Robust Optimization of Closed-Loop Supply Chain Operations under Third-Party Recycling Volume Uncertainty Analysis

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Abstract. In order to improve the collaborative operation performance of a closed-loop supply chain system under the uncertain environment of waste product recycling volume, a multi-objective robust optimization method based on scenario analysis was developed for a third-party recycling-type closed-loop supply chain system consisting of suppliers, manufacturers and third-party recycling-type closed-loop supply chain system composed of suppliers, manufacturers and recycling processing centers, a multi-objective robust optimization model is established using a robust optimization method based on scenario analysis. . The model takes into full consideration the overall coordination of the system operation and also meets the profit maximization goal of each enterprise. The example analysis shows that through the robust optimization analysis shows that through the robust optimization control, the overall profit of the system and the profit of each enterprise can be stabilized within a certain range under the fluctuation of the recycling volume of waste products. When the recycling rate is increased, the overall profit of each enterprise and the system can be increased significantly.

Keywords: closed-loop supply chain; robust optimization; uncertainty.

1 Introduction

The accelerated rate of product replacement leads to more and more significant waste of resources, and recycling and remanufacturing of used and end-of-life products can reduce the environmental The recycling and remanufacturing of used products can reduce environmental pressure, reduce energy consumption, reduce production costs and many other advantages[1].Therefore, product recycling and remanufacturing is beginning to be emphasized by more and more enterprises, there are manufacturers engaged in recycling and remanufacturing, such as Huawei and Xiaomi; there are also third-party remanufacturers engaged in recycling and remanufacturing, such as GEM. The product recycling and remanufacturing process has been emphasized by more and more enterprises. In the process of product recycling and remanufacturing, it is not possible to simply separate suppliers, manufacturers, retailers and recycling centers. In

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the process of product recycling and remanufacturing, suppliers, manufacturers, retailers, and recycling centers cannot be simply separated, so how to better improve the collaborative operation of enterprises in the supply chain and enhance their overall performance has attracted the attention of scholars.

The research on product recycling and remanufacturing in the existing literature was initially based on reverse logistics collaborative operations, and the closed-loop supply chain research started late in China and was developed on the basis of reverse supply chain because of the advantages of saving resources and reduce environmental pollution and other advantages, it has now become the main way to realize circular economy in many developed countries[2].Since uncertainty factors such as market demand, recycling volume of used products, recycling utilization rate, and recycled product quality have a greater impact on the closed-loop supply chain and the volatility of enterprise profit, therefore, under the uncertainty conditions, the study of how the closed-loop supply chain system operates has become the focus of scholars. Therefore, the study of how closed-loop supply chain system operates under uncertain conditions has become the focus of scholars' research. For example, Navid Zarbakhshnia et al. developed a mixed-integer linear programming model under product demand uncertainty to determine the reverse goods transportation strategies for reverse flows[3].Yu Hao et al. developed a fuzzy stochastic multi-objective mathematical model for sustainable closed-loop supply chain network design for balancing cost-effectiveness and environmental performance under different types of uncertainties[4]; Baptista et al. used a two-stage multi-period stochastic hybrid 0+1 bilinear optimization model to maximize the net present value of the total profit over a certain period of time in closed-loop supply chain operations[5]. Xu J W et al. constructed an operational model of a closed-loop supply chain using robust optimization in an environment of demand uncertainty[6]. Hadi et al.used an improved genetic algorithm to construct an environmental hazard model for the closed-loop supply chain of the melting industry in an uncertain environment to optimize the overall profit[7].

At present, domestic and foreign scholars' research methods on supply chain network under uncertainty conditions mainly include stochastic planning, fuzzy planning and robust optimization methods. The advantage of the robust optimization method is that it can consider the variation of the objective function value under the interference of uncertainty factors and increase the robustness of the system at the same time, instead of only focusing on the mathematical expectation value of the objective function. Therefore, based on the existing literature, this paper establishes a robust optimization model for the operation of the third-party recycling-type closed-loop supply chain system under the uncertainty environment, taking into account the uncertainty of the recycling volume of the third-party recycling-type closed-loop supply chain and the optimal cost of the closed-loop supply chain system operation, and aiming at the overall coordination of the operation of the closed-loop supply chain system and the maximization of the profit of the members, and analyzes and illustrates the model through the calculation examples. The model is also analyzed through examples to illustrate the application of the model in enterprise operation, which provides new ideas for the design and operation of the third-party recycling-type closed-loop supply chain system.

2 Description of the Problem

In this paper, through a multi-tier, multi-product, third-party recycling-based closed-loop supply chain system. the forward logistics consists of suppliers, manufacturers and customers, where suppliers buy raw materials from the raw material market to process them into materials, and manufacturers buy materials from suppliers to process and manufacture them into new products and then sell them directly to the customer points; and the reverse network consists of customers, recycling centers, manufacturers, and suppliers, where Among them, the recycling center recovers the consumed products from the customers and inspects them to divide them into four categories:

(1) Parts suitable for repair, which are shipped to manufacturers for repair and re-sale; (2) Parts suitable for dismantling, which are dismantled into components and shipped to suppliers for disposal; (3) Parts that are suitable for complete disassembly into raw materials will be disassembled into raw materials and shipped to the raw material market for disposal. (4) Parts that cannot be reused are directly discarded and transported to the garbage disposal station for disposal.

The main task in the optimization of a third-party recycling-based closed-loop supply chain system under uncertainty in the amount of used and end-of-life products to be recycled is to determine the manufacturer's sales and profit, the producer's production and profit, the recycling center's actual recycling volume and profit, and the overall profit of the closed-loop supply chain system for a given closed-loop supply chain system operating cycle as well as the closed-loop supply and demand for the products in the closed-loop supply chain system, the product price, the price of the raw materials, the recycling costs, the disposal costs of the products, and the other operational costs of the closed-loop supply chain system.

In establishing the closed-loop supply chain model under the uncertainty of the recycling volume of waste products, the following four objective functions are to be considered comprehensively: (1) Coordination of the overall operation of the supply chain, i.e., the manufacturer orders the same amount of material and the supplier delivers the same amount of material. (2) Manufacturers to maximize profits. (3) Suppliers maximize profits. (4) Recycling processing center to maximize profits. The specific parameter settings and variable descriptions are shown in Table 1.

Table 1. Model Parameters and Variables Explained

Parameter	Parameter definition	Parameter	Parameter definition
i	Materials of the manufacturer (i=1,2,…,I)	u_i^y	Manufacturer's unit inventory cost for material i
.j	final product(j=1,…,J)	u_i^z	Supplier's unit inventory cost for material i
t	stage(t=1,2,…,T)	u_j^w	The unit inventory cost of the third-party recycling center for the waste product j

h	Raw materials of suppliers(h=1,2,…,H)	o_j^x	Unit Material i Occupies Supplier's Inventory
a_{jt}	Sales volume of product j at stage t	$x_{j0}^{L^*}$	Initial inventory of final product j
x_{jt}	Production of product j in stage t	$y_{j0}^{L^*}$	Manufacturer's initial inventory of material i
x_{jt}^L	Inventory of product j in stage t	$z_{j0}^{L^*}$	Supplier's initial inventory of material i
y_{it}^L	The manufacturer's inventory of material i in stage t	$g_{j0}^{L^*}$	The initial inventory of waste product j by the third-party recycling center
v_{it}	The manufacturer's order quantity of material i in stage t	$X^{L_{max}}$	Total inventory capacity of the manufacturer 's products
l_{it}	Supplier's delivery of material i in stage t	$Y^{L_{max}}$	Ttotal inventory capacity of manufacturer 's materials
z_{it}	Supplier's productive output of material i in stage t	$Z^{L_{max}}$	Total inventory capacity of supplier raw materials
z_{it}^L	The supplier 's inventory of material i in stage t	$G^{L_{max}}$	Third-party recycling center total inventory capacity
f_{jt}	The actual recovery amount of product j in stage t	s_{ji}^x	Bill of materials coefficient of product j to material i
g_{jt}^L	The inventory of waste product j by the third-party recycling center in stage t	s_{ih}^x	Bill of materials coefficient of material i to raw materials
d_{jt}	The demand for product j in stage t	s_{ht}	The supply of raw material h in stage t
p_{jt}	Price of product j in stage t	μ_j^k	Consumption rate per unit production capacity of product j
q_{jt}	Price of material i in stage t	μ_i^e	Consumption rate per unit production capacity of material i
r_{ht}	Price of raw material h in stage t	K^{max}	Manufacturer's maximum production capacity
β_{jt}	The recovery cost of waste product j in stage t	E^{max}	Supplier maximum production capacity
c_j^x	Variable manufacturing cost per unit of product j	F^{max}	The maximum waste disposal capacity of the third-party recycling center
c_i^z	Supplier's unit variable cost of producing material i	γ_{jt}^1	Maintenance cost of recycling waste product j in stage t
u_j^x	The unit inventory cost of product j	γ_{jt}^2	Disassembly cost of waste product j in stage t
γ_{jt}^3	Decomposition cost of waste product j in stage t	θ_{jt}^1	Maintenance rate of waste product j in stage t

θ_{jt}^{2}	Disassembly rate of waste product j in stage t	θ_{jt}^{3}	Decomposition rate of waste product j in stage t
α_{jt}^{1}	The cost of recovering the repairable waste product j by the manufacturer in stage t	α_{jt}^{2}	The cost of materials purchased by the supplier from the third-party recycling center in the stage t
α_{jt}^{3}	Raw material market cost of purchasing raw materials from third-party recycling centers in stage t	e_{jt}	Supplier's shortage of product j in stage t
ε_{ht}	Remaining supply of raw material h in stage t	ς_{jt}	Recovery rate of waste product j in stage t
μ_{j}^{ι}	The unit processing capacity consumption rate of waste product j	o_{j}^{w}	Unit product j Occupies the inventory of third-party recycling centers
η_{jt}	Transportation cost of waste product j in stage t	k_{jt}	The recovery amount of waste product j in stage t

The following assumptions are made when building the model:

Assumption 1: The third-party recycling and processing center recycles and processes used products, and sells repairable used products directly to the main manufacturer, assuming that there is no quality difference between the repaired product and the newly manufactured product.

Assumption 2: It indicates the delayed recycling of used products, i.e., products sold to customers at stage t can only be recycled after a period of time.

Assumption 3: When disassembling, the disassembled materials of the unit of waste products can be completely recycled and reused, and there is no quality difference; when disassembling, all the raw materials of the waste products can be completely recycled and reused, and there is no quality difference.

Assumption 4: The maximum use time of product is N_j.

3 Closed-Loop Supply Chain Robust Optimization Model

3.1 Specific Operational Objectives the Above 4 Objectives are Modeled as Follows

Objective 1: Overall supply chain coordination:

$$v_{it} = l_{it} \qquad \forall i,t$$

Objective 2: Manufacturer profit maximization:

$$\max c^{R} = \sum_{t=1}^{T}[\sum_{j=1}^{J}(p_{jt}a_{jt} - c_{j}^{x}x_{jt} - u_{j}^{x}x_{jt}^{L} - w_{1j}e_{jt}) - \sum_{i=1}^{I}(q_{it}v_{it} + u_{i}^{y}y_{it}^{L})]$$
$$-\sum_{s\in\Omega} p_{s}[\sum_{t=1}^{T}\sum_{j=1}^{J}(\alpha_{jt} + \gamma_{jt})\sum_{k=1}^{t-\pi} f_{j,k}^{s}\theta_{jt}^{1}]$$

Objective 3: Supplier profit maximization:

$$\max c^z = \sum_{t=1}^{T}\sum_{i=1}^{I}(q_{it}l_{it} - c_i^z z_{it}^L - u_i^z z_{it}^L - z_{it}\sum_{h=1}^{H} r_{ht}s_{it}) - \sum_{t=1}^{T}\sum_{h=1}^{I}(w_{2h}\varepsilon_{ht})$$
$$+\sum_{s\in\Omega} p_s[\sum_{t=1}^{T}\sum_{j=1}^{J}(r_{ht} - \alpha_{jt}^2)\sum_{k=1}^{t-\pi}(f_{jk}^s\theta_{jt}^2)\sum_{i=1}^{I}\sum_{h=1}^{H}(s_{jt}^x s_{th}^z)]$$

Objective 4: Maximize the profit of the recycling and processing center:

$$\max c^N = \sum_{s\in\Omega} p_s[\sum_{t=1}^{T}\sum_{j=1}^{J}(\alpha_{jt}^1\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^1 + \alpha_{jt}^2\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^2 + \alpha_{jt}^3\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^3)$$
$$-\sum_{k=1}^{t-\pi}\sum_{j=1}^{J}\beta_{jt}f_{jk}^s - \sum_{j=1}^{J}\sum_{t=1}^{T}u_j^w g_{it}^L] - \sum_{s\in\Omega} p_s\sum_{j=1}^{J}\sum_{k=1}^{t-\pi}(\gamma_{jt}^2 f_{jk}^s\theta_{jt}^2 + \gamma_{jt}^3 f_{jk}^s\theta_{jt}^3)$$
$$-\sum_{s\in\Omega} p_s\sum_{k=1}^{t-\pi}\sum_{j=1}^{J}\eta_{jt}f_{jk}^s(1-\theta_{jt}^1 - \theta_{jt}^2 - \theta_{jt}^3)$$

3.2 Description of the Basic Model

In this paper, the above four specific objectives are to be considered comprehensively when constructing the basic model of closed-loop supply chain operation. However, the realization of multiple objectives is contradictory to each other, so this model realizes the coordination between different objectives by adding different priority levels. Since the overall coordination of supply chain is the first condition for supply chain operation and satisfying customer demand, the overall coordination of supply chain is set as the maximum priority level, while the other three objectives have the same priority level. Assume that MR is the manufacturer's desired profit, MZ is the supplier's desired profit, MN is the third-party recycling and processing center's desired profit, d_r^- is the manufacturer's desired profit unrealized, d_z^- is the supplier's desired profit unrealized, d_N^- is the third-party recycling and processing center's unrealized, d_{it}^+ and d_{it}^- denote the surplus and shortage values of the material i delivered by the supplier and the material i ordered by the manufacturer at stage, respectively. The multi-objective model of closed-loop supply chain operation under the uncertainty of recycling quantity of used products can be obtained by setting different priority factors and considering multiple operational objectives.

$$\min \kappa_s = p_T\sum_{t=1}^{T}\sum_{i=1}^{I}(d_{it}^+ + d_{it}^-) + p_R d_R^- + p_Z d_Z^- + p_N d_N^-$$

3.3 Constraints

(1) Transform objective 1 into objective constraints

$$v_{it} - l_{it} + d_{it}^{-} - d_{it}^{+} = 0 \ \forall i,t$$

(2) Transform objective 2 into objective constraints

$$c^R + d_R^- - d_R^+ = M^R$$

$$c^R \le \sum_{t=1}^{T}[\sum_{j=1}^{J}(p_{jt}a_{jt} - c_j^x x_{jt} - u_j^x x_{jt}^L - w_{1j}e_{jt}) - \sum_{i=1}^{I}(q_{it}v_{it} + u_i^y y_{it}^L)]$$
$$-\sum_{s\in\Omega} p_s[\sum_{t=1}^{T}\sum_{j=1}^{J}(\alpha_{jt} + \gamma_{jt})\sum_{k=1}^{\pi} f_{jk}^s \theta_{jt}^1]$$

(3) Transform objective 3 into objective constraints

$$c^Z + d_z^- - d_z^+ = M^Z$$

$$c^Z \le \sum_{t=1}^{T}\sum_{i=1}^{I}(q_{it}l_{it} - c_i^z z_{it}^L - u_i^z z_{it}^L - z_{it}\sum_{h=1}^{H} r_{ht}s_{it}) - \sum_{t=1}^{T}\sum_{h=1}^{I}(w_{2h}\varepsilon_{ht})$$
$$+\sum_{s\in\Omega} p_s[\sum_{t=1}^{T}\sum_{j=1}^{J}(r_{ht} - \alpha_{jt}^2)\sum_{k=1}^{t-\pi}(f_{jk}^s\theta_{jt}^2)\sum_{i=1}^{I}\sum_{h=1}^{H}(s_{jt}^x s_{th}^z)]$$

(4) Transform objective 4 into objective constraints

$$c^N + d_N^- - d_N^+ = M^N$$

$$c^N \le \sum_{s\in\Omega} p_s[\sum_{t=1}^{T}\sum_{j=1}^{J}(\alpha_{jt}^1\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^1 + \alpha_{jt}^2\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^2 + \alpha_{jt}^3\sum_{k=1}^{t-\pi} f_{jk}^s\theta_{jt}^3)$$
$$-\sum_{k=1}^{t-\pi}\sum_{j=1}^{J}\beta_{jt}f_{jk}^s - \sum_{j=1}^{J}\sum_{t=1}^{T}u_j^w g_{it}^L] - \sum_{s\in\Omega} p_s\sum_{j=1}^{J}\sum_{k=1}^{t-\pi}(\gamma_{jt}^2 f_{jk}^s\theta_{jt}^2 + \gamma_{jt}^3 f_{jk}^s\theta_{jt}^3)$$
$$-\sum_{s\in\Omega} p_s\sum_{k=1}^{t-\pi}\sum_{j=1}^{J}\eta_{jt}f_{jk}^s(1-\theta_{jt}^1 - \theta_{jt}^2 - \theta_{jt}^3)$$

(5) Manufacturer's production capacity

$$\sum_{j=1}^{J}\mu_j^k x_{jt} \le K^{\max}$$

(6) Manufacturer's final product inventory constraints

$$x_{jt}^L = x_{j,t-1}^L + x_{jt} + \sum_{k=1}^{t-\pi} f_{j,t-k}^s\theta_{jt}^1 - a_{jt} \ \ \forall j,t,s$$

$$x_{j0}^{L} = x_{j0}^{L_0} \ \forall i$$

$$\sum_{j=1}^{J} x_{jt}^{L} o_j^{x} \le X^{L\max}$$

(7) Manufacturer's material inventory constraint

$$y_{it}^{L} = y_{i,t-1}^{L} + v_{it} - \sum_{j=1}^{J} s_{jt}^{x} x_{jt} \ \forall j, t, s$$

$$y_{i0}^{L} = y_{i0}^{L_0} \ \forall i$$

$$\sum_{i=1}^{I} y_{it}^{L} o_i^{y} \le Y^{L\max} \ \forall t$$

(8) Manufacturer's product sales volume

$$a_{jt} + e_{jt} = d_{jt} \ \forall j, t$$

(9) Supplier material absolute constraint

$$z_{it}^{L} = z_{i,t-1}^{L} + z_{it} + \sum_{k=1}^{t-\pi} f_{j,t-k}^{s} \theta_{jt}^{2} - l_{it} \ \forall i, j, t, s$$

$$z_{i0}^{L} = z_{i0}^{L_0} \ \forall i$$

$$\sum_{i=1}^{I} z_{it}^{L} o_i^{z} \le z^{L\max} \ \forall t$$

(10) Supplier's production capacity absolute constraint

$$\sum_{i=1}^{I} \mu_i^{\varepsilon} z_{it} \le E^{\max} \ \forall t$$

(11) Raw material supply absolute constraint

$$\sum_{i=1}^{I} s_{ih}^{z} [z_{it} - \sum_{j=1}^{J} s_{jt}^{x} \sum_{k=1}^{t-\pi} f_{j,t-k}^{s} \theta_{jt}^{2}] <= s_{ht} \ \forall h, t, s$$

(12) Absolute constraints on the processing capacity of third-party recycling and processing centers

$$\sum_{j=1}^{J} \mu_j^{\iota} f_{jk}^{s} \le F^{\max} \ \forall k, s$$

(13) Absolute constraints on inventory of used products at third-party recycling and processing centers

$$g_{jt}^{L} = g_{j,t-1}^{L} + f_{jt} - \sum_{k=1}^{t-\pi} f_{jk}^{s}(\theta_{jt}^{1} + \theta_{jt}^{2} + \theta_{jt}^{3}) \ \forall j,t,s$$

$$g_{j0}^{L} = g_{j0}^{L_0} \ \forall j$$

$$\sum_{j=1}^{J} g_{jt}^{L} o_{j}^{w} \le G^{L\max} \ \forall t$$

(14) Actual recycling constraints of the third-party recycling processing center

$$f_{jt}^{s} \times \varsigma_{jt}^{s} <= k_{jt}^{s} \ \forall s,j,t$$

(15) Non-negative constraints

$$a_{jt}, x_{jt}, x_{jt}^{L}, y_{jt}^{L}, v_{it}, l_{it}, z_{it}, z_{it}^{L}, f_{jt}, g_{jt}^{L}, d_{it}^{-}, d_{it}^{+}, d_{R}^{-}, d_{R}^{+}, d_{Z}^{-}, d_{Z}^{+}, d_{N}^{-}, d_{N}^{+}, c^{R}, c^{Z}, c^{N} \ge 0$$

3.4 Robust Optimization Model

In this paper, the coordination of the supply chain system operation and the uncertainty of the recycling volume of used products are considered together, and different scenarios are analyzed to describe the uncertainty of the recycling volume of used products. In order to ensure that the model is feasible and optimal in any possible scenario, this paper establishes a closed-loop supply chain system design model that considers both solution robustness and model robustness based on the robust optimization method proposed by Mulvey et al[8].

$$\min[\sum_{s=1}^{S} p_s \kappa_s \text{-} \lambda \sum_{s=1}^{S} p_s [(\sum_{s'} p_{s'} \kappa_{s'} - \kappa_s) + 2v_s]] - \omega \sum_{s=1}^{S} \sum_{h=1}^{H} \sum_{j=1}^{J} \sum_{t=1}^{T} p_s (e_{jt} + \varepsilon_{ht})$$

4 Conclusion

This paper investigates the optimization design problem of a third-party recycling-type closed-loop supply chain system, with the purpose of exploring how to keep the operation of the system robust under the influence of uncertainty while maximizing the profit of the enterprise. Using the robust optimization method based on scenario analysis, a robust optimization model is established under the uncertainty of the recycling volume of used products, and the model is proved to be both solution-robust and model-robust through simulation analysis. The optimization design of the supply chain system model can maintain the continuity of the third-party recycling closed-loop supply chain system operation under the fluctuation of the recycling volume of used products and obtain the optimal enterprise operation strategy, which can provide corresponding suggestions for the decision makers.

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