Building a Multi-Objective Flexible Optimal Decision Model for Green Supply Chains

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Abstract. Due to climate change, the importance of environmental protection, and the operation of the global supply chain influenced by the pandemic, building a flexible green supply chain model can help enterprises keep operational sustainability and strengthen competitive advantages. However, it can be found from relevant literature that research on green supply chain flexibility is still insufficient. This study aims to fill the research gap, and attempts to develop a multi-objective mixed integer programming model for a flexible green supply chain network design to maximize the profit, the amicable production level. To our knowledge, this proposed model is the first effort to take economic factors, environmental factors, supply flexibility, manufacturing flexibility, distribution flexibility and reverse logistics flexibility into account simultaneously, and can be a reference for supporting effectively management of the green supply chain network design. The research result and findings can be a reference for related academic researches and also can be used to guide the development of a green supply chain model for making better decision.

1 Introduction

Economic growth and the demand for energy and material consumption has led to increased attention to the environmental protection and conservation of natural resources [1]. In response to such environmental pressure and industrial development ecology, enterprises are forced to pay attention to green and sustainable business transformation and development.

Under the development of globalized supply chain operations, how to confirm that the supply chain must be resilient to survive in a changing environment is another major issue for enterprises. Due to the sudden outbreak and continuous spread of the epidemic, the ability of the supply chain to maintain normal operations has become extremely important. In recent years, the flexibility of the supply chain has received more and more attention [2]. Faced with the uncertainty of customer demand and market changes, enterprises should have the capability to quickly adjust and reorganize the operation of the supply chain to effectively and instantly respond to the needs of the market and customers for maintaining their competitive advantages. Supply chain flexibility is an important element in creating high-performance supply chain operations [3].

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Due to government legislation, the potential of economic value growth and consumer demand for green practices, manufacturers must focus on the interaction of flexibility and green issues into supply chain management which can effectively respond to sudden changes in the environment, reduce business interruption opportunities or reduce business losses [4]. Making good use of the flexible operation of the supply chain can help the operation of the enterprise's green supply chain to be more flexible and agile, and can more effectively respond to emergencies in the external environment, and can continue to maintain the stability of the enterprise's operation and maintenance.

The combination of green/sustainable supply chain issues and supply chain flexibility will be the key direction of enterprise supply chain development in the near future, but so far, the research for the combination of green supply chain and supply chain flexibility is still insufficient [2,5,6]. This study proposes multi-objective mixed-integer programming model of the closed-loop supply chain network with two objective functions including maximizing the profit and the amicable production level. In the proposed model, supply flexibility, manufacturing flexibility, distribution flexibility and reverse logistics flexibility are considered simultaneously. The rest of this paper is organized as follows. Section 2 reviews relevant literature. Section 3 is devoted to the proposed mathematical model. Conclusions are discussed in section 4.

2 Literature Review

Hervani et al. [7] defined that green supply chain management includes green procurement, green manufacturing and material management, green distribution/marketing and reverse logistics. Srivastava [8] defined that green supply chain integrates environmental considerations into supply chain management, including product design, raw material search and purchase, manufacturing process, final product delivery process to consumers, and the end of the product life cycle management. In order to improve green supply chain management, Zhao et al. [9] proposed a multi-objective optimization model to minimize the hidden risks of hazardous substances, minimize related carbon emissions, and minimize economic costs. Three scenarios were used to analyse the impact of green factors on supply chain management. Mahdi Saffar [10] proposed a supply chain network design model with two objective functions. The first objective function is to minimize the total cost, including equipment fixed costs, distribution costs, production and maintenance costs; the second objective function is to minimize carbon dioxide emissions.

Supply chain flexibility refers to the ability that allows all supply chain members to adapt or respond to the unpredictability of the external environment and meet the diversity of customer needs without bearing additional costs, time, organizational disturbances, and performance losses. Supply chain flexibility is a process-oriented view, and the flexibility it considers includes all activities in the value chain [11]. In order to construct a measurement tool for supply chain flexibility in the textile industry, Moon et al. [12] defined four types of supply chain flexibility, including procurement flexibility, operating system flexibility, distribution flexibility, and information system flexibility. Esmaeilikia et al. [13] developed a strategic supply chain model including procurement flexibility, manufacturing flexibility, and logistics flexibility to analyse the flexible adjustment in the existing supply chain. Das [14] developed a mixed integer nonlinear supply chain planning model, including output flexibility, product mix flexibility, supply flexibility, customer service satisfaction flexibility to maximize profit, and utilized sensitivity analysis to find the impact of flexible changes to the output of supply chain model.

Green supply chain flexibility is a multifaceted concept that covers at least four major closed-loop supply chain processes including supply, manufacturing, distribution/logistics, and reverse logistics [13]. Green supply flexibility includes the ability to adjust available green suppliers, influence suppliers' green material and service performance, etc. [15]. Green manufacturing flexibility includes the ability to convert acquired resources to produce more diverse green products and services. Green distribution flexibility is the ability to control the distribution function of material movement and storage among supply chain member companies [16]. Reverse logistics flexibility is the reverse logistics functional capability to manage reverse logistics in response to external stakeholder requirements. Considering flexible lead time, nonlinear procurement and shortage cost functions, and demand uncertainty, Mirzapour et al. [17] developed a mixed integer programming model to solve multi-period, multi-product, multi-level green supply chain production planning questions. Karimi et al. [18] developed an environmental supply chain flexibility model including employee team training flexibility, procurement flexibility, production line flexibility, and budget flexibility to minimize cost and environmental pollution.

From the relevant literature, there is no flexible green supply chain resource allocation optimization model that simultaneously considers supply flexibility, manufacturing flexibility, distribution/logistics flexibility and reverse logistics flexibility. In order to fulfilling the research gap, this study develops a multi-objective resource allocation decision-making model for green supply chain flexibility. The two objectives are maximizing profit and amicable production level, while including the supply flexibility, manufacturing flexibility, distribution flexibility and reverse logistics flexibility in the constraints.

3 Model Formulation

3.1 Problem Definition

This study considers a multi-period, multi-product, multi-echelon flexible green closed-loop supply chain network, including suppliers, manufacturing centers, customers, and collection centers. The suppliers offer general materials or green materials to manufacturing centers. The new products are manufactured by manufacturing centers with normal facilities or with green facilities. The products are sent to customers using normal transport facilities or green transport facilities. The products are returned from customers and sent to collection centers. After the returned products are decomposed by the collection centers (either in-house collection centers or outsourced collection centers), returned materials are sent back to the manufacturing centers for new products. The proposed closed-loop supply chain network is illustrated in Figure 1.

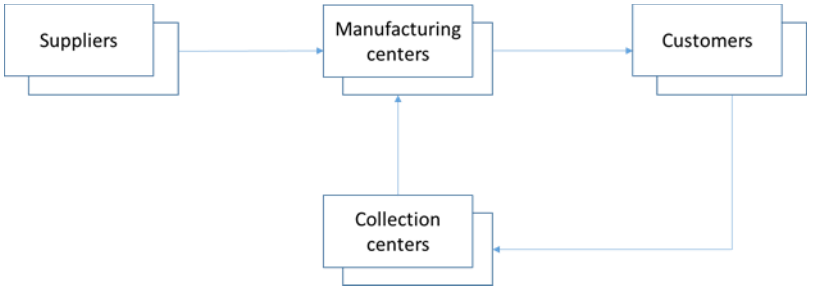

Fig. 1. The proposed closed-loop supply chain network.

According to the processes mentioned above, this study proposes a resource allocation optimization model for maxing the total profit and the amicable production level, simultaneously taking supply flexibility, manufacturing flexibility, distribution flexibility and reverse logistics flexibility into account. The hypotheses of this research are drawn as follows:

- Locations of suppliers and customers are known and fixed.
- Locations of manufacturing centers and collection centers are known and fixed.
- Inventory in manufacturing centers is considered.
- The limited capacity of the suppliers, the manufacturing centers and collection centers is considered.
- There is no limitation of transportation time between nodes in the network.

3.2 Model Description

To describe the aforementioned supply chain network and solve the defined problems, the formulation of objective functions and constraints are shown as follows.

3.2.1 Objective functions

This goal of this proposed multi-objective closed-loop supply chain model is to optimize resource allocation for attaining the two objectives: maximizing the total profit and the amicable production level.

Max OB1= Revenue- Purchase cost- Production cost- Reused processing cost- Distribution cost- Inventory cost (1)

Revenue=

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m'=1}^{y}\sum_{p=1}^{P} QS_{pm'ct} \times P_{pct} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m''=y+1}^{M}\sum_{p=1}^{P} QS_{pm''ct} \times P_{pct} \quad (1.1)$$

Purchase cost=

$$\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{r'=1}^{x} QR_{sr'pt} \times SP_{sr'} + \sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{r''=x+1}^{R} QR_{sr''pt} \times SP_{sr''} \quad (1.2)$$

Production cost=

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m'=1}^{y}\sum_{p=1}^{P} QP_{pm'ct} \times MC_{m'p} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m''=y+1}^{M}\sum_{p=1}^{P} QP_{pm''ct} \times MC_{m''p} \quad (1.3)$$

Reused processing cost=

$$\sum_{t=1}^{T}\sum_{l'=1}^{z}\sum_{c=1}^{C}\sum_{p=1}^{P} QR_{pcl't} \times LC_{l'p} + \sum_{t=1}^{T}\sum_{l''=z+1}^{L}\sum_{c=1}^{C}\sum_{p=1}^{P} QR_{pcl''t} \times LC_{l''p} \quad (1.4)$$

Distribution cost=

$$\sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m'=1}^{y}\sum_{p=1}^{P} QS_{pm'cd't} \times DC_{pm'cd'} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m'=1}^{y}\sum_{p=1}^{P} QS_{pm'cd''t} \times DC_{pm'cd''} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m''=y+1}^{M}\sum_{p=1}^{P} QS_{pm''cd't} \times DC_{pm''cd'} + \sum_{t=1}^{T}\sum_{c=1}^{C}\sum_{m''=y+1}^{M}\sum_{p=1}^{P} QS_{pm''cd''t} \times DC_{pm''cd''} + \sum_{t=1}^{T}\sum_{l'=1}^{z}\sum_{m'=1}^{y}\sum_{u=1}^{U} QU_{ul'm't} \times UC_{ul'm'} + \sum_{t=1}^{T}\sum_{l'=1}^{z}\sum_{m''=y+1}^{M}\sum_{u=1}^{U} QU_{ul'm''t} \times UC_{ul'm''} + \sum_{t=1}^{T}\sum_{l''=z+1}^{L}\sum_{m'=1}^{y}\sum_{u=1}^{U} QU_{ul''m't} \times UC_{ul''m'} + \sum_{t=1}^{T}\sum_{l''=z+1}^{L}\sum_{m''=y+1}^{M}\sum_{u=1}^{U} QU_{ul''m''t} \times UC_{ul''m''} \quad (1.5)$$

Inventory cost=

$$\sum_{t=1}^{T}\sum_{m'=1}^{y}\sum_{p=1}^{P} QI_{pm't} \times IC_{pm'} + \sum_{t=1}^{T}\sum_{m''=y+1}^{M}\sum_{p=1}^{P} QI_{pm''t} \times IC_{pm''} \quad (1.6)$$

Max OB2=

$$\sum_{t=1}^{T}\sum_{p=1}^{P}\sum_{s=1}^{S}\sum_{r''=x+1}^{R} QR_{sr''pt} + \sum_{t=1}^{T}\sum_{l''=z+1}^{L}\sum_{c=1}^{C}\sum_{p=1}^{P} QR_{pcl''t} + \sum_{t=1}^{T}\sum_{m'=1}^{y}\sum_{c=1}^{C}\sum_{p=1}^{P} QS_{pm'cd''t} + \sum_{t=1}^{T}\sum_{m''=z+1}^{M}\sum_{c=1}^{C}\sum_{p=1}^{P} QS_{pm''cd''t} \quad (2)$$

The first objective function is to maximize the total profit which is computed by subtracting purchase cost, production cost, reused processing cost, distribution cost, and inventory cost from total revenue. The purchase cost is for purchasing general raw materials or green materials from suppliers to produce products. The production cost is for producing products by manufacturing centers using normal or green facilities. The reused processing cost is for inspection, collection, and decomposition of returned products by collection centers. The distribution cost is for shipping products or reused materials between facilities in the proposed supply chain network. The inventory cost is for stored products by manufacturing centers. The second objective function is to maximize the amicable production level including the amount of using green materials, green manufacturing, and green distribution.

3.2.2 Constraints

$$\sum_{s=1}^{S} QR_{sr'pt} + QR_{sr''pt} \geq \sum_{c=1}^{C}\left(\sum_{m'=1}^{y} QP_{pm'ct} + \sum_{m''=y+1}^{M} QP_{pm''ct}\right) \times R_{rp} \quad \forall r,p,t \tag{3}$$

$$\sum_{p=1}^{P} QR_{sr'pt} \leq SP_{sr'} \times IS_{sr't} \quad \forall s,r',t \tag{4}$$

$$\sum_{p=1}^{P} QR_{sr''pt} \leq SP_{sr''} \times IS_{sr''t} \quad \forall s,r'',t \tag{5}$$

$$LN \times IS_{sr''t} \geq SP_{sr''} - \sum_{p=1}^{P} QR_{sr''pt} \quad \forall s,r'',t \tag{6}$$

$$IS_{sr''t} \times \sum_{p=1}^{P} QR_{sr''pt} \geq IS_{sr''t} \times \sum_{p=1}^{P}\left(R_{rp} \times \sum_{m=1}^{M}\sum_{c=1}^{C} QP_{pmct}\right) \quad \forall s,r'',t \tag{7}$$

$$IS_{sr''t} \times \sum_{p=1}^{P} QR_{sr'pt} = 0 \quad \forall s,r'',t \tag{8}$$

$$QP_{pm'ct} + QI_{pm'(t-1)} - QI_{pm't} = QS_{pm'ct} \quad \forall p,m',c,t \tag{9}$$

$$QP_{pm''ct} + QI_{pm''(t-1)} - QI_{pm''t} = QS_{pm''ct} \quad \forall p,m'',c,t \tag{10}$$

$$\sum_{c=1}^{C} QP_{pm'ct} \leq IM_{m't} \times MP_{m'p} \quad \forall p,m',t \tag{11}$$

$$\sum_{c=1}^{C} QP_{pm''ct} \leq IM_{m''t} \times MP_{m''p} \quad \forall p,m'',t \tag{12}$$

$$QI_{pm't} \leq IM_{m't} \times IP_{m'p} \quad \forall p,m',t \tag{13}$$

$$QI_{pm''t} \leq IM_{m''t} \times IP_{m''p} \quad \forall p,m'',t \tag{14}$$

$$LN \times IM_{m''t} \geq MP_{m''p} - \sum_{c=1}^{C} QP_{pm''ct} \quad \forall p,m'',t \tag{15}$$

$$IM_{m''t} \times \sum_{c=1}^{C} QS_{pm''ct} \geq IM_{m''t} \times \sum_{c=1}^{C} DP_{pct} \quad \forall p,m'',t \tag{16}$$

$$IM_{m''t} \times \sum_{c=1}^{C} QS_{pm'ct} = 0 \quad \forall p,m'',t \tag{17}$$

$$\sum_{m'=1}^{Y} QS_{pm'ct} + \sum_{m''=1}^{M} QS_{pm''ct} \geq DP_{pct} \quad \forall c,p,t \tag{18}$$

$$QS_{pm'cd't} + QS_{pm'cd''t} = QS_{pm'ct} \quad \forall c,p,m',t \tag{19}$$

$$QS_{pm''cd't} + QS_{pm''cd''t} = QS_{pm''ct} \quad \forall c,p,m'',t \tag{20}$$

$$\sum_{c=1}^{C} QS_{pm'cd't} \leq IM_{m't} \times FP_{m'pd'} \quad \forall p,m',t \tag{21}$$

$$\sum_{c=1}^{C} QS_{pm'cd''t} \leq IM_{m't} \times FP_{m'pd''} \quad \forall p,m',t \tag{22}$$

$$\sum_{c=1}^{C} QS_{pm''cd't} \leq IM_{m''t} \times FP_{m''pd'} \quad \forall p,m'',t \tag{23}$$

$$\sum_{c=1}^{C} QS_{pm''cd''t} \leq IM_{m''t} \times FP_{m''pd''} \quad \forall p,m'',t \tag{24}$$

$$LN \times ID_{m'd''t} \geq FP_{m'pd''} - \sum_{c=1}^{C} QS_{pm'cd''t} \quad \forall p,m',t \tag{25}$$

$$ID_{m'd''t} \times \sum_{c=1}^{C} QS_{pm'cd''t} \geq ID_{m'd''t} \times \sum_{c=1}^{C} DP_{pct} \quad \forall p,m',t \tag{26}$$

$$ID_{m'd''t} \times \sum_{c=1}^{C} QS_{pm'cd't} = 0 \quad \forall p,m'',t \tag{27}$$

$$LN \times ID_{m''d''t} \geq FP_{m''pd''} - \sum_{c=1}^{C} QS_{pm''cd''t} \quad \forall p,m'',t \tag{28}$$

$$ID_{m''d''t} \times \sum_{c=1}^{C} QS_{pm''cd''t} \geq ID_{m''d''t} \times \sum_{c=1}^{C} DP_{pct} \quad \forall p,m'',t \tag{29}$$

$$ID_{m''d''t} \times \sum_{c=1}^{C} QS_{pm''cd't} = 0 \quad \forall p,m'',t \tag{30}$$

$$\sum_{c=1}^{C}\sum_{l'=1}^{z} QR_{pcl't} + \sum_{c=1}^{C}\sum_{l''=z+1}^{L} QR_{pcl''t} \leq RP_{pt} \times \sum_{c=1}^{C} DP_{pct} \quad \forall p,t \tag{31}$$

$$\sum_{c=1}^{C} QR_{pcl't} \leq IL_{l't} \times LP_{l'p} \quad \forall p,l',t \tag{32}$$

$$\sum_{c=1}^{C} QR_{pcl''t} \leq IL_{l''t} \times LP_{l''p} \quad \forall p,l'',t \tag{33}$$

$$\sum_{m'=1}^{y} QU_{ul'm't} + \sum_{m''=y+1}^{M} QU_{ul'm''t} \leq R_{up} \times \sum_{c=1}^{C} QR_{pcl't} \quad \forall p,u,l',t \tag{34}$$

$$\sum_{m'=1}^{y} QU_{ul''m't} + \sum_{m''=y+1}^{M} QU_{ul''m''t} \leq R_{up} \times \sum_{c=1}^{C} QR_{pcl''t} \quad \forall p,u,l'',t \tag{35}$$

$$LN \times IL_{l't} \geq LP_{l'p} - \sum_{c=1}^{C} QR_{pcl't} \quad \forall p,l',t \tag{36}$$

$$IL_{l't} \times \left(\sum_{m'=1}^{y} QU_{ul'm't} + \sum_{m''=y+1}^{M} QU_{ul'm''t}\right) \leq IL_{l't} \times R_{up} \times \sum_{c=1}^{C} QR_{pcl't} \quad \forall p,u,l',t \tag{37}$$

$$IL_{l't} \times \left(\sum_{m'=1}^{y} QU_{ul''m't} + \sum_{m''=y+1}^{M} QU_{ul''m''t}\right) = 0 \quad \forall p,u,l'',t \tag{38}$$

$$QR_{sr'pt},\ QR_{sr''pt},\ QP_{pm'ct},\ QI_{pm't},\ QI_{pm''t},\ QR_{pcl't},\ QR_{pcl''t},\ QU_{ul'm't},\ QU_{ul'm''t},\ QU_{ul''m't},\ QU_{ul''m''t},\ QS_{pm'cd't},\ QS_{pm'cd''t},\ QS_{pm''cd't},\ QS_{pm''cd''t},\ QS_{pm'ct},\ QS_{pm''ct} \tag{39}$$

$$IS_{sr't},\ IS_{sr''t},\ IM_{m't},\ IM_{m''t},\ IL_{l't},\ IL_{l''t},\ ID_{m'd't},\ ID_{m'd''t},\ ID_{m''d't},\ ID_{m''d''t} \in \{0,1\} \tag{40}$$

Constraint (3) ensures that the quantity of each material supplied from suppliers is greater than the quantity needed for production. Constraints (4)-(5) describe the capacity limitations of the suppliers for materials offering. Constraints (6)-(8) describe that green materials are supplied from suppliers if they have enough capacity to supply. Constraints (9)-(10) set the quantity of products sent from manufacturing centers to customers. Constraints (11)-(12) describe the capacity limitations of the manufacturing centers for products production. Constraints (13)-(14) describe the capacity limitations of the manufacturing centers for products stored. Constraints (15)-(17) describe that products are manufactured from manufacturing centers with green facilities if they have enough capacity to produce. Constraint (18) ensures that the quantity of each product deliveryed to each customer is greater than the demand. Constraints (19)-(20) set the total quantity of products sent to customers using green and normal transport facilities. Constraints (21)-(24) describe the capacity limitations of the manufacturing centers for products delivering. Constraints (25)-(27) describe that products are delivered from manufacturing centers with normal facilities using green transport facilities if they have enough capacity to delivery. Constraints (28)-(30) describe that products are delivered from manufacturing centers with green facilities using green transport facilities if they have enough capacity to delivery. Constraint (31) ensures the maximum return quantity of each product from customers to collection centers. Constraints (32)-(33) describe the capacity limitations of the collection centers for returned products processing. Constraints (34)-(35) ensure the maximum quantity of each reused material from collection centers to manufacturing centers. Constraints (36)-(38) describe that returned products are sent to in-house collection centers if they have enough capacity to processing. Constraint (39) preserves the non-negativity restriction on the decision variables, and constraint (40) imposes the binary restriction on the decision variables.

3.3 Illustrative Example

To demonstrate the applicability of the proposed supply chain model, we consider a case example to compare the objective values between the cost-oriented model and the proposed flexible model. In order to simplify the problem, we suppose there are two suppliers with normal materials, two suppliers with green materials, two materials, two products, two manufacturing centers with normal facilities, two manufacturing centers with green facilities, two in-house collection centers, two outsourced collection centers and two customers in the example supply chain network. For simplicity, only one time period is considered. The case data is illustrated in Table 1-9.

Table 1. Supplier data.

Materials	Parameters	Suppliers with material		Suppliers with green material	
		1	2	1	2
	Fixed cost	5	5	10	8
1	Capacity	100	200	100	100
	Cost	3	3	7	5
2	Capacity	300	100	200	200
	Cost	5	5	3	5

Table 2. Manufacturing center data.

Products	Parameters	Manufacturing centers with normal facilities		Manufacturing centers with green facilities	
		1	2	1	2
	Fixed cost	4	6	8	10
1	Capacity	70	50	60	40

	Cost	5	7	8	8
	Inventory Capacity	20	15	10	10
2	Capacity	50	50	30	40
	Cost	4	4	7	7
	Inventory Capacity	20	15	10	10

Table 3. Manufacturing center data.

Products	**Parameters**	**In-house collection centers**		**Outsourced collection centers**	
		1	2	1	2
	Fixed cost	5	5	10	8
1	Capacity	80	60	80	40
	Cost	3	3	7	5
2	Capacity	200	150	200	100
	Cost	5	5	8	6

Table 4. Manufacturing center distribution data.

Products	**Parameters**	**Manufacturing centers with normal facilities**			
		1		2	
		Normal transport facilities	***Green transport facilities***	***Normal transport facilities***	***Green transport facilities***
1	Capacity	70	50	60	80
	Cost	20	30	20	30
2	Capacity	60	60	80	80
	Cost	25	30	25	30
		Manufacturing centers with green facilities			
		1		2	
		Normal transport facilities	***Green transport facilities***	***Normal transport facilities***	***Green transport facilities***
1	Capacity	40	60	50	50
	Cost	30	40	30	40
2	Capacity	40	60	60	60
	Cost	30	50	30	50

Table 5. Collection center distribution data.

Reused materials	**Parameters**	**In-house collection centers**		**Outsourced collection centers**	
		Manufacturing centers with normal facilities	***Manufacturing centers with green facilities***	***Manufacturing centers with normal facilities***	***Manufacturing centers with green facilities***
1	Cost	10	10	10	10
2	Cost	10	10	10	10

Table 6. Product data.

Products	**Parameters**	**Customer**	
		1	2
1	Quantity	70	100
	Unit Price	150	420
2	Quantity	60	80
	Unit Price	100	300

Table 7. Product and material data.

Products	Parameters	Materials		Reused Materials	
		1	2	1	2
1	Ratio	0.4	0.4	0.1	0.1
2	Ratio	0.3	0.5	0.1	0.1

Table 8. Reused material data.

Returned Products	Parameters	Reused Materials	
		1	2
1	Ratio	0.2	0.2
2	Ratio	0.3	0.3

Table 9. the objective values of the two models.

	OB1	OB2
Cost-oriented model	70629	342
Flexible model	65427	960

From the result above, it is shown that there is a trade-off between economic factors and environmental factors. In order to fully respond to various business problems such as conflicted goals in the real industrial environment, the multi-objective planning model can be used to generate an optimal solution or a near-optimal solution. In the following study, NSGA-II algorithm will be used to solve this multi-objective programming model problem.

4 Conclusions

According to the climate changes, government legislation, global competition, and fluctuating market needs, enterprises face big challenge to survive and to keep competitive advantages in the recent industry environment. Developing a flexible green supply chain to maintain operational activities and have quickly-response capability to market needs is crucial for business development. This study proposes a multi-objective closed-loop supply chain model to maximize the total profit and the amicable production level, while considering supply flexibility, manufacturing flexibility, distribution flexibility and reverse logistics flexibility. This proposed mathematical model can be a reference for supporting effectively multifaceted integrated management of the closed-loop supply chain network design, and contribute to the academia and practices.

5 Nomenclature

The following indices, parameters, decision variables are used in the above model formulation:

Indices:

s suppliers, $s \in \{1, 2, \cdots, S\}$

r′ material supplied for production, $r' \in \{1, 2, \cdots, x\}$

r″ green material supplied for production, $r'' \in \{x+1, x+2, \cdots, R\}$

r full material range, $r \in \{1, 2, \cdots, R\}$

u reused material, $u \in \{1, 2, \cdots, U\}$

p full product range, $p \in \{1,2,\cdots,P\}$

m′ manufacturing centers with normal facilities, $m' \in \{1, 2, ..., y\}$

m″ manufacturing centers with green facilities, $m'' \in \{y+1, y+2, ..., M\}$

m manufacturing centers (in the total two kinds facilities), $m \in \{1,2,\cdots,M\}$

c customers, $c \in \{1, 2, \cdots, C\}$

l′ in-house collection centers, $l' \in \{1, 2, ..., z\}$

l'' outsourced collection centers, $l'' \in \{z+1, z+2, \ldots, L\}$
l collection centers (in the total two kinds of centers), $l \in \{1,2,\cdots,L\}$
d transportation mode, $d \in \{d'$:normal facilities, d'':green facilities$\}$
t time period, $t \in \{1,2,\cdots,T\}$

Parameters:

$SP_{sr'}$ supply capacity of supplier s for supplying material r′
$SP_{sr''}$ supply capacity of supplier s for supplying green material r″
$MP_{m'p}$ production capacity of manufacturing center m′ for product p
$MP_{m''p}$ production capacity of manufacturing center m″ for product p
MP_{mp} production capacity of manufacturing center m for product p
$LP_{l'p}$ processing capacity of collection center l′ for product p
$LP_{l''p}$ processing capacity of collection center l″ for product p
LP_{lp} processing capacity of collection center l for product p
$IP_{m'p}$ inventory capacity of manufacturing center m′ for product p
$IP_{m''p}$ inventory capacity of manufacturing center m″ for product p
$FP_{m'pd'}$ distribution capacity of manufacturing center m′ for product p using normal transport facilities
$FP_{m'pd''}$ distribution capacity of manufacturing center m′ for product p using green transport facilities
$FP_{m''pd'}$ distribution capacity of manufacturing center m″ for product p using normal transport facilities
$FP_{m''pd''}$ distribution capacity of manufacturing center m″ for product p using green transport facilities
$SC_{sr'}$ purchasing cost of material r′ from supplier s
$SC_{sr''}$ purchasing cost of material r″ from supplier s
$MC_{m'p}$ production cost of product p in manufacturing center m′
$MC_{m''p}$ production cost of product p in manufacturing center m″
$LC_{l'p}$ processing cost of product p in collection center l′
$LC_{l''p}$ processing cost of product p in collection center l″
$IC_{pm'}$ inventory cost of product p for manufacturing center m′
$IC_{pm''}$ inventory cost of product p for manufacturing center m″
$DC_{pm'cd'}$ cost of distributing product p produced in manufacturing center m′ to customer c using normal transport facilities
$DC_{pm'cd''}$ cost of distributing product p produced in manufacturing center m′ to customer c using green transport facilities
$DC_{pm''cd'}$ cost of distributing product p produced in manufacturing center m″ to customer c using normal transport facilities
$DC_{pm''cd''}$ cost of distributing product p produced in manufacturing center m″ to customer c using green transport facilities
$UC_{ul'm'd}$ cost of distributing reused material u from collection center l′ to manufacturing center m′
$UC_{ul'm''d}$ cost of distributing reused material u from collection center l′ to manufacturing center m″
$UC_{ul''m'd}$ cost of distributing reused material u from collection center l″ to manufacturing center m′
$UC_{ul''m''d}$ cost of distributing reused material u from collection center l″ to manufacturing center m″
$FM_{m'}$ fixed cost for setting up manufacturing center m′
$FM_{m''}$ fixed cost for setting up manufacturing center m″

$FL_{l'}$ fixed cost for setting up in-house collection center l′
$FL_{l''}$ fixed cost for arranging outsourced collection center l″
DP_{pct} demand quantity of product p from customer c in period t
RP_{pct} return ratio of product p in period t
P_{pct} unit price of product p for customer c in period t
R_{rp} the requirement of material r for per unit production of product p
R_{up} the ratio of reused material u processed from product p
LN a large number

Decision variable:

$QR_{sr'pt}$ amount of material r′ supplied by supplier s for product p produced in period t
$QR_{sr''pt}$ amount of green material r″ supplied by supplier s for product p produced in period t
$QP_{pm'ct}$ quantity of product p produced in manufacturing center m′ for customer c in period t
$QP_{pm''ct}$ quantity of product p produced in manufacturing center m″ for customer c in period t
$QI_{pm't}$ quantity of product p stored in manufacturing center m′ in period t
$QI_{pm''t}$ quantity of product p stored in manufacturing center m″ in period t
$QR_{pcl't}$ quantity of product p returned from customer c to collection center l′ in period t
$QR_{pcl''t}$ quantity of product p returned from customer c to collection center l″ in period t
$QU_{ul'm't}$ quantity of reused material u sent from collection center l′ to manufacturing center m′ in period t
$QU_{ul'm''t}$ quantity of reused material u sent from collection center l′ to manufacturing center m″ in period t
$QU_{ul''m't}$ quantity of reused material u sent from collection center l″ to manufacturing center m′ in period t
$QU_{ul''m''t}$ quantity of reused material u sent from collection center l″ to manufacturing center m″ in period t
$QS_{pm'cd't}$ quantity of product p sent to customer c from manufacturing center m′ in period t using normal transport facilities
$QS_{pm'cd''t}$ quantity of product p sent to customer c from manufacturing center m′ in period t using green transport facilities
$QS_{pm''cd't}$ quantity of product p sent to customer c from manufacturing center m″ in period t using normal transport facilities
$QS_{pm''cd''t}$ quantity of product p sent to customer c from manufacturing center m″ in period t using green transport facilities
$QS_{pm'ct}$ quantity of product p sent to customer c from manufacturing center m′ in period t
$QS_{pm''ct}$ quantity of product p sent to customer c from manufacturing center m″ in period t
$IS_{sr't}$ equals 1, if supplier s offers material r′ in period t, otherwise 0
$IS_{sr''t}$ equals 1, if supplier s offers green material r″ in period t, otherwise 0
$IM_{m't}$ equals 1 if manufacturing center m′ is open in period t, otherwise 0
$IM_{m''t}$ equals 1 if manufacturing center m″ is open in period t, otherwise 0
$IL_{l't}$ equals 1 if collection center l′ is open in period t, otherwise 0
$IL_{l''t}$ equals 1 if collection center l″ is open in period t, otherwise 0
$ID_{m'd't}$ equals 1 if manufacturing center m′ send product using normal transport facilities, otherwise 0
$ID_{m'd''t}$ equals 1 if manufacturing center m′ send product using green transport facilities, otherwise 0
$ID_{m''d't}$ equals 1 if manufacturing center m″ send product using normal transport facilities, otherwise 0

$ID_{m''d''t}$ equals 1 if manufacturing center m″ send product using green transport facilities, otherwise 0

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