APEM journal
Advances in Production Engineering & Management
Volume 16 | Number 2 | June 2021 | pp 161–172
https://doi.org/10.14743/apem2021.2.391
ISSN 1854-6250
Journal home: apem-journal.org
Original scientific paper

A multi-objective optimal decision model for a green closed-loop supply chain under uncertainty: A real industrial case study

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ABSTRACT

Green closed-loop supply chain management is an important topic for business operations today because of increasing resource scarcity and environmental issues. Companies not only have to meet environmental regulations, but also must ensure high quality supply chain operation as a means to secure competitive advantages and increase profits. This study proposes a multi-objective mixed integer programming model for an integrated green closed-loop supply chain network designed to maximize profit, amicable production level (environmentally friendly materials and clean technology usage), and quality level. A scenario-based robust optimization method is used to deal with uncertain parameters such as the demand of new products, the return rates of returned products and the sale prices of remanufactured products. The proposed model is applied to a real industry case example of a manufacturing company to illustrate the applicability of the proposed model. The result shows a robust optimal resource allocation solution that considers multiple scenarios. This study can be a reference for closed-loop supply chain related academic research and also can be used to guide the development of a green closed-loop supply chain model for better decision making.

ARTICLE INFO

Keywords:
Green closed-loop supply chain;
Sustainability;
Modelling;
Robust optimization;
Mixed integer programming model;
Supply chain management;
Uncertainty;
LP-metric method

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Article history:
Received 5 June 2021
Revised 23 June 2021
Accepted 24 June 2021

1. Introduction

Due to increasing awareness of environmental issues, governments' legislation, and natural resource limitation, related research on the closed-loop supply chain which integrate the forward and reverse supply chain are increasingly growing [1-5]. According to Govindan *et al.* [6], the research gaps of closed-loop supply chain include the discussion of green/ sustainable issues, the utilization of robust optimization method, the consideration of uncertain factors such as return rate, and multi-objective functions with environmental indicators.

The economic and environmental factors are mostly considered in the multiple objective functions [7-16], while other evaluation indicators of supply chain performance are seldom included. Promoting better quality of the supply chain operations is the method to sustain the long-term competition for earning the market share [17]. This study proposes a multi-objective mixed-integer programming model of the closed-loop supply chain network to maximize profit, amicable production level, and quality level.

In order to describe real industry environments, uncertain parameters are considered in the mathematical model. With sensitivity analysis, the demand of new products, the return rates of returned products and the sale prices for remanufactured products which are highly sensitive to the objective functions are selected. A scenario-based robust optimization method is utilized for solving the uncertain problem. After the uncertainty problem is solved, the multi-objective problem is solved by LP-metric method. A real industry case example of a manufacturing company is applied to illustrate the applicability of the proposed model. The goal of this study is to develop the multi-objective mathematical model for supporting better decision making in the green closed-loop supply chain network management. Besides, the impact of the economic, environmental, and quality factors to the green closed-loop supply chain model is discussed in this study.

This paper advances current research into closed-loop supply chain models in two ways. First, the amicable production level and quality level are considered in the objective functions for analysing simultaneously the impacts of three objective functions in different parameter settings. Second, sensitivity analysis is used to determine the multiple uncertain parameters for fully consideration of the important factors in this model. The rest of this paper is organized as follows. Section 2 reviews related literature. Section 3 is devoted to the proposed multi-objective mixed-integer linear programming model. Section 4 shows an illustrative case example, and section 5 discusses conclusions.

2. Literature review

The objectives of closed-loop supply chain models include carbon emissions, costs, profits, environmental influence/ cost, environmentally friendly materials, and clean technology etc. Zhao *et al*. [8] proposed a multi-objective optimization model for minimizing the inherent risk occurred by hazardous materials, associated carbon emission, and economic cost. Three scenarios are discussed in this study for analyzing the green impact in the supply chain management. Talaei *et al*. [9] proposed a bi-objective mixed-integer linear programming model for minimizing the total network costs and the rate of carbon dioxide emission. The effects of uncertainties of the variable costs and demand rate are considered in the closed-loop supply chain network design. In order to improve economic and environmental performance in an environmental closed-loop supply chain for enterprises' competitiveness, Ma *et al*. [10] proposed a robust multi-objective mixed integer nonlinear programming model to minimize two conflicting objectives simultaneously, the economic cost and the environmental influence. Also, the uncertain cost parameters and demand fluctuations are considered in the supply chain network design. To illustrate the relationships between supply chain management policies and natural environmental impacts, Altmann and Bogaschewsky [11] proposed a robust multi-objective closed-loop supply chain design model which minimizes expected total costs as well as carbon dioxide equivalents. Customer demand and used-product return rate are considered to be the uncertain parameters. For considering the environmental factors in the closed-loop supply chain facility-location model, Amin and Zhang [12] proposed a mixed-integer linear programming model to minimize the total costs and to maximize the environmentally friendly materials and clean technology usage. The impact of uncertain demand and return is investigated on the network configuration. Pourjavad and Mayorga [16] developed a fuzzy multi-objective mixed integer linear programming model to minimize costs and environmental impacts and maximize social impacts. Three fuzzy parameters such as return rates of products from customer centers, the capacity of all facilities, and product demand are considered. The related literatures are summarized in Table 1.

Some performance indicators such as quality in the traditional supply chain model are less frequently included in the green closed-loop supply chain model for comparing the impacts of performance indicators simultaneously (shown as Table 1). Quality is an important concern in response to the performance in supply chain operations [5,14, 17-20]. Liu *et al*. [13] proposed a bi-objective mathematical programming model considering uncertain demand in a green closed loop supply chain network. Two objectives are minimizing the total costs including production cost, operation cost, transportation cost, and construction cost, while maximizing the satisfaction of customers which includes shipping time, product quality, and recovery quantity. Liu *et al.* [13] only considers the recovery quantity as the environmental indicator that can't effectively and suitably reveal the impact of green manufacturing to the whole supply chain performance, and only treat demand as the uncertain parameter. For fulfilling the research gap, this study considers the economic, amicable production level, and quality simultaneously for optimizing the green closed-loop supply chain model which is referenced by Fang and Lin [5]. For in-depth analysis, this study utilizes the sensitivity analysis to determine the uncertain parameters such as the demand of new products, the return rates of returned products, and the sale prices of remanufactured products which are highly sensitive to the three objective functions. Besides, the comparison between the infeasibility weight and model robustness is made to provide more helpful information for decision making.

For solving stochastic problems in closed-loop supply chain, Govindan *et al.* [6] suggested that two-stage stochastic method or robust optimization method can be considerable solutions in the future directions of the related researches. Compared with stochastic programming method, the robust optimization method has the advantage of implementing without the known probability distributions of uncertain parameters. Besides, the robust optimization is easier than stochastic programming method for finding the optimal solution [24].

In terms of the suggestions mentioned above, the multi-objective stochastic problem of this study is solved by robust optimization method and LP-metrics method referenced by Altmann and Bogaschewsky [11], Ma *et al.* [10] and Fang and Lin [5] to find the final optimal solution. Sensitivity analysis is utilized to determine the selected uncertain parameters and the AHP method is used to determine the weights of three objective functions for being combined into a single objective function.

Table 1 Summary of related literature

Papers	Uncertain parameters		Objective function indicators			Solutions/Methods
	Single	Multiple	Environmental	Economic	Quality	
Amin and Zhang (2013)		*	*	*		Multi-objective approach Stochastic programming
Ramezani *et al.* (2013)		*		*	*	Pareto-optimal solutions
Altmann and Bogaschewsky (2014)		*	*	*		Robust optimization
Das and Rao Posinasetti (2015)			*	*		Bi-objective Pareto optimal solutions, Goal programming
Saffar *et al.* (2015)		*	*	*		Jimenez approach
Ma *et al.* (2016)		*	*	*		Robust optimization
Talaei *et al.* (2016)		*	*	*		Robust fuzzy optimization
Mohammed *et al.* (2017)		*		*		Robust optimization
Zhao *et al.* (2017)			*	*		Big data analytic approach, Scenario analysis
Liu *et al.* (2018)	*		*	*	*	Approximation, ε-constraint method, MOSA, NSGA-II
Pourjavad and Mayorga (2018)		*	*	*		NSGA-II, NRGA
Karimi *et al.* (2019)	*			*		NSGA-II, NRGA
Valizadeh *et al.* (2020)	*			*		Bertsimas and Sim stable optimization approach
This study		*	*	*	*	Multi-objective approach, Robust optimization

3. Model formulation

3.1 Problem definition

Referenced by Fang and Lin [5], the green closed-loop supply chain network model in this study (depicted as Fig. 1) includes manufacturing centers, customers, collection centers, and customers of the other market. The new products are manufactured by manufacturing centers and sent to customers. The returned products are purchased from customers and sent to collection centers. After the returned products are dismantled by the collection centers, some reused materials are sent back to the manufacturing centers for new products, and some reused materials are manufactured by the collection centers for remanufactured products. The remanufactured products are sent from collection centers to customers of the other market.

The goal of this study is to maximize total profit, amicable production level, and quality of products with three uncertain parameters. The assumptions of this research are referenced by Fang and Lin [5].

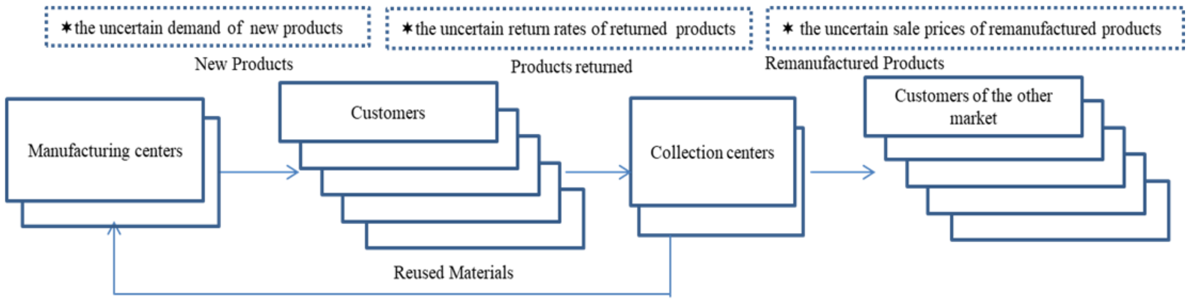

Fig. 1 Green closed-loop supply chain network model in this study

3.2 Model description

The sets, indices, parameters, decision variables, and scenario variables for the model formulation are shown in Table 2.

Objective functions:

$$Max\ F1 = Revenue - Purchase\ Cost - Processing\ Cost - Transportation\ Cost \tag{1}$$

$$Revenue = \sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{c=1}^{C} QM_{pmc} \times P_{pc} + \sum_{r\in re}\sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} QE_{relt} \times P_{et} \tag{2}$$

$$Purchase\ Cost = \sum_{c=1}^{C}\sum_{p=1}^{P}\sum_{l=1}^{L} CC_{cp} \times QL_{plc} \tag{3}$$

$$Processing\ Cost = \sum_{m=1}^{M} FC \times IM_m + \sum_{p=1}^{P}\sum_{c=1}^{C}\sum_{m=1}^{M} PC_{mp} \times QM_{pmc} + \sum_{l=1}^{L} FC \times IL_l + \sum_{r\in re}\sum_{e=1}^{E}\sum_{t=1}^{T}\sum_{l=1}^{L} RC_{le} \times QE_{relt} \tag{4}$$

$$Transportation\ Cost = \sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{c=1}^{C} TC_{pmc} \times QM_{pmc} + \sum_{p=1}^{P}\sum_{r\in rm}^{R}\sum_{l=1}^{L}\sum_{m=1}^{M} TC_{prlm} \times QR_{rlmp} + \sum_{r\in re}\sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} TC_{elt} \times QE_{relt} \tag{5}$$

$$Max\ F2 = W_{em} \times \left(\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{c=1}^{C} EM_{pm} \times QM_{pmc} + \sum_{r\in re}\sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} EM_{le} \times QE_{relt}\right) + W_{ct} \times \left(\sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{c=1}^{C} CTM \times QM_{pmc} + \sum_{p=1}^{P}\sum_{m=1}^{M}\sum_{c=1}^{C} CTS \times QM_{pmc} + \sum_{r\in re}\sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} CTM \times QE_{relt} + \sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} CTS \times QE_{relt} + \sum_{p=1}^{P}\sum_{r=1}^{R}\sum_{l=1}^{L}\sum_{m=1}^{M} CTS \times QR_{rlmp}\right) \tag{6}$$

$$Min\ F3 = \sum_{m=1}^{M}\sum_{p=1}^{P}\sum_{c=1}^{C} DR_{pm} \times W_p \times QM_{mpc} + \sum_{r\in re}\sum_{e=1}^{E}\sum_{l=1}^{L}\sum_{t=1}^{T} DR_{le} \times W_e \times QE_{relt} \tag{7}$$

Table 2 The descriptions of variables and parameters

Sets & indices			
C	index of fixed locations of customers, c = 1, 2,…, C	E	index of remanufactured products, e = 1, 2,…, E
F	index of objective functions, f = 1, 2,…, F	I	index of scenarios, i = 1, 2,…, I
L	index of potential locations of collection centers, l = 1, 2,…, L	M	index of potential locations of manufacturing centers, m = 1, 2,…, M
R	index of reused materials, $R = RM \cup RE$, RM is for manufacturing centers, RE is for customers of the other markets	T	index of fixed locations of customers of the other market, t = 1, 2,…, T
P	index of new products, p = 1, 2,…, P		
Parameters			
PC_{pm}	unit production cost of product p from manufacturing center m	RC_{le}	unit remanufacturing cost of remanufactured product e from collection center l
CC_{cp}	purchasing cost of product p from customer c	FC	fixed cost for opening manufacturing center and collection center
DE_{et}	demand of customer t of the other market for remanufactured product e	CM_{lp}	capacity of collection center l for product p
DP_{cp}	demand of customer c for product p	RA_p	the return rate of product p
CP_{pm}	capacity of manufacturing center m for product p	CE_{le}	capacity of collection center l for remanufactured product e
P_{et}	unit sale price of remanufactured product e for customer t of the other market	P_{pc}	unit sale price of product p for customer c
DR_{le}	defect rate of remanufactured product e from collection center l	DR_{mp}	defect rate of product p from manufacturing center m
RM_{rp}	the rate of reused material r ($r \in rm$) dismantled from returned product p	RE_{rp}	the rate of reused material r ($r \in re$) dismantled from returned product p
W_p	weight factor for importance of product p	W_f	weight factor of objective function f
W_e	weight factor for importance of remanufactured product e	W_{em}	weight factor of using environmentally friendly materials
W_{ct}	weight factor of using clean technology	EM_{pm}	the rate of using environmentally friendly materials by manufacturing center m for product p
EM_{le}	the rate of using environmentally friendly materials by collection center l for remanufactured product e	CTM	the rate of using clean technology for producing product p and remanufactured product e
CTS	the rate of using clean technology for shipping product p and remanufactured product e between facilities	TC_{pmc}	unit distribution cost for product p shipped from manufacturing center m to customer c
TC_{prlm}	unit distribution cost for reused material r ($r \in rm$) of product p shipped from collection center l to manufacturing center m	TC_{elt}	unit distribution cost for remanufactured product e shipped from collection center l to customer t of the other market
Decision variables			
QM_{pmc}	quantity of product p produced from manufacturing center m to customer c	QL_{plc}	quantity of product p returned from customer c to collection center l
QR_{rlmp}	quantity of reused material r ($r \in rm$) for product p from collection center l to manufacturing center m	QE_{relt}	quantity of reused material r ($r \in re$) for producing remanufactured product e from collection center l to customer t of the other market
IM_m	1 if manufacturing center m is opened, otherwise 0	IL_l	1 if collection center l is opened, otherwise 0
Scenario variables			
QU_{pc}	unfulfilled quantity of product p for customer c	QU_{et}	unfulfilled quantity of remanufactured product e for customer t of the other market
SP_i	the occurrence probability of scenario i	ω	the infeasibility weight
λ	the weight of risk	θ_{1i}	the linearization variable of the first objective function under scenario i
θ_{2i}	the linearization variable of the second objective function under scenario i	θ_{3i}	the linearization variable of the third objective function under scenario i

The first objective function $F1$ is to maximize the total profit which is computed by subtracting purchase cost, processing cost, and transportation cost from total revenue. The total revenue includes the sale revenue of new products and remanufactured products. The purchase cost includes purchasing cost of returned products from customers. The processing cost includes fixed cost of manufacturing centers, production cost of new products, fixed cost of collection centers, and production cost of remanufactured products. The transportation cost is for shipping products or materials between facilities in the closed-loop supply chain network. The second objective function $F2$ is to maximize the amicable production level which means the level of using environmental parameters such as environmentally friendly materials or clean technology in the supply chain operations. The third objective function $F3$ is to maximize the quality level by minimizing the defect rate of new products and remanufactured products.

Constraints:

$$\sum_{m=1}^{M} QM_{pmc} \geq DP_{cp} \quad \forall c,p \quad (8)$$

$$\sum_{r=1}^{R} \sum_{l=1}^{L} QE_{relt} \geq DE_{et} \quad \forall t,e \quad (9)$$

$$\sum_{c=1}^{C} QM_{pmc} \leq IM_m \times CP_{pm} \quad \forall p,m \quad (10)$$

$$\sum_{c=1}^{C} QL_{plc} \leq IL_l \times CM_{lp} \quad \forall l,p \quad (11)$$

$$\sum_{r \in r2} \sum_{t=1}^{T} QE_{relt} \leq IL_l \times CE_{le} \quad \forall l,e \quad (12)$$

$$\sum_{l=1}^{L} QL_{plc} = DP_{pc} \times RA_p \quad \forall p,c \quad (13)$$

$$\sum_{m=1}^{M} QR_{rlmp} = \sum_{c=1}^{C} QL_{plc} \times RM_{rp} \quad \forall p,l,r \in rm \quad (14)$$

$$\sum_{e=1}^{E} \sum_{t=1}^{T} QE_{relt} = \sum_{c=1}^{C} QL_{plc} \times RE_{rp} \quad \forall p,l,r \in re \quad (15)$$

$$QN_{nspm}, QM_{pmc}, QL_{plc}, QR_{rlmp}, QE_{relt}, QU_{pc}, QU_{et}, \theta_{1i}, \theta_{2i}, \theta_{3i} \geq 0 \quad \forall r,s,p,c,m,l,n,t,e \quad (16)$$

$$IM_m, IL_l \in \{0,1\} \quad \forall m,l \quad (17)$$

Eq. 8 ensures that the sum of the produced quantity of each product for each customer can meet customer demand. Eq. 9 ensures that the sum of the produced quantity of each remanufactured product for each customer of the other market can meet the customer demand of the other market. Eq. 10 states that the sum of each product produced for customers by each manufacturing center does not exceed the capacity of this manufacturing center. Eq. 11 presents that the sum of each returned product collected by each collection center does not exceed the capacity of this collection center. Eq. 12 presents that the sum of each remanufactured product produced by each collection center does not exceed the capacity of this collection center. Eq. 13 ensures the returned quantity of each product from customers to collection centers. Eq. 14 ensures the quantity of each reused material which is dismantled from each returned product in each collection center supplied to manufacturing centers for manufacturing products. Eq. 15 ensures the quantity of each reused material which is dismantled from each returned product in each collection center used for producing remanufactured products. Eq. 16 preserves the non-negativity restriction on the decision variables, and Eq. 17 imposes the binary restriction on the decision variables.

3.3 The transformation to a robust optimization model

The proposed multi-objective mixed integer programming model can be transformed to a robust optimization model by the approach proposed by Mulvey *et al.* [25] and a more suitable formulation for the first term of the objective function introduced by Yu and Li [26]. The three objective functions and additional constraints of the proposed model can be expressed as follows [5]:

$$Max\ ob1 = \sum_{i=1}^{I} SP_i\, F1_i - \lambda \sum_{i=1}^{I} SP_i \left[\left(F1_i - \sum_{i'=1}^{I} SP_{i'} F1_{i'}\right) + 2\theta_{1i}\right] - \omega \sum_{i=1}^{I} SP_i (QU_{pc} + QU_{et}) \quad (18)$$

$$Max\ ob2 = \sum_{i=1}^{I} SP_i\, F2_i - \lambda \sum_{i=1}^{I} SP_i \left[\left(F2_i - \sum_{i'=1}^{I} SP_{i'} F2_{i'}\right) + 2\theta_{2i}\right] - \omega \sum_{i=1}^{I} SP_i (QU_{pc} + QU_{et}) \quad (19)$$

$$Min\ ob3 = \sum_{i=1}^{I} SP_i\, F3_i + \lambda \sum_{i=1}^{I} SP_i \left[\left(F3_i - \sum_{i'=1}^{I} SP_{i'} F3_{i'}\right) + 2\theta_{3i}\right] + \omega \sum_{i=1}^{I} SP_i (QU_{pc} + QU_{et}) \quad (20)$$

s.t.

$$F1_i - \sum_{i=1}^{I} SP_i F1_i + \theta_{1i} \geq 0 \quad \forall\, i \in \Omega \quad (21)$$

$$F2_i - \sum_{i=1}^{I} SP_i F2_i + \theta_{2i} \geq 0 \quad \forall\, i \in \Omega \quad (22)$$

$$F3_i - \sum_{i=1}^{I} SP_i F3_i + \theta_{3i} \geq 0 \quad \forall\, i \in \Omega \quad (23)$$

$$\sum_{m=1}^{M} QM_{pmc} + QU_{pc} \geq DP_{cp} \qquad \forall c, p \qquad (24)$$

$$\sum_{r=1}^{R} \sum_{l=1}^{L} QE_{relt} + QU_{et} \geq DE_{et} \qquad \forall t, e \qquad (25)$$

$$\sum_{l=1}^{L} QL_{plc} = (DP_{cp} - QU_{pc}) \times RA_p \qquad \forall p, c \qquad (26)$$

Where $F1_i$ denotes the first objective function in the proposed model as Eq. 1, $F2_i$ denotes the second objective function as Eq. 6, and $F3_i$ denotes the third objective function as Eq. 7. Eqs. 21-23 can be interpreted that if the Fx_i is greater than $\sum_{i=1}^{I} SP_i Fx_i + \theta_{xi}$, then θ_{xi} is equal to 0. If the $\sum_{i=1}^{I} SP_i Fx_i + \theta_{xi}$ is greater than Fx_i, then $Fx_i - \sum_{i=1}^{I} SP_i Fx_i = \theta_{xi}$. Eqs. 10-12 and Eqs.14-17 in section 3.2 are still considered in the robust optimization model.

3.4 The transformation to single objective function model

The LP-metrics method is utilized for solving the multi-objective problem in this study referenced by Fang and Lin [5]. Firstly, each objective function of the proposed multi-objective model is solved separately and the objective value $ob1^*$, $ob2^*$ and $ob3^*$ is gained respectively. Then, the objective function can be formulated as Eq. 27. W_1, W_2, and W_3, the weights of the three components in the Eq. 27, are determined by the AHP method and W_1+W_2+W_3=1.

$$Min\ W_1 \times \frac{(ob1 - ob1^*)}{ob1^*} + W_2 \times \frac{(ob2 - ob2^*)}{ob2^*} - W_3 \times \frac{(ob3 - ob3^*)}{ob3^*} \qquad (27)$$

4. Results and discussion: A case study

4.1 Example description

A real case example of a manufacturing company referenced by Fang and Lin [5] is provided to illustrate the applicability of the proposed green closed-loop supply chain model. According to the supply chain operations of this company, the closed-loop supply chain network includes two products, two manufacturing centers, five customers, two collection centers, two kinds of reused materials (the first one is for new products, the second one is for remanufactured products), two remanufactured products, and five customers of the other market. The two new products can be manufactured by the two manufacturing centers and sent to the five customers. The returned products can be purchased and sent to collection centers for recycling use. The returned products can be dismantled into several kinds of reusable materials in collection centers. The returned product 1 can be dismantled into two kinds of reused materials, namely, $R11$ and $R12$. $R11$ will be sent back to the manufacturing centers for new product 1, $R12$ will be input material for remanufactured product 1. The returned product 2 can be dismantled into three kinds of reused materials, namely, $R21$, $R22$, and $R23$. $R21$ and $R22$ will be sent back to the manufacturing centers for new product 2, and $R23$ will be input material for remanufactured product 2. The two remanufactured products can be produced by the two collection centers and sent to the five customers of the other markets.

4.2 Parameters setting

In order to consider the confidentiality of the company data, the real company data is modified in different scenarios. The parameter data is shown in Table 3-8. The AHP method is used for assigning the weights of the three objective functions and the weights of the environmentally friendly materials and clean technology usage. The weight of $ob1$, $ob2$ and $ob3$ is 0.36, 0.36, and 0.28. The weight of the environmentally friendly materials and clean technology usage is 0.5 and 0.5. The weight factor for importance of new product 1 and 2 is 0.3 and 0.2, the same as remanufactured product 1 and 2 is. The return rate of new products is 0.9. The defect rate of new products and remanufactured products is 0.1. The fixed cost is 30. For the sake of computation convenience, the rates of using environmentally friendly materials and clean technology will be transformed to the corresponding scores as follows: the rate which is less than or equal to 25 % is set to be 25, the rate which is 26-50 % is set to be 50, the rate which is 51-75 % is set to be 75, and the rate which is greater than 75 % is set to be 100.

Table 3 New products and customer data

Parameters	New products	Customers				
		1	2	3	4	5
Unit selling price (P_{pc})	1/2	80/55	85/60	90/65	95/70	100/75
Purchase cost (CC_{cpr})	1/2	90/80	90/80	90/80	90/80	90/80

Table 4 Remanufactured products and customers of the other market data

Parameters	Remanufactured products	Customers of the other market				
		1	2	3	4	5
Demand amount (DE_{et})	1/2	55/154	55/110	110/55	66/55	110/154

Table 5 Manufacturing centers and new products data

Parameters	Manufacturing centers	New product 1	New product 2
Production cost (PC_{mp})	1/2	80/85	40/35
Capacity limitation (CP_{pm})	1/2	800/600	1000/800

Table 6 Collection centers and remanufactured products data

Parameters	Collection centers	Remanufactured product 1	Remanufactured product 2
Production cost (RC_{le})	1/2	80/60	45/35
Capacity limitation (CE_{le})	1/2	500/500	300/300

Table 7 The rates of reused materials dismantled from the returned products

Returned products	The rates of reused materials (RM_{rp})			The rates of reused materials (RE_{rp})	
	$R11$	$R21$	$R22$	$R12$	$R23$
1	0.5	-	-	0.5	-
2	-	0.55	0.05	-	0.4

Table 8 Other parameters data

Parameters	Values	Parameters	Values
The rate of clean technology use (CT_{mp}, CT_{le})	0.1	Distribution cost (TC_{pmc})	2
The rate of clean technology use (CT_{prlm})	0.2	Distribution cost (TC_{prlm})	30
The rate of clean technology use (CT_{elt})	0.1	Distribution cost (TC_{elt})	20
The rate of clean technology use (CT_{pmc})	0.1/m1,0.2/m2	The rate of environmentally friendly material use (EM_{le})	1
The rate of environmentally friendly material use (EM_{pm})	0.2/p1,0.9/p2		
Capacity limitation(CM_{lp})	600/p1,700/p2		

4.3 Scenarios setting

Sensitivity analysis is used for determining which uncertain parameters are highly sensitive to the three objective functions in this study. Referencing the result of sensitivity analysis, the parameters including the demand of new products, the return rates of returned products, and the sale prices of remanufactured products are taken into account for expressing uncertain situations in the real business environment. In this study, each uncertain parameter has 2 scenarios (high and low), so the combination of three uncertain parameters provides eight scenarios. The probability of each scenario is assumed to be the same. The high and low product return rates are 0.9 and 0.7 for new product 1 and 0.9 and 0.8 for new product 2. The setting of the new product demand and the sale prices of remanufactured products are shown in Table 9.

Table 9 The setting of the new product demand and the sale prices of remanufactured products

New products demand		Customers				
		1	2	3	4	5
1	High/Low	220/180	220/180	220/180	220/180	220/180
2	High/Low	344/296	344/296	384/336	124/76	124/76
The sale prices of remanufactured products		Customers of the other market				
		1	2	3	4	5
1	High/Low	1400/1000	1400/1000	1500/1100	1500/1100	1600/1200
2	High/Low	680/280	700/300	700/300	700/300	720/320

4.4 Computing results

To solve the proposed model using the test case data, the Lingo 12.0 software was employed. λ is set to be 1 and ω is set to be 90. The computing results are shown in Table 10-13. Using the robust optimization approach to solve the uncertain problems, multiple scenarios are considered and the infeasibility in the control constraints can be allowed by means of penalties. Through the solution solving procedures, we have the following findings:

- From the sensitivity analysis, the demand of new products, the return rates of returned products, and the sale prices of remanufactured products was highly sensitive to the three objective functions of the proposed model. It can be inferred that the three parameters are relatively important elements to the total performance of this proposed model. The company manager should pay more attention to evaluating the impacts of the three parameters to keep good performance of the green closed-loop supply chain.
- Using the AHP method, the weight of the economic objective is the same with the weight of the environmental objective. Also, the weights of the economic and environmental objectives are higher than the weight of the quality objective. It can be inferred that the environmental issues have gotten much attention in the closed-loop supply chain operations, and are treated as important as the company's profit.

Table 10 The allocation of new products

New products	Manufacturing centers	Customers				
		1	2	3	4	5
1	1/2	57.5/122.5	43.6/136.4	108.1/71.9	61.7/118.3	529.1/150.9
2	1/2	243.6/52.4	127.3/168.7	0/336	0/76	629.1/166.9

Table 11 The allocation of returned products

Returned products	Collection centers	Customers				
		1	2	3	4	5
1	1/2	0/126	15.5/110.5	0/126	0/126	14.5/111.5
2	1/2	0/236.8	17.4/219.4	95/173.8	25.9/34.9	25.6/35.2

Table 12 The allocation of reused materials offered to manufacturing centers

New products	Reused materials	Manufacturing centers	Collection centers		Manufacturing centers	Collection centers	
		1	1	2	2	1	2
1	$R11$		0	0		15	300
2	$R21/R22$		0/0	0/0		90.2/8.2	385/35

Table 13 The allocation of remanufactured products

Remanufactured products	Collection centers	Customers of the other market				
		1	2	3	4	5
1	1/2	0/0	0/29	0/110	15/51	0/110
2	1/2	0/0	18.7/91.3	20.9/19.7	20.9/20.1	5/149

4.5 Trade-off between the infeasibility weight and model robustness

The infeasibility weight ω is applied as the model infeasibility under the scenarios of having the unfulfilled demand. Fig. 2 shows the comparison between the infeasibility weight and the unfulfilled demand of remanufactured products. We can find that when the value of ω increases to 90, we get the lowest unfulfilled demand of remanufactured products. Therefore, the best value for ω in the test case is 90.

We can find the relations between objective functions and infeasibility weights shown as Fig. 3. As the infeasibility weight increases, the value of objective function 1 and 2 decreases but the value of objective function 3 increases. The decreased percentage of objective function 1 and 2 are 25 % and 30 % respectively, and the increased percentage of objective function 3 is 199 %. It is shown that the value of objective function 3 is influenced most appreciably by the change of the infeasibility weight, while the value of objective function 1 and 2 is influenced a little by the change of the infeasibility weight. From this analysis, the decision maker may consider the differences between the three objective functions generated by the infeasibility weight to find a suitable decision for the green closed-loop supply chain management.

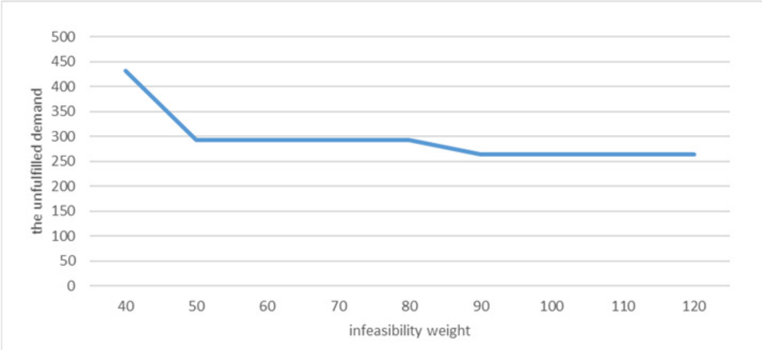

Fig. 2 Comparison between the infeasibility weight and model robustness

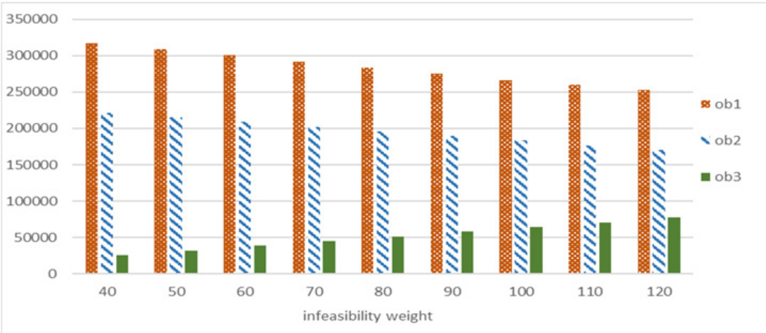

Fig. 3 Value of objective functions in different infeasibility weights

5. Conclusion

Given resource limitation and environmental issues, companies not only have to strive to stay competitive to make more profit, but also have to consider the effective recycling utilization for environmental protection and social legislations. In order to have the holistic view to discuss the optimization of the supply chain, the closed-loop supply chain network model is adopted in this study. Referenced by Fang and Lin [5], this study proposes a multi-objective model for a green closed-loop supply chain network to maximize profit, amicable production level, and quality level. The uncertain parameters such as the demand of new products, the return rates of returned products, and the sale prices of remanufactured products are selected by sensitivity analysis. The multi-objective stochastic problem of this study is solved by robust optimization method and LP-metrics method. A real case example is provided for demonstrating the applicability of this proposed model. Through the computation result, we can find a robust optimal resource allocation solution for the proposed multi-objective mixed integer programming model.

There are several important managerial insights for managers. First, in order to gain competitive advantages and sustainable development, considering the multiple objectives in the closed-loop supply chain help managers obtain more completed and precise information to make better decision. Second, uncertain factors will affect the performance of the closed-loop supply chain operations. Utilizing sensitivity analysis to determine the critical uncertain parameters in this proposed model help managers pay more attention to evaluating the impacts of the uncertain parameters to keep good performance of the green closed-loop supply chain. Third, economic factors and environmental factors have the same importance for optimizing green closed-loop supply chain operations in this study. It is found that green manufacturing should be noticed more seriously for supply chain management.

In future research, regarding environmental issues, other environmental metrics, such as Oršič *et al.* [27] mentioned, can be considered in the environmental objective function. The impacts of green closed-loop supply chain performance by the environmental factors can be further evaluated and discussed. This proposed model can also be applied to another industry to compare the impacts of the three objectives to the green closed-loop supply chain operations in different industries. For solving large scale and stochastic models, many algorithms such as generalized outer approximation, generalized cross decomposition, generalized benders decomposition, genetic algorithm, simulated annealing, etc. can be good references for further research of this study.

Acknowledgement

The authors are grateful to the Ministry of Science and Technology, ROC, for the partial financial support of this work under the grant MOST 105-2410-H-004-111.

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