{ikj}^{r} is the fraction of the quantity of return-products at customer site i that is taken back through CRC k or integrated center k to remanufacturing factory j or integrated factory j.

The above model is a capacitated facility location problem. Solving the problem allows us to decide the locations of six types of logistics facilities while considering simultaneously the forward and reverse flows and to ascertain their quantitative correlation.

The objective of the model (1) is to minimize the total costs of the system, which includes the transportation costs, the fixed costs and the variable costs.

Constraints (2) and (3) stipulate respectively that the demands for products and return-items must be fully met.

Constraint (4) stipulates that no matter what kind of factory (including producer, remanufacturing factory and integrated factory) is located at potential site $j(j \in J)$, the amount of the products to meet customer demand is greater than or equal to the amount of remanufactured products from reverse flows. Specifically speaking: ① If a producer is located at potential site j, the amount of the remanufactured products is zero and the supply is equal to the amount of new products; ② If a remanufacturing factory is located at potential site j, the amount of new products is zero and the supply is equal to the amount of the remanufactured products; ③ If an integrated factory is located at potential site j, the supply is composed of two parts: The amount of the remanufactured products $(1-\gamma)(1-\beta)\sum_{k \in K}\sum_{i \in I} d_i^{\mathrm{r}} X_{ikj}^{\mathrm{r}}$ and the amount of new products denoted as $X_j^{\mathrm{m}}\left(\sum_{k \in K}\sum_{i \in I} d_i^{\mathrm{f}} X_{ikj}^{\mathrm{f}} - (1-\gamma)(1-\beta)\sum_{k \in K}\sum_{i \in I} d_i^{\mathrm{r}} X_{ikj}^{\mathrm{r}}\right), X_j^{\mathrm{m}} \geqslant 0$. The above analysis means constraint (4) is satisfied.

Constraints (5) to (8) link the location and allocation variables, in which six types of logistics facilities are related to different location variables and two flows are linked to corresponding allocation variables. Specifically, the location and numbers of producers are determined by the quantitative relationship between the forward and reverse flows at potential site j by constraint (5). Constraint (5) also restricts that no new products can be provided if no producer is set up at potential site j and ensures that the amount of new products does not exceed the maximum capacity of the producer at potential site j. Constraint (6) provides the relationship between flow fraction X_{ikj}^{r} and location variable Y_j^{rm}. Constraint (7) provides the relationship between flow fraction X_{ikj}^{f} and location variable Y_k^{p}. Constraint (8) provides the relationship between flow fraction X_{ikj}^{r} and location variable Y_k^{h}.

Constraint (9) restricts that if a DC is located at potential site k, the amount of products transported to site k does not exceed its maximum capacity. Constraint (10) restricts that if a CRC is located at potential site k, the amount of return-products shipped back to site k does not exceed its maximum capacity. Constraint (11) restricts that if a remanufacturing factory is located at potential site j, the amount of remanufacturing products does not exceed its maximum capacity.

Constraint (12) assures the binary integrality of decision variables Y_j^{m}, Y_j^{rm}, Y_k^{p} and Y_k^{h}. Constraint (13) is a non-negative constraint. Formulae (14) and (15) incorporate the coefficients of various cost terms related respectively to variables X_{ikj}^{f} and X_{ikj}^{r} into their corresponding unified coefficients c'_{ikj} and c''_{ikj} in the objective function of the model.

4 Algorithm

This is an MINLP model. As the number of various logistics facilities increases, the complexity of the problem increases exponentially. So it belongs to a class of the typical NP-hard problem. Generally speaking, it is difficult to find the optimal solution of the NP-hard problem in a limited time by using conventional methods (such as the simplex method, the branch and bound method or the cutting plane method). In this paper we propose an algorithm based on enumeration.

Because of the particularity of the model, it can be converted into sub-problem f' which belongs to LP after binary variables (Y_j^{m}, Y_j^{rm}, Y_k^{p}, Y_k^{h}) are established because the nonlinearity of the model is generated by binary variables, and not by continuous variables. Moreover, sub-problem f' can be solved by the LP solver (such as Lingo 8.0 and Matlab) in polynomial time. So we can obtain the optimal solution of overall problem f. The procedure is as follows:

1) Generate all the combinations by enumeration which consist of the values of four kinds of binary variables (Y_j^{m}, Y_j^{rm}, Y_k^{p}, Y_k^{h}) representing decision variables related to producers, remanufacturing factories, DCs and CRCs, respectively. The number of different combinations is $C(M, P) = 2^M \times 2^M \times 2^P \times 2^P = 2^{2(M+P)}$.

2) After four kinds of binary variables (Y_j^{m}, Y_j^{rm}, Y_k^{p}, Y_k^{h}) are established, the feasibilities of all the sub-problems are analyzed by checking whether they satisfy the capacity constraints or not. A feasible sub-problem must satisfy the following four constraints:

① The total capacities of all the producers plus the quantity of remanufactured products are no less than the total demands of customers:

$$\sum_{j \in J}\sum_{k \in K} d_i^{\mathrm{f}} X_{ikj}^{\mathrm{f}} \leqslant \sum_{j \in J} Y_j^{\mathrm{m}} M_j^{\mathrm{m}} + (1-\gamma)(1-\beta)\sum_{k \in K}\sum_{i \in I} d_i^{\mathrm{r}} X_{ikj}^{\mathrm{r}}$$

② The total capacities of all the remanufacturing factories are no less than the total returns from CRCs.

$$\sum_{j \in J}\sum_{k \in K}\sum_{i \in I}(1-\beta) d_i^{\mathrm{r}} X_{ikj}^{\mathrm{r}} \leqslant \sum_{j \in J} Y_j^{\mathrm{rm}} M_j^{\mathrm{rm}}$$

③ The total capacities of all the DCs are no less than the total demands of customers.

$$\sum_{j\in J}\sum_{k\in K}\sum_{i\in I} d_i^{\mathrm{f}} X_{ikj}^{\mathrm{f}} \leqslant \sum_{k\in K}\sum_{v=1}^{3} Y_k^{\mathrm{p}} M_k^{\mathrm{p}}$$

④ The total capacities of all the CRCs are no less than the total returns of customers.

$$\sum_{j\in J}\sum_{k\in K}\sum_{i\in I} d_i^{\mathrm{r}} X_{ikj}^{\mathrm{r}} \leqslant \sum_{k\in K}\sum_{v=1}^{3} Y_k^{\mathrm{h}} M_k^{\mathrm{h}}$$

Use the LP solver to solve every feasible sub-problem f'.

3) Compare the objective values of all the feasible sub-problems and obtain the optimal solution of overall problem f.

5 Model Experiment

Construct a remanufacturing (such as copying machines) logistics network. There are three potential sites for factories, three potential sites for intermediate facilities and three customer zones. The parameters and the data of the model are noted in Tab. 1 to Tab. 5.

Tab. 1 The related data of customer zones I 10^3

Parameters	i = 1	2	3
d_i^{r}	6	13	9
d_i^{f}	20	30	28

Tab. 2 The related data of potential sites for factories J 10^3

Parameters	j = 1	2	3
F_j^{m}	1 200	750	1 250
F_j^{rm}	600	400	650
M_j^{m}	80	45	85
M_j^{rm}	25	15	27

Tab. 3 The related data of potential sites for intermediate facility K 10^3

Parameters	k = 1	2	3
F_k^{p}	300	250	280
F_k^{h}	600	450	500
M_k^{p}	40	45	35
M_k^{h}	18	20	12

Tab. 4 The distance between customer zones I and potential sites for intermediate facility K

k	i = 1	2	3
1	10	15	18
2	12	11	16
3	18	16	13

Tab. 5 The distance between potential sites for factories J and potential sites for intermediate facility K

j	k = 1	2	3
1	12	10	15
2	18	15	12
3	21	17	14

The other parameters are as follows:

$E_1=1$, $E_2=0.8$, $\beta=0.2$, $\gamma=0.3$, $c_k^{\mathrm{p}}=3$, $c_k^{\mathrm{h}}=4$, $c_k^{\mathrm{d}}=1$, $\alpha_k=0.1(k\in K)$, $c_j^{\mathrm{m}}=30$, $c_j^{\mathrm{rm}}=12$, $c_j^{\mathrm{d}}=1.5$, $\alpha_j=0.1(j\in J)$.

Input the above data into the facility model and find the optimal solution with the above algorithm. The optimal solution is shown in Tabs. 6 and 7.

Tab. 6 The optimal solution of non-zero binary variables

Y_1^{m}	Y_1^{rm}	Y_1^{p}	Y_2^{p}	Y_1^{h}	Y_2^{h}
1	1	1	1	1	1

Tab. 7 The optimal solution of non-zero allocation variables

X_{111}^{f}	X_{221}^{f}	X_{311}^{f}	X_{321}^{f}	X_{111}^{r}	X_{221}^{r}	X_{311}^{r}	X_{321}^{r}
1	1	0.464	0.536	1	1	0.222	0.778

It can be seen from Tab. 6 that the first potential site for factories is chosen as an integrated factory and the first and the second potential sites for intermediate facilities are chosen as integrated centers. The logistics flows are allocated according to Tab. 7. The total cost is $7\,917.24\times10^3$. Fig. 2 gives a sensitivity analysis of parameters α_j and α_k.

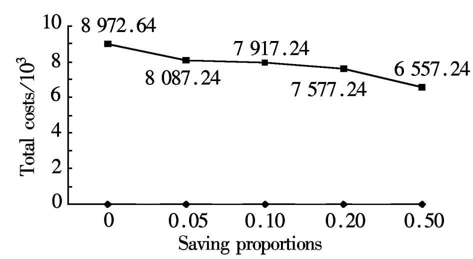

Fig. 2 Sensitivity to changes in parameters α_j and $\alpha_k(\alpha_j=\alpha_k)$

It can be seen from Fig. 2 that as the saving rates α_j and α_k increase, the total costs decrease. In other words, the higher the degree of the integration of homogeneous facilities, the more total costs are saved. Furthermore, the optimal solution is likely to change as the saving proportions vary. For example, when $\alpha_j=\alpha_k=0$, the first potential site for factories is chosen as a producer and the third as a remanufacturing factory, the second potential site for an intermediate facility is chosen as an integrated center, the first as a DC and the third as a CRC. The network has only one integrated facility. When $\alpha_j=\alpha_k\geqslant0.05$, the obtained optimal solutions are equal to the above one, which has three integrated facilities. The results indicate that the integration of homogeneous facilities may influence the optimal solution of the problem to a certain degree.

6 Conclusion

First, we construct a remanufacturing logistics network, in which it is assumed that the remanufactured products can be used together with new products by producers to meet the product demands of customers and all the logistics facilities are capacitated. Then we develop an MINLP facility location model of the remanufacturing logistics network with six types of facilities to be sited, in which forward and reverse logistics are simultaneously considered. Finally, we propose an algorithm to find the optimal solution of small-scale examples and give a sensitivity analysis of the saving rates.

Because the number of potential sites of various facilities in this experiment is small, we can find the optimal solution in a very short time. However, as the scale of the problem expands and the number of potential sites increases, the algorithm in this paper is not likely to solve the problem with-in a few minutes. So it is significant to develop other effective and rapid algorithms to solve large-scale examples of the model.

Moreover, uncertainty is an important characteristic of the reverse logistics. In our model, we assume that all the factors in the network are known and deterministic, which does not accord with reality. It is necessary to improve on the model by adding some indeterministic factors.

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一个再制造物流网络的设施选址模型

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摘要:首先构建了一个再制造物流网络. 在该网络中,正向物流和逆向物流都是双层结构,所有的设施均有能力限制,再制造产品和新产品都可以用来满足顾客的需求,且假设同类设施可以共同设计成集成设施. 在此基础上建立了一个包含6 种设施的再制造物流网络设施选址的混合整数非线性规划(MINLP)模型. 然后给出了基于枚举的求解算法. 用该算法搜索整型变量的可行组合,用线性规划软件解决剩下的子问题. 最后,通过一个算例说明了模型和算法的有效性. 参数灵敏度分析的结果表明,同类设施的集成可能在一定程度上影响问题的最优解.

关键词:逆向物流;再制造物流网络;设施选址

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