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A Multi-Objective Closed-Loop Supply Chain Planning Model With Uncertainty

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ABSTRACT

Due to the topics such as the environmental issues, the governments' legislation, natural resource limitations have attracted attention, the research of closed-loop supply chain is increasingly important. Effectively integrated management of a closed-loop supply chain can be a challenge for companies. Companies not only have to meet the environmental regulations, but also have to sustain high-quality supply chain operations as a means to stay competitive advantages and the profit capability. This study proposes a multi-objective mixed integer programming model for an integrated closed-loop supply chain network to maximize the profit, the amicable production level and the quality level. To our knowledge, this proposed model is the first effort to take economic factors, environmental factors, quality factors and uncertain parameters into account simultaneously, and can be a reference for supporting effectively integrated management of a closed-loop supply chain network.

Keywords: Closed-loop supply chain, uncertainty, multi-objective mixed integer programming model.

INTRODUCTION

A closed-loop supply chain is integrated with a forward supply chain and a reverse supply chain [3]. For the increasing environmental turbulence and more intense competitive pressures, the integration of forward and reverse supply chains to gain more productivity and customer satisfaction becomes important for companies to keep sustainable competitive advantages [10]. Besides, designing integrated forward-reverse supply chain networks is highly recommended to avoid the sub-optimality arising from the separate design of forward and reverse networks [5][6][10]. Due to the increased environmental concerns, government legislations, awareness of natural resource limitations in worldwide, social and economic factors, a closed-loop supply chain has attracted growing attention among both academia and practitioners [2][13].

Although the environmental supply chain design is a very important and complex decision that forms in a dynamic and uncertain environment [8] [9], there are only few researches trying to work on green and sustainability subjects in view of integrated reverse logistics and closed-loop supply chains [2]. In order to gain competitive advantages, companies not only have to meet the environmental regulations, but also have to maintain high quality of the supply chain as a means to stay in business over their lifetime. The quality level is one of the appropriate performance measures to determine efficiency and/or effectiveness of a company's supply chain system [12]. This study formulates a supply chain network model simultaneously considering amicable production for environmental protection and high-quality supply chain management.

As real world problems are usually complicated and involve multi-faceted issues, the performance of the supply chain network design is only measured by an economic factor, namely cost minimization or profit maximization, is not realistic [12]. It is necessary for researchers to pay more attention to multiple objective functions [2]. This study proposes a multi-objective mixed-integer linear programming model of the closed-loop supply chain network with three objective functions including maximizing the profit, the amicable production level and the quality level. As for the stochastic nature of demand and return, this proposed mathematical model considers uncertain demand and return. The rest of the paper is organized as follows. Section 2 reviews relevant literature. Section 3 is devoted to the proposed multi-objective mixed-integer linear programming model. Conclusions are discussed in section 4.

LITERATURE REVIEW

Guide & Van Wassenhove [3] used the business view to define closed-loop supply chain management as the design, control, and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time. Based on environmental, legal, social, and economic factors, closed-loop supply chain issues have attracted attention by the evidence of many publications in scientific journals which have been published in recent years [2].

From reviewing the relevant literatures, it can be found that multiple objectives should be considered in the design of a closed-loop supply chain to maximize value creation of the whole supply chain ecosystem [3] [11]. The supply chain network should be designed in a way that it could handle the uncertainty of parameters; otherwise the impact of uncertain parameters will be larger than necessary [10].

Amin & Zhang [1] proposed a multi-objective facility location model for a closed-loop supply chain under uncertain demand and return. A mixed-integer linear programming model is utilized that minimizes the total cost and maximizes the environmental parameters such as friendly materials and clean technology. The model also is developed by stochastic programming (scenario-based) to examine the effects of uncertain demand and return on the network configuration.

Pishvaee & Razmi [9] proposed an environmental supply chain network design using multi-objective fuzzy mathematical programming model. The two objective functions of the proposed model are minimization of total cost and total environmental impact. Alife cycle assessment-based (LCA-based) method is applied to assess and quantify the environmental impact of different options for supply chain network configuration. Besides, an interactive fuzzy approach is developed and a real industrial case is investigated to assess the effectiveness of the proposed model and the usefulness of the proposed solution approach.

Ramezani, Bashiri, & Tavakkoli-Moghaddam [12] formulated a multi-objective stochastic model for a forward-reverse logistic network design considering the responsiveness level and the quality level under an uncertain environment. The objectives are to maximize the total profit, the customer service level and minimize the total number of raw material defects obtained from suppliers for increasing the sigma quality level. Ramezani et al. [11] designed a multi-product, multi-period, closed-loop supply chain network with three objective functions: profit maximization, delivery time minimization, and quality maximization. A fuzzy optimization approach is utilized considering incomplete or imprecise information in data and the flexibility of constraints.

As summarized above, there is a research gap for building a closed-loop supply chain network model simultaneously taking economic factors, environmental factors, quality factors and uncertain parameters into account. This study proposes a multi-objective mixed-integer programming model with uncertain demand and return to maximize the total profit, the amicable production level, and the quality level.

MODEL FORMULATION

Problem Definition

This study considers a single-period, multi-product, multi-echelon closed-loop supply chain network, including four layers in the forward supply chain network (i.e. suppliers, plants, distribution centers, customers) and four layers in the reverse supply chain network (i.e. customers, collection centers, remanufacturing centers and disposal centers).

In the forward supply chain flow, the suppliers offer the raw materials to plants. The new products are shipped from plants to distribution centers. The distribution centers then distribute the new products to customers to meet the customer demand. In the reverse supply chain flow, the returned products from customers are shipped to collection centers for inspection. After being inspected in the collection centers, the reusable products are shipped to the remanufactured centers and the disposable products are shipped to the disposal centers. The reused materials in the remanufactured centers are shipped to the plants for producing new products and the disposable parts are shipped to the disposal centers. The structure of the proposed closed-loop supply chain network is illustrated in Fig. 1.

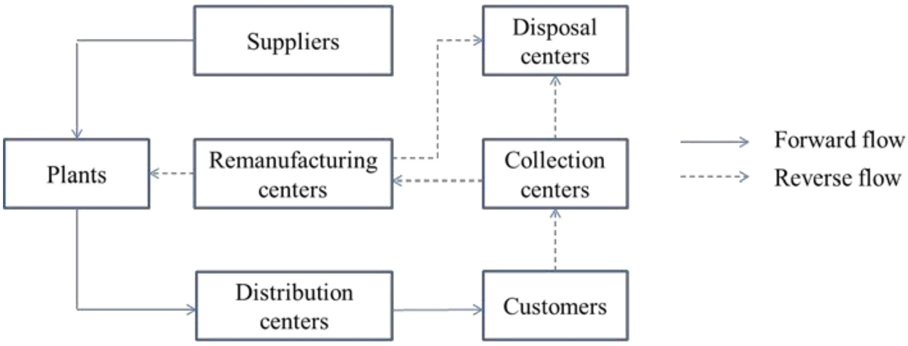

Fig.1 the proposed closed-loop supply chain network The following assumptions are made in the network configuration:

1. The model is designed for a single-period.
2. Locations of suppliers and customers are known and fixed.
3. Locations of plants, distribution centers, collection centers, remanufactured centers and disposal centers are known.
4. The capacity of plants, distribution centers, collection centers, remanufactured centers and disposal centers are restricted.
5. The quantity of demand and return are uncertain.
6. The inventory issue is not considered.

Model Description

To describe the aforementioned supply chain network, the following indices, parameters, decision variables are used in the model formulation:

Indices:

S index of fixed locations of suppliers, S=1,2,…,S C index of fixed locations of customers, C=1,2,…,C P index of potential locations of plants, P=1,2,…,P

D	index of potential locations of distribution centers, D=1,2,…,D
L	index of potential locations of collection centers, L=1,2,…,L
M	index of potential locations of remanufacturing centers, M=1,2,…,M
O	index of potential locations of disposal centers, O=1,2,…,O
J	index of products, J=1,2,…,J
R	index of materials, R=1,2,…,R

Parameters:

SC_{rs}	purchasing cost of raw material r from supplier s
PC_{jp}	production cost of product j from plant p
RC_{jm}	remanufactured cost of product j from remanufacturing center m
CCj_{l}	inspection and collection cost of product j from collection center l
DC_{o}	disposal cost from disposal center o
FC_{p}	fixed cost for opening the plant p
FC_{m}	fixed cost for opening the remanufacturing center m
FC_{d}	fixed cost for opening the distribution center d
FC_{l}	fixed cost for opening the collection center l
FC_{o}	fixed cost for opening the disposal center o
TC_{pdj}	unit transportation cost for product j shipped from plant p to distribution center d
TC_{dcj}	unit transportation cost for product j shipped from distribution center d to customer c
TC_{clj}	unit transportation cost for product j shipped from customer c to collection center l
TC_{lmj}	unit transportation cost for product j shipped from collection center l to remanufacturing center m
TC_{loj}	unit transportation cost for product j shipped from collection center l to disposal center o
TC_{mpr}	unit transportation cost for reused material r shipped from remanufacturing center m to plant p
TC_{mor}	unit transportation cost for scrapped material r shipped from remanufacturing center m to disposal center o
CS_{sr}	capacity of supplier s for raw material r
CP_{pj}	capacity of plant p for product j
CM_{mj}	capacity of remanufacturing center m for product j
CD_{dj}	capacity of distribution center d for product j
CL_{lj}	capacity of collection center l for product j
CO_{oj}	capacity of disposal center o for product j
CP_{pr}	capacity of plant p for material r
CO_{or}	capacity of disposal center o for material r
DP_{cj}	demand of customer c for product j
RP_{cj}	return of customer c for product j
DF_{j}	minimum of disposal fraction of product j
P_{jc}	unit price of product j to customer c
EM_{pj}	the ratio of using environmental materials by plant p for product j
CT_{lj}	the ratio of using clean technology by collection center l for product j
DR_{rs}	defect rate of raw material from suppliers s
W_{r}	weight factor for importance of raw material r

Decision variables:

QR_{rsj}	quantity of raw material r offered from supplier s for product j
QP_{jpc}	quantity of product j produced by plant p for customer c
QD_{jpd}	quantity of product j shipped from plant p to distribution center d
QC_{jdc}	quantity of product j shipped from distribution center d to customer c
QL_{jcl}	quantity of returned product j shipped from customer c to collection center l
QO_{jlo}	quantity of returned product j shipped from collection center l to disposal center o
QM_{jlm}	quantity of returned product j shipped from collection center l to remanufacturing center m
QRM_{rmp}	quantity of reused material r made by remanufacturing center m to plant p
QRO_{rmo}	quantity of scrapped material r shipped from remanufacturing center m to disposal center o
IP_{p}	1 if plant p is opened, otherwise 0
ID_{d}	1 if distribution center is opened, otherwise 0
IL_{l}	1 if collection center is opened, otherwise 0
IM_{m}	1 if remanufacturing center is opened, otherwise 0
IO_{o}	1 if disposal center is opened, otherwise 0

Objective functions

The goal of this proposed multi-objective closed-loop supply chain model is to optimize resource allocation for attaining the three objectives: maximizing the total profit, the amicable production level and the quality level. The environmental parameters such as friendly materials and clean technology are utilized for the amicable production level which is referenced by Amin & Zhang [1]. The defect rate of raw materials is utilized for the evaluation of the quality level which is referenced by Ramezani, Bashiri, & Tavakkoli-Moghaddam[12].

$$\text{Max ob1} = \text{Revenue} - \text{Purchase Cost} - \text{Processing Cost} - \text{Transportation Cost} - \text{Disposal Cost} \quad (1)$$

$$\text{Revenue} = \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{c=1}^{C} QP_{jpc} \times P_j \quad (2)$$

$$\text{Purchase Cost} = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{j=1}^{J} SC_{rs} \times QR_{rsj} \quad (3)$$

$$\text{Processing Cost} = \sum_{p=1}^{P} FC_p \times IP_p + \sum_{m=1}^{M} FC_m \times IM_m + \sum_{l=1}^{L} FC_l \times IL_l + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{c=1}^{C} PC_{jp} \times QP_{jpc} + \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{m=1}^{M} RC_{jm} \times QM_{jcm} + \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{l=1}^{L} CC_{jl} \times QL_{jcl} \quad (4)$$

$$\text{Transportation Cost} = \sum_{d=1}^{D} FC_d \times ID_d + \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{d=1}^{D} TC_{pdj} \times QD_{jpd} + \sum_{j=1}^{J}\sum_{d=1}^{D}\sum_{c=1}^{C} TC_{dcj} \times QC_{jdc} + \sum_{j=1}^{J}\sum_{c=1}^{C}\sum_{l=1}^{L} TC_{clj} \times QL_{jcl} + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{m=1}^{M} TC_{lmj} \times QM_{jlm} + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{o=1}^{O} TC_{loj} \times QO_{jlo} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{p=1}^{P} TC_{mpr} \times QRM_{rmp} + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{o=1}^{O} TC_{mor} \times QRO_{rmo} \quad (5)$$

$$\text{Disposal cost} = \sum_{o=1}^{O} FC_o \times IO_o + \sum_{r=1}^{R}\sum_{m=1}^{M}\sum_{o=1}^{O} DC_o \times QRO_{rmo} + \sum_{j=1}^{J}\sum_{l=1}^{L}\sum_{o=1}^{O} DC_o \times QO_{jlo} \quad (6)$$

$$\text{Max ob2} = \sum_{j=1}^{J}\sum_{p=1}^{P}\sum_{c=1}^{C} EM_{pj} \times QP_{jpc} + \sum_{j=1}^{J}\sum_{l=1}^{L} CT_{lj}\left(\sum_{c=1}^{C} QL_{jcl} + \sum_{m=1}^{M} QM_{jlm} + \sum_{o=1}^{O} QO_{jlo}\right) \quad (7)$$

$$\text{Min ob3} = \sum_{r=1}^{R}\sum_{s=1}^{S}\sum_{j=1}^{J} DR_{rs} \times W_r \times QR_{rsj} \quad (8)$$

The first objective function is to maximize the total profit which is computed by subtracting purchase cost, processing cost, transportation cost from total revenue. The purchase cost is for purchasing raw materials from suppliers to produce products. The processing cost is for producing products by plants, inspection and collection of returned products by collection centers, processing returned products by remanufacturing centers. The transportation cost is for shipping products or reused materials between facilities in the proposed supply chain network. The disposal cost is for disposing scrapped products or materials by disposal centers. The second objective function is to maximize the amicable production level using the environmental parameters such as friendly materials or clean technology. The third objective function is to maximize the quality level by minimizing the defect rate of raw materials from suppliers.

Constraints

$$\sum_{p=1}^{P} QP_{jpc} \geq DP_{cj} \qquad \forall c,j \qquad (9)$$

$$\sum_{l=1}^{L}\sum_{o=1}^{O} QO_{jlo} = \sum_{c=1}^{C} RP_{cj} \times DF_j \qquad \forall j \qquad (10)$$

$$\sum_{j=1}^{J} QR_{rsj} \leq CS_{sr} \qquad \forall r,s \qquad (11)$$

$$\sum_{c=1}^{C}\sum_{j=1}^{J} QP_{jpc} \leq IP_p \times \sum_{j=1}^{J} CP_{pj} \qquad \forall p \qquad (12)$$

$$\sum_{l=1}^{L}\sum_{j=1}^{J} QM_{jlm} \leq IM_m \times \sum_{j=1}^{J} CM_{mj} \qquad \forall m \qquad (13)$$

$$\sum_{p=1}^{P}\sum_{j=1}^{J} QD_{jpd} \leq ID_d \times \sum_{j=1}^{J} CD_{dj} \qquad \forall d \qquad (14)$$

$$\sum_{c=1}^{C}\sum_{j=1}^{J} QL_{jcl} \leq IL_l \times \sum_{j=1}^{J} CL_{lj} \qquad \forall l \qquad (15)$$

$$\sum_{l=1}^{L}\sum_{j=1}^{J} QO_{jlo} \leq IO_o \times \sum_{j=1}^{J} CO_{oj} \qquad \forall o \qquad (16)$$

$$\sum_{m=1}^{M}\sum_{r=1}^{R} QRM_{rmp} \leq IP_p \times \sum_{r=1}^{R} CP_{pr} \qquad \forall p \qquad (17)$$

$$\sum_{m=1}^{M}\sum_{r=1}^{R} QRO_{rmo} \leq IO_o \times \sum_{r=1}^{R} CO_{or} \qquad \forall o \qquad (18)$$

$$\sum_{p=1}^{P} QD_{jpd} = \sum_{c=1}^{C} QC_{jdc} \qquad \forall d,j \qquad (19)$$

$$\sum_{d=1}^{D} QC_{jdc} \geq \sum_{l=1}^{L} QL_{jcl} \qquad \forall c,j \qquad (20)$$

$$\sum_{c=1}^{C} QL_{jcl} = \sum_{o=1}^{O} QO_{jlo} + \sum_{m=1}^{M} QM_{jlm} \qquad \forall l,j \qquad (21)$$

$$QR_{rsj},\ QP_{jpc},\ QD_{jpd},\ QC_{jdc},\ QL_{jcl}\ QO_{jlo},\ QM_{jlm},\ QRM_{rmp},\ QRO_{rmo} \geq 0 \quad \forall r,s,p,c,d,m,o,l,j \qquad (22)$$

$$IP_p,\ ID_d,\ IL_l,\ IM_m,\ IO_o \in \{0,1\} \qquad \forall p,d,m,o,l \qquad (23)$$

Constraint (9) ensures that the quantity of each product produced for each customer is greater than the demand. Constraint (10) shows that, for each product, the flow exiting from each collection center to disposal centers is equal to the flow of returned products from customers multiplied by the disposal ratio. Constraint (11) ensures that the sum of each raw material offered from each supplier to plants does not exceed the capacity of this supplier. Constraint (12) states that the sum of each product produced for customers by each plant does not exceed the capacity of this plant. Constraint (13) presents that the sum of each returned product processed by each remanufacturing center from collection centers does not exceed the capacity of this remanufacturing center. Constraint (14) states that the sum of each product shipped to customers from each distribution center does not exceed the capacity of this distribution center. Constraint (15) presents that the sum of each returned product inspected or collected by each collection center from customers does not exceed the capacity of this collection center. Constraint (16) ensures that the sum of each scrapped product disposed by each disposal center from collection centers does not exceed the capacity of this disposal center. Constraint (17) states that the sum of each material offered from remanufacturing centers for producing products does not exceed the capacity of this plant. Constraint (18) ensures that the sum of each material shipped from remanufacturing centers for disposal does not exceed the capacity of this disposal center. Constraint (19) represents that, for each product, the flow entering each distribution center from all plants is equal to the sum of the flow exiting from each distribution center to customers. Constraint (20) shows that the sum of each product shipped to each customer is greater than the sum of each product returned from this customer. Constraint (21) represents that, for each returned product, the flow entering each collection center from all customers is equal to the sum of the flow exiting from each collection center to disposal centers and remanufacturing centers. Constraint (22) preserves the non-negativity restriction on the decision variables, and constraint (23) imposes the binary restriction on the decision variables.

Solution Approach

In order to solve the multi-objective problem, this study will utilize weighted sums method and ε -constraint method to transform our multi-objective optimization problem to mono-objective optimization problem. In the weighted sums method, objective functions are combined by assigning appropriate weights, which can be determined by decision makers. In the ε -constraint method, the objective function with high priority is considered as objective function and the other objective functions are considered as constraints with allowable bounds [7].

Uncertainty of demand and return in the proposed model will be handled via a robust optimization approach. The solution of the model is 'robust feasible' if it remains feasible in response to all possible realizations of the uncertain parameters within their uncertainty bound. In addition, the solution of the model is 'robust optimal' if there is no other robust feasible solution with a better objective function value from the objective function of the robust optimal solution [4].

CONCLUSIONS

In order to gain competitive advantages, companies not only have to meet the environmental regulations, but also have to sustain high-quality supply chain operations as a means to stay in business over their lifetime. This study proposes a multi-objective model for an integrated closed-loop supply chain network, which simultaneously takes economic factors, environmental factors and quality factors and uncertain parameters into account to maximize the profit, the amicable production level and the quality level. Considering the multiple objectives in the closed-loop supply chain help companies obtain more precise information to make better decision. The proposed mathematical model can be a reference for supporting effectively integrated management of the closed-loop supply chain network, and thus contribute to the academia and practices.

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