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An Interactive Possibilistic Programming Approach to Designing a 3PL Supply Chain Network Under Uncertainty

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Abstract– *The design of closed-loop supply chain networks has attracted increasing attention in recent decades with environmental concerns and commercial factors. Due to the rapid growth of knowledge and technology, the complexity of the supply chain operations is increasing daily and organizations are faced with numerous challenges and risks in their management. Most organizations with limited resources, capabilities, and knowledge outsource their logistics services to reduce costs and increase customer satisfaction. The Third-Party Logistics (3PL) Providers have been set up to outsource various supply chain activities to specialized companies. This paper proposes a bi-objective possibilistic mixed-integer nonlinear programming model for designing a closed-loop supply chain network from the perspective of 3PL. To solve the proposed multi-objective model, a two-stage solving approach was applied first to converting the possibilistic model into its equivalent crisp counterpart and second, to converting the crisp multi-objective model into a single-objective one. Using this approach, a single-objective equivalent auxiliary crisp model was obtained and solved optimally by IBM ILOG CPLEX software. Solving numerical examples proved the effectiveness of the proposed bi-objective, possibilistic framework. Several sensitivity analyses were performed to gain managerial insights.*

Keywords– *Network design, Closed-loop supply chain, Third-Party Logistics (3PL) providers, Possibilistic programming, Fuzzy multi-objective optimization.*

I. INTRODUCTION

Reverse logistics flow is not controlled by most systems due to the lack of equipment. The transportation, storage, and repair of returned products are more complex than outgoing products and may involve higher costs. For this reason, many companies outsource all or part of their reverse logistics processes to third-party logistics companies (Efendigil et al., 2008).

With the increasing trend of outsourcing of logistics services, the attention of practitioners and researchers has been drawn to supply chain management and third-party logistics (Bask, 2006). Among the reasons for focusing on integrated study of 3PL and supply chain management, the following can be mentioned (Bask, 2006): i) the expected increase in outsourcing of logistics services (Coyle et al., 1992); ii) young and growing third-party logistics industry and its positive impact on the future of the logistics industry, iii) increasing growth of services offered by third-party logistics companies and improve in their proposed operations; and iv) increasing customer interest in outsourcing of more logistics services.

The 2017 21st Annual Third-Party Logistics Study (Capgemini, 2017) showed the willingness to make meaningful partnerships between clients and their Third-Party Logistics (3PL) providers. It has been argued that clients and their

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3PL providers work together to strengthen their relationships and optimize the supply chain, and that clients choose third-party firms to find innovative solutions and a true competitive advantage.

The transactional approach to the 3PL and its clients specifically encompassed in this article is to share the 3PL with the gradual income earned from selling the recycled products, which is likely to result in less pressure on clients. In this paper, we try to show if this idea could be an efficient and appropriate way for both 3PL providers and their clients. To this end, we seek to outsource a large part of the forward and reverse logistics processes and, instead, give the whole or part of income from the sale to the secondary market for the third party company.

In the network design process for the supply chain, it is decided which of the potential facilities and at what level of capacity they will open; also, the quantities of purchases, inventories/shortages, and transfers between opened facilities are determined to maximize customer satisfaction and chain value (Ramezani et al., 2014).

The problem of designing the supply chain network for 3PL that has been studied in this paper integrates two well-studied problems in the Supply Chain Management (SCM), namely network design and outsourcing. In spite of the great importance of these two issues in the supply chain, few studies have examined their integration.

In this study, we consider companies that decide to outsource their distribution operations in forward logistics as well as reverse logistics operations to 3PL companies. Instead, they obtain a higher level of customer satisfaction and possibly bear a lower total cost through performing more specialized logistics operations.

Due to the changing needs of individual clients and client markets over time, 3PL providers need to make their decisions interrelated. The challenges faced by 3PL providers to make the right decisions are: the uncertainty of clients and, therefore, the location of their manufacturing facilities and markets, and the uncertainty about the volume of products and even the products themselves that should be managed by third-party companies (Ko and Evans, 2007). To handle this problem, we employ a fuzzy modeling approach in which non-deterministic parameters are considered as fuzzy numbers.

Another challenge for 3PL is the exchange between service levels for different clients, which means that improving service level for a client may worsen the level of another client service (Ko and Evans, 2007). On the other hand, timely performance, the percentage of shipments delivered without damage, penalties for non-compliance of both 3PL providers and clients, and distance and cost increases or saving are the outcomes in the field of logistics outsourcing, which can be considered as criteria for the involvement of justice in the problem (Kashyap et al. 2008). Considering the mentioned concept of fairness and given the fact that 3PL is contracted by various companies, since 3PL is responsible for the distribution of products to the customers of contracting companies in forward network and the distances between the customers are different with 3PL distribution centers, modeling should be done in such a way that fairness in the distribution of products, regardless of the distance between each customer and 3PL distribution centers, is ensured and the amount of shortage created in the problem is uniformly distributed among different customers. Distributive justice is therefore considered through the objective of minimizing the maximum shortage among all clients. By the bi-objective modeling of the problem, it is possible to recognize the relationship between the economic and service-level aspects of 3PL supply chain network. Therefore, we can extract the exchange between the profits of the 3PL operations and the maximum level of service.

The remainder of this paper is structured as follows: in Section II, the studies related to supply chain network design are reviewed and the existing gaps covered by the innovations of our research are expressed. In Section III, the assumptions and structure of the 3PL supply chain network are described. Then, the mathematical formulation of the problem is presented. Section IV describes the fuzzy multi-objective problem solving method. In Section V, a numerical example is given; several sensitivity analyses are carried out; and the findings of this study are discussed. Finally, in Section VI, the conclusions of this research along with some future research directions in the field of 3PL network design are presented.

II. LITERATURE REVIEW

Recently, the integration of forward and reverse logistics in the supply chain has received special attention of the researchers due to its significant effects on reducing the environmental pollution and non-renewable energy consumption (Ramezani, et al., 2014).

The literature devoted to the reverse logistics networks can be divided into two parts: the research that focuses only on the backward network and the research that integrates the backward and forward networks (i.e., closed-loop network) (Melo et al., 2007).

Closed-Loop Supply Chain (CLSC) network design problem has widely been studied by many researchers in different aspects, e.g., CLSC design problem with the greenness concept (Sarkis, 2003; Wang and Hsu, 2010), management of bioenergy supply network (Razm et al., 2019), simultaneous design and planning networks (Gomes et al., 2009; Salema et al., 2009), incorporating of risk in the design of forward and reverse logistics networks (El-Sayed et al., 2010), sustainable supply chain (Yousefi et al., 2017), review of closed-loop supply chains problems (Govindan and Soleimani, 2017), incorporating of responsiveness and quality level in network design (Ramezani et al., 2013a), considering a financial approach to supply chain design (Ramezani et al., 2013b), design of dynamic distribution networks (Ko and Evans, 2007), incorporating of the cost of inventories in closed-loop supply chain networks (Motaghedi Larijani and Jabalameli, 2016), and even post-sales network design (Eskandarpour et al., 2014). In addition, in the area of 3PL supply chain network design, although several years have been passed since the appearance of this problem, little research has been conducted in this regard (e.g., Ko and Evans, 2007; Zhang et al., 2007; Min and Ko, 2008; Daghigh et al., 2016; Motaghedi Larijani and Jabalameli, 2016; Eskandarpour et al., 2014). Also, in terms of the types of entities included in the 3PL supply chain network design, the number of studies that are general and can be expanded to real-world issues is almost negligible.

Ko and Evans (2007) studied an integrated dynamic closed-loop network driven by 3PL in certain environment. In their paper, the forward and reverse logistics was examined and a hybrid solution method was presented. Min and Ko (2008) developed the model provided by Ko and Evans, considering the constraint in number of times the capacity increases. They provided a dynamic design for a closed-loop logistics network in a deterministic environment and proposed the GA method for solving the problem that involved locating and allocating repair facilities for 3PL. Daghigh et al. (2016) presented a multi-objective model for designing a logistics network from the point of view of 3PL by considering sustainable objectives under uncertainty. The objective functions were minimizing the total cost, minimizing greenhouse gas emission, and maximizing social responsibility for fair access to products. A fuzzy programming approach was used to modeling the problem and the epsilon-constraint method was used to solve it. Eskandarpour et al. (2014) studied the design of a post-sales reverse logistics network for 3PL in certain environments. They proposed a bi-objective MILP model to minimize costs of network as well as total weighted tardiness of returning products to customers.

In Table III, a review of important studies of the design of supply chain network in terms of network structure and modeling approach is provided. The codes in Table III are based on Tables I and II. The table shows that few studies have been conducted on supply chain network design for 3PL. Based on the literature review, the number of studies in the field of designing the supply chain network of third-party logistics companies is one-tenth the number of studies in the field of designing supply chain network in general or for an individual company. Accordingly, the future research requirements for the problems of the first category are clearly observed.

Supply chain network design models for 3PL focus primarily on cost-oriented goals. In the design of the supply chain network for 3PL, multi-objective models are scarce. Only Eskandarpour et al. (2014) developed a multi-objective analysis to identify the exchanges that existed between different aspects of the decision making process. Obviously, the 3PL network does not meet the expectations of its clients by cost minimization alone and if designed only with this objective, it may be a completely inefficient network for clients. It is also worth noting that none of the existing studies of the 3PL supply chain network design has considered the economic aspect of maximizing profit. Also, none of the studies aimed to maximize the customer service level, which is very important in competitive market. Therefore, in this paper, we examine the relationship between service level and 3PL supply chain profit indices. The revenue of the considered 3PL is earned by selling the repaired/recycled products to a secondary market. In the area of 3PL supply chain network design, the literature that considers shortage is very narrow (e.g., Daghigh et al., 2016). In this paper, it is assumed that the unfulfilled demand is fully transferred to the subsequent periods. Therefore, we can analyze the second objective function of the problem, which is minimizing the maximum shortage among all clients in all periods.

Table I. Acronyms in network structure

Category	*Detail*	*Code*
Network type	Forward	F
	Reverse	R
Layers of network (Type of layers)	Supply	SU
	Manufacturing	MA
	Distribution	DS
	Collection	CO
	Repair	RP
	Redistribution	RD
	Remanufacturing	RM
	Recycling	RY
	Disposal	DP

Table II. Acronyms in the modeling approach

Category	*Detail*		*Code*
Features of the model	Period	Multi	MPE
		Single	SPE
	Product	Multi	MPO
		Single	SPO
	Parameter	Fuzzy	F
		Non-fuzzy	NF
	Facility capacity	Limitation of capacity	LOC
		Capacity expansion	CE
	3PL		3PL
Decisions of the model	Inventory value		IV
	Transportation value		TV
	Satisfaction value of demand		SVD
	Capacity of facility		COF
	Location/allocation		LA
Objectives of the model	Responsiveness		R
	Service level		SL
	Profit/cost		P/C

In the given literature review, research needs have become clear with regard to various features of the 3PL supply chain network design problem. As seen in Table III, few research studies have been done on the design of closed-loop networks for 3PL companies and no study has considered a comprehensive network from the viewpoint of 3PL companies so far. Also, most studies have considered the 3PL network merely as a simple backward distribution network and limited operations such as warehousing and transportation have been outsourced to them. This gap is covered in this study and a completely new network will be developed for 3PL companies, allowing them to use the economies of scale for designing an integrated forward-reverse logistics system. Using a transactional approach through embedding a secondary market motivates the 3PL to earn an activity-based revenue.

Table III. Overview of the related literature on SCND

Reference	*Logistic network echelons*									*Model features*									*Variables*					*Goals*		
	F			*R*						*Period*		*Product*		*Parameter*		*CE*	*LOC*	*3PL*	*IV*	*TV*	*SVD*	*COF*	*LA*	*R*	*SL*	*P/C*
	SU	*MA*	*DS*	*CO*	*RP*	*RD*	*RM*	*RY*	*DP*	*SPE*	*MPE*	*SPO*	*MPRZ*	*F*	*NF*											
(Wang and Hsu, 2010)	✓	✓	✓	✓			✓	✓		✓		✓		✓			✓			✓			✓			✓
(Salema et al., 2009)		✓	✓			✓	✓				✓		✓	✓			✓			✓			✓			✓
(El-Sayed et al., 2010b)	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓		✓			✓			✓			✓			✓
(Ramezani et al., 2013b)	✓	✓	✓	✓		✓			✓	✓			✓		✓		✓			✓		✓	✓	✓		✓
(M Ramezani et al., 2014)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓		✓		✓			✓		✓	✓			✓
(Ramezani et al., 2013b)	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓		✓			✓		✓	✓			✓			
(Ko and Evans, 2007)		✓	✓		✓		✓				✓		✓	✓		✓	✓	✓		✓			✓			✓
(Zhang et al., 2007)				✓						✓			✓		✓		✓	✓		✓			✓			✓
(Min and Ko, 2008)		✓	✓		✓		✓				✓		✓	✓		✓	✓	✓		✓			✓			✓
(Daghigh et al., 2016)		✓	✓								✓		✓		✓		✓	✓	✓	✓	✓		✓			✓
(Motaghedi Larijani and Jabalameli, 2016)		✓	✓		✓						✓		✓	✓			✓	✓	✓	✓			✓			✓
(Eskandarpour et al., 2014)		✓		✓	✓				✓	✓			✓	✓			✓	✓		✓			✓	✓		✓
(Ramezani et al., 2013c)	✓	✓	✓	✓	✓				✓	✓			✓		✓		✓			✓			✓			✓
(Pishvaee et al., 2009)				✓	✓	✓			✓	✓		✓			✓		✓			✓	✓		✓			✓
(Zeballos et al., 2014)	✓	✓	✓	✓	✓				✓	✓			✓		✓		✓		✓	✓			✓			✓
Pishvaee and Torabi, 2010)		✓	✓	✓	✓			✓			✓	✓			✓		✓			✓			✓	✓		✓
This research		✓	✓	✓	✓	✓	✓		✓		✓		✓		✓		✓	✓	✓	✓	✓	✓	✓		✓	✓

In addition, it is observed that most papers do not pay attention to the uncertainty in supply chain network design models for 3PL service providers, which requires more attention in this regard, because in the real world, most of the parameters are uncertain due to environmental conditions and different policies. In addition, the nature of the reverse logistics and the uncertainty of the quantity and quality of return products will double the need to consider the uncertainty issue. Moreover, In the 3PL network design area, few studies have been conducted on multi-objective models and in none of them, the goal of maximizing service level is included. Therefore, 'multi-objective' modeling of the 3PL supply chain network design and development of solving methods for these models can be seen as research needs in this field.

III. PROBLEM DESCRIPTION AND MATHEMATICAL MODELING

In this paper, a multi-objective possibilistic mixed-integer nonlinear programming model for designing a closed-loop supply chain network for 3PL is presented. The objectives of the model are maximizing the total profit of the 3PL supply chain network and maximizing the customer service level. The general structure of the proposed closed-loop logistic network for 3PL is illustrated in Fig. (1).

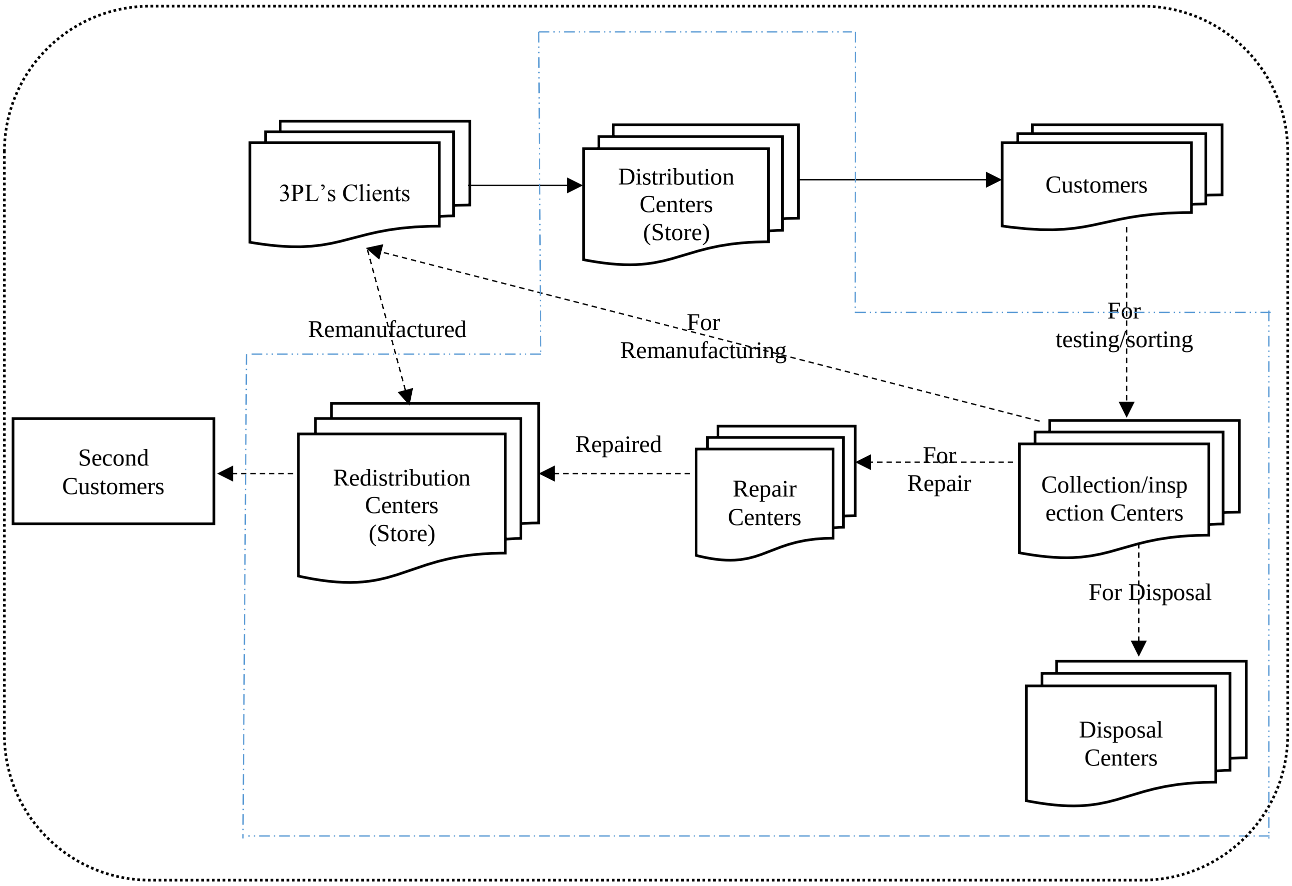

Figure 1. 3PL forward-reverse supply chain network structure

The network consists of the facilities of the clients, distribution centers, redistribution centers, repair centers, collection/ inspection centers, disposal centers, customers, and second customers. In the forward flow, manufacturers produce products at factories and store them at warehouses operated by 3PL, from which they are shipped to the customers over time. In the contract between 3PL providers and their customers, providers are required to distribute products in forward flow as well as to collect returned goods from customers and replace them with new products. Otherwise, providers will be penalized for not collecting the returned products. They are liable to gain profits from the sale of repaired goods for direct logistics activities and the collection of reciprocated goods under a contract with their clients. For forward logistics activities and the collection of returned products, 3PL providers earn the profit from the sale of repaired or remanufactured goods. The cost of repairing, remanufacturing, or disposing of returned products based on their quality is determined by 3PL itself and this kind of contract and network for 3PL is one of the aspects of innovation in this research. In the backward direction, the returned products are transmitted by the 3PL provider from the customers of the remanufacturing centers to the collection/inspection centers and then, classified into three categories of repairable, remanufactureable, and disposable based on their qualities. Repairable products are transferred to repair centers operated by the 3PL provider and remanufactureable products are transferred to manufacture/remanufacture centers. These centers receive remanufacturing costs from the 3PL provider for remanufacturing of products. Disposable products are also sent to disposal centers for proper disposal. Repaired and re-manufactured products are shipped to redistribution centers operated by the 3PL provider and distributed through redistribution centers to the secondary market. In the forward flow, shortages in meeting the demands of first customers are allowed and considered as back-order shortage. In the reverse flow, repaired and re-manufactured products are placed in sites to be distributed and buying is not done physically. After submitting a request by customers, who are not centralized and have no specified place , the product is sent. It is assumed that all products are sold in reverse flow. In this model, the return rate for products which are collected and inspected at the collection centers, the disposal rate, the repair rate and the rate of products which are sent to manufacturing centers for remanufacturing, the demand of the first customers, and the price of the repaired or remanufactured product are influenced by the uncertain environment and considered as triangular fuzzy parameters. The applied modeling approach is possibilistic programming and to solve the proposed multi-objective possibilistic model, a two-stage solution approach is used by combining a number of efficient solution approaches from the recent literature.

A. Model Assumptions

- The model is multi-product.
- Locations of the first customer is known and fixed with fuzzy demands.
- The potential locations of distribution, collecting, repair, redistribution, and disposal centers, which are operated by the 3PL provider, are known.
- Transportation of flow is permitted only between two consecutive stages; but, in order to moderate demand variations and prevent facing shortage, lateral transshipment is used among distribution and redistribustion centers.
- The number of facilities that can be opened and their capacities are both restricted.
- Shortage is considered in the form of back-order and demand of the first customer can be met with a delay.
- The model is a multi-period.
- The returned values depend on satisfied demand of the first customer in each period.
- The qualities of repaired and remanufactured products are different from the new ones.
- Holding cost depends on the residual inventory at the end of each period.
- First customers are owned by the clients of 3PL and secondary customers are owned by 3PL.

B. Model Formulation

The model involves the following sets, parameters, and decision variables:

Sets:

F: Clients of 3PL, indexed by *f*

D: Potential number of distributors, indexed by *d*

C: First customers, indexed by *c*

A: Potential number of collection/inspection centers, indexed by *a*

Q: Potential number of repair centers, indexed by *q*

R: Potential number of redistribution centers, indexed by *r*

P: Potential number of disposal centers, indexed by *p*

T: Number of periods, indexed by *t*

H: Set of capacity levels available for potential locations, indexed by *h*

M: Set of product types, indexed by *m*

Parameters:

$\widetilde{D}_{cmt}$: Demand of the first customer *c* for product *m* in period *t*

$\widetilde{Price}_{mt}$:Unit price for repaired or remanufactured product *m* in period *t*

F_{ih}: Fixed cost for opening location *i* with capacity level *h*

DS_{ij}: Distance between any two locations *i* and *j*

FC_{ft}: Manufacturing capacity of client *f* in period *t* in hours

RFC_{ft}: Remanufacturing capacity of client *f* in period *t* in hours

DC_{dht}: Capacity of distribution center *d* with capacity level *h* in period *t*

AC_{aht}: Capacity of collection center *a* with capacity level *h* in period *t*

RC_{qht}: Capacity of repair center *q* with capacity level *h* in period *t*

REC_{rht}: Capacity of redistribution center *r* with capacity level *h* in period *t*

PC_{pht}: Capacity of disposal center *p* with capacity level *h* in period *t*

$RFCO_{fmt}$: Unit remanufacturing cost of product *m* at remanufacture center *f* in period *t*

DAC_{amt}:Unit inspection and test cost of product *m* at collection center *a* in period *t*

RPC_{qmt}: Unit repair cost of product *m* at repair center *q* in period *t*

PCO_{pmt}: Unit disposal cost of product *m* at disposal center *p* in period *t*

SC_{mt}: Unit shortage cost of product *m* in period *t*

Fh_{fm}: Unit manufacturing time of product *m* in hours at manufacture center *f*

RFh_{mf}: Unit remanufacturing time of product *m* in hours at remanufacture center *f*

DH_{dmt}: Unit holding cost of product *m* in period *t* at the store of distribution center *d*

Rm_m: Capacity utilisation rate per unit of product *m*

RDH_{rmt}: Unit holding cost of product *m* in period *t* at the store of redistribution center *r*

$B_{rm}, B_{qm}, B_{am}, B_{dm}, B_{fm}, B_{cm}$: Batch sizes from redistribution center *r*, repair center *q*, inspection/collection center *a*, distribution center *d*, client *f*, and customer *c*, respectively

TC_m: Unit transportation cost of product *m* per unit distance

fm_{fm}: 1 if client *f* produces product *m*; 0 otherwise

$\widetilde{RR}_m$: Return ratio at the first customer for product *m*

$\widetilde{\mathrm{RRm}}_{\mathrm{m}}$: Remanufacturing ratio for product *m*

$\widetilde{\mathrm{RRc}}_{\mathrm{m}}$: Repairing ratio for product *m*

$\widetilde{\mathrm{RRp}}_{\mathrm{m}}$: Disposal ratio for product *m*

Pc_{cmt}: Penalty for not collecting product *m* from customer *c* in period *t*

Decision variables:

Li_{ih}: 1 if location *i* with capacity level *h* is opened; 0 otherwise

Lij_{ij}: 1 if a transportation link is established between any two locations *i* and *j*; 0 otherwise

Q_{ijmt}: Flow of product *m* batches from location *i* to location *j* in period *t*

ID_{dmt}: Residual inventory of product *m* at distribution center *d* at the end of period *t*

IRD_{rmt}: Residual inventory of product *m* at redistribution center *r* at the end of period *t*

SD_{cmt}: Shortage value of product *m* for customer *c* in period *t*

V_{cmt}: The value of not collecting returned product *m* from customer *c* in period *t*

The formulation of the bi-objective possibilistic nonlinear programming model for designing a 3PL forward-reverse supply chain network is as follows:

$$
\begin{aligned}
Max\ Z1 = &\sum_{r,m,t} Q_{rmt} B_{rm} \widetilde{Price}_{mt} \\
&- \Big[\sum_{d,h} F_{dh} L_{dh} + \sum_{a,h} F_{ah} L_{ah} + \sum_{q,h} F_{qh} L_{qh} + \sum_{p,h} F_{ph} L_{ph} + \sum_{r,h} F_{rh} L_{rh} \\
&+ \sum_{c,a,m,t} Q_{camt} B_{cm} DAC_{amt} \\
&+ \sum_{f,r,m,t} Q_{frmt} B_{fm} RFCO_{fmt} + \sum_{q,r,m,t} Q_{qrmt} B_{qm} RPC_{qmt} \\
&+ \sum_{a,p,m,t} Q_{apmt} B_{am} PCO_{pmt} + \sum_{f,d,m,t} Q_{fdmt} B_{fm} TC_m\, DS_{fd} \\
&+ \sum_{a,f,m,t} Q_{afmt} B_{am} TC_m\, DS_{af} + \sum_{a,p,m,t} Q_{apmt} B_{am} TC_m\, DS_{ap} \\
&+ \sum_{c,a,m,t} Q_{camt} B_{cm} TC_m DS_{ca} + \sum_{a,q,m,t} Q_{aqmt} B_{am} TC_m\, DS_{aq} \\
&+ \sum_{q,r,m,t} Q_{qrmt} B_{qm} TC_m\, DS_{qr} + \sum_{f,r,m,t} Q_{frmt} B_{fm} TC_m\, DS_{fr} \\
&+ \sum_{r,m,t} Q_{rmt} B_{rm} TC_m\, DS_r + \sum_{d,c,m,t} Q_{dcmt} B_{dm} TC_m DS_{dc} \\
&+ \sum_{d,d',m,t} Q_{dd'mt} B_{dm} TC_m\, DS_{dd'} + \sum_{r,r',m,t} Q_{rr'mt} B_{rm} TC_m\, DS_{rr'} \\
&+ \sum_{d,m,t} ID_{dmt} DH_{dmt} + \sum_{r,m,t} IRD_{rmt} RDH_{rmt} + \sum_{c,m,t} V_{cmt} Pc_{cmt}\Big]
\end{aligned} \tag{1}
$$

$$\text{Min } Z2 = U \tag{2}$$

s.t.

$$\sum_{m,t} SD_{cmt} \leq U \qquad \forall c \tag{3}$$

$$\sum_{f} Q_{fdmt}B_{fm} + ID_{dm(t-1)} + \sum_{d'} Q_{d'dmt}B_{d'm} = ID_{dmt} + \sum_{c} Q_{dcmt}B_{dm} + \sum_{d'} Q_{dd'mt}B_{dm} \qquad \forall d, m, t > 1 \tag{4}$$

$$\sum_{f} Q_{fdm1}B_{fm} + ID_{dm0} + \sum_{d'} Q_{d'dm1}B_{d'm} = ID_{dm1} + \sum_{c} Q_{dcm1}B_{dm} + \sum_{d'} Q_{dd'm1}B_{dm} \qquad \forall d, m, t = 1 \tag{5}$$

$$\sum_{d} Q_{dcmt}B_{dm} \leq \widetilde{D}_{cmt} + SD_{cm(t-1)} \qquad \forall c,m,t>1 \tag{6}$$

$$\sum_{d} Q_{dcm1}B_{dm} \leq \widetilde{D}_{cm1} \qquad \forall c, m, t = 1 \tag{7}$$

$$SD_{cmt} = \sum_{i=1}^{t} \widetilde{D}_{cmi} - \sum_{d}\sum_{i=1}^{t} Q_{dcmi}B_{dm} \qquad \forall c, m, t \tag{8}$$

$$\sum_{a} Q_{camt}B_{cm} + V_{cmt} = (\sum_{d} Q_{dcmt}B_{dm})\widetilde{RR}_{m} \qquad \forall c, m, t \tag{9}$$

$$\sum_{c} Q_{camt}B_{cm} = \sum_{f} Q_{afmt}B_{am} + \sum_{q} Q_{aqmt}B_{am} + \sum_{p} Q_{apmt}B_{am} \qquad \forall a, m, t \tag{10}$$

$$\sum_{c} Q_{camt}B_{cm}\widetilde{RRm}_{m} = \sum_{f} Q_{afmt}B_{am} \qquad \forall a, m, t \tag{11}$$

$$\sum_{c} Q_{camt}B_{cm}\widetilde{RRc}_{m} = \sum_{q} Q_{aqmt}B_{am} \qquad \forall a, m, t \tag{12}$$

$$\sum_{c} Q_{camt}B_{cm}\widetilde{RRp}_{m} = \sum_{p} Q_{apmt}B_{am} \qquad \forall a, m, t \tag{13}$$

$$\sum_{a} Q_{aqmt}B_{am} = \sum_{r} Q_{qrmt}B_{qm} \qquad \forall q,m,t \tag{14}$$

$$\sum_{a} Q_{afmt} B_{am} = \sum_{r} Q_{frmt} B_{fm} \qquad \forall f, m, t \tag{15}$$

$$\sum_{q} Q_{qrmt} B_{qm} + \sum_{f} Q_{frmt} B_{fm} + \sum_{r'} Q_{r'rmt} B_{r'm} = Q_{rmt} B_{rm} + \sum_{r'} Q_{rr'mt} B_{rm} \qquad \forall r, m, t \tag{16}$$

$$\sum_{d,m} Q_{fdmt} \, B_{fm} Fh_{fm} \leq FC_{ft} \qquad \forall f, t \tag{17}$$

$$\sum_{r,m} Q_{frmt} \, B_{fm} RFh_{fm} \leq RFC_{ft} \qquad \forall f, t \tag{18}$$

$$\sum_{f,m} Q_{fdmt} \, B_{fm} Rm_m + \sum_{m} ID_{dm(t-1)} Rm_m + \sum_{d',m} Q_{d'dmt} B_{d'm} Rm_m \leq \sum_{h} DC_{dht} L_{dh} \qquad \forall d, t > 1 \tag{19}$$

$$\sum_{f,m} Q_{fdm1} \, B_{fm} Rm_m + \sum_{m} ID_{dm0} Rm_m + \sum_{d',m} Q_{d'dm1} B_{d'm} Rm_m \leq \sum_{h} DC_{dh1} L_{dh} \qquad \forall d, t = 1 \tag{20}$$

$$\sum_{f,m} Q_{afmt} \, B_{am} Rm_m + \sum_{q,m} Q_{aqmt} B_{am} Rm_m + \sum_{p,m} Q_{apmt} B_{am} Rm_m \leq \sum_{h} AC_{aht} L_{ah} \qquad \forall a,t \tag{21}$$

$$\sum_{r,m} Q_{qrmt} \, B_{qm} Rm_m \leq \sum_{h} RC_{qht} L_{qh} \qquad \forall q, t \tag{22}$$

$$\sum_{q,m} Q_{qrmt} \, B_{qm} Rm_m + \sum_{f,m} Q_{frmt} B_{fm} Rm_m + \sum_{m} IRD_{rm(t-1)} Rm_m + \sum_{r',m} Q_{r'rmt} B_{r'm} Rm_m \leq \sum_{h} REC_{rht} L_{rh} \qquad \forall r, t > 1 \tag{23}$$

$$\sum_{q,m} Q_{qrm1} \, B_{qm} Rm_m + \sum_{f,m} Q_{frm1} B_{fm} Rm_m + \sum_{m} IRD_{rm0} Rm_m + \sum_{r',m} Q_{r'rm1} B_{r'm} Rm_m \leq \sum_{h} REC_{rh1} L_{rh} \qquad \forall r, t = 1 \tag{24}$$

$$\sum_{a,m} Q_{apmt} B_{am} Rm_m \leq \sum_h PC_{pht} L_{ph} \quad \forall p,t \quad (25)$$

$$\sum_{m,t} Q_{fdmt} \leq M \times \sum_h L_{dh} \quad \forall f,d \quad (26)$$

$$\sum_{m,t} \mathrm{Q_{dcmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{dh}} \quad \forall d,c \quad (27)$$

$$\sum_{m,t} \mathrm{Q_{camt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{ah}} \quad \forall a,c \quad (28)$$

$$\sum_{m,t} \mathrm{Q_{afmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{ah}} \quad \forall a,f \quad (29)$$

$$\sum_{m,t} \mathrm{Q_{aqmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{ah}} \quad \forall a,q \quad (30)$$

$$\sum_{m,t} \mathrm{Q_{aqmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{qh}} \quad \forall a,q \quad (31)$$

$$\sum_{m,t} \mathrm{Q_{apmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{ah}} \quad \forall a,p \quad (32)$$

$$\sum_{m,t} \mathrm{Q_{apmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{ph}} \quad \forall a,p \quad (33)$$

$$\sum_{m,t} \mathrm{Q_{qrmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{qh}} \quad \forall q,r \quad (34)$$

$$\sum_{m,t} \mathrm{Q_{qrmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{rh}} \quad \forall q,r \quad (35)$$

$$\sum_{m,t} \mathrm{Q_{frmt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{rh}} \quad \forall f,r \quad (36)$$

$$\sum_{m,t} \mathrm{Q_{dd'mt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{rh}} \quad \forall d,d' \quad (37)$$

$$\sum_{m,t} \mathrm{Q_{dd'mt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{d'h}} \quad \forall d,d' \quad (38)$$

$$\sum_{m,t} \mathrm{Q_{rr'mt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{rh}} \quad \forall r,r' \quad (39)$$

$$\sum_{m,t} \mathrm{Q_{rr'mt}} \leq \mathrm{M} \times \sum_h \mathrm{L_{r'h}} \quad \forall r,r' \quad (40)$$

$$\sum_{d,h} L_{dh} \leq D \tag{41}$$

$$\sum_{a,h} L_{ah} \leq A \tag{42}$$

$$\sum_{q,h} L_{qh} \leq Q \tag{43}$$

$$\sum_{r,h} L_{rh} \leq R \tag{44}$$

$$\sum_{p,h} L_{ph} \leq P \tag{45}$$

$$\sum_{h} L_{dh} \leq 1 \qquad \forall d \tag{46}$$

$$\sum_{h} L_{ah} \leq 1 \qquad \forall a \tag{47}$$

$$\sum_{h} L_{qh} \leq 1 \qquad \forall q \tag{48}$$

$$\sum_{h} L_{rh} \leq 1 \qquad \forall r \tag{49}$$

$$\sum_{h} L_{ph} \leq 1 \qquad \forall p \tag{50}$$

$$QFD_{fdmt} \leq M \times fm_{fm} \qquad \forall f,d,m,t \tag{51}$$

$$QAF_{afmt} \leq M \times fm_{fm} \qquad \forall a,f,m,t \tag{52}$$

$$Li_{fd} \leq \sum_{m,t} Q_{fdmt} \qquad \forall f,d \tag{53}$$

$$Li_{dc} \leq \sum_{m,t} Q_{dcmt} \qquad \forall d\,,c \tag{54}$$

$$Li_{ca} \leq \sum_{m,t} Q_{camt} \qquad \forall c,a \tag{55}$$

$$Li_{af} \leq \sum_{m,t} Q_{afmt} \qquad \forall a,f \tag{56}$$

$$Li_{aq} \leq \sum_{m,t} Q_{aqmt} \qquad \forall a,q \tag{57}$$

$$Li_{qr} \leq \sum\nolimits_{m,t} Q_{qrmt} \qquad \forall q, r \qquad (58)$$

$$Li_{ap} \leq \sum\nolimits_{m,t} Q_{apmt} \qquad \forall a, p \qquad (59)$$

$$Li_{fr} \leq \sum\nolimits_{m,t} Q_{frmt} \qquad \forall f\ , r \qquad (60)$$

$$Li_{dd'} \leq \sum\nolimits_{m,t} Q_{dd'mt} \qquad \forall d, d' \qquad (61)$$

$$Li_{rr'} \leq \sum\nolimits_{m,t} Q_{rr'mt} \qquad \forall r, r' \qquad (62)$$

$$\sum\nolimits_{m,t} Q_{fdmt} \leq MLi_{fd} \qquad {}^{f},d \qquad (63)$$

$$\sum\nolimits_{m,t} Q_{dcmt} \leq MLi_{dc} \qquad \forall d, c \qquad (64)$$

$$\sum\nolimits_{m,t} Q_{camt} \leq MLi_{ca} \qquad \forall c, a \qquad (65)$$

$$\sum\nolimits_{m,t} Q_{afmt} \leq MLi_{af} \qquad \forall a, f \qquad (66)$$

$$\sum\nolimits_{m,t} Q_{aqmt} \leq MLi_{aq} \qquad \forall a, q \qquad (67)$$

$$\sum\nolimits_{m,t} Q_{qrmt} \leq MLi_{qr} \qquad \forall q, r \qquad (68)$$

$$\sum\nolimits_{m,t} Q_{apmt} \leq MLi_{ap} \qquad \forall a, p \qquad (69)$$

$$\sum\nolimits_{m,t} Q_{frmt} \leq MLi_{fr} \qquad \forall f, r \qquad (70)$$

$$\sum\nolimits_{m,t} Q_{dd'mt} \leq MLi_{dd'} \qquad \forall d, d' \qquad (71)$$

$$\sum\nolimits_{m,t} Q_{rr'mt} \leq MLi_{rr'} \qquad \forall r, r' \qquad (72)$$

The first objective function maximizes the total profit, which is the difference between total income and total cost of the 3PL supply chain network (Total profit = total income – total cost). Total income of network is the income of sale to second customers and the total cost is the sum of fixed, shortage (for distributor), collection/inspection, remanufacturing, repairing, disposal, transportation, inventory holding, and returned products non-collecting costs. The second objective function seeks to maximize the customer service level in forward network and involves minimizing the maximum shortage. Constraint (3) is used to linearize the second nonlinear objective function $(\text{Min Max} \sum_{m,t} SD_{cmt})$. Constraint (4) ensures that, for product m, the sum of the flows entering each distribution center from manufacturing centers and other distribution centers and its residual inventory from the previous period are equal to the sum of the flows exiting the respective distribution center toward all customers and other distribution centers and the residual inventory of the existing period, respectively. Constraint (5) is the same as the constraint (4), which is written for the first period. Constraint (6) ensures that, for product m, the flow entering each first customer from all distributors does not exceed the sum of the existing period demand and the previous accumulated back-orders. Constraint (7) ensures that, for product m, the flow entering each first customer from all distributors in the first period does not exceed the demand in the first period. Constraint (8) calculates the amount of accumulated back-orders per customer, per product, and per period. Constraint (9) ensures that, for each product and period, the sum of the flow exiting each first customer toward all collection centers and the amount of non-collected returned products is equal to the amount of the products of the flow entering each first customer from all distributors in return rate. Constraint (10) ensures that, for each product and period, the flow entering each collection center from all the first customers is equal to the sum of the flows going to repair centers for repair, to remanufacture centers for remanufacturing, and to disposal centers for proper disposal. Constraint (11) ensures that, for each product and period, the flow exiting collection center toward all manufacture centers to be remanufactured is equal to the sum of flows entering each collection center from all customers multiplied by the remanufacturing ratio. Constraint (12) ensures that, for each product and period, the flow exiting collection center toward all rapair centers to be repaired is equal to the sum of flows entering each collection center from all customers multiplied by the repairing ratio. Constraint (13) ensures that, for each product and period, the flow exiting collection center toward all disposal centers to be properly disposed is equal to the sum of flows entering each collection center from all customers multiplied by the disposal ratio. Constraint (14) ensures that, for each product and period, the flow entering each repair center from all collection centers is equal to the sum of the exiting flows from the respective repair center to redistribution centers. Constraint (15) ensures that, for each product and period, the total flow entering each remanufacturing center from all collection centers is equal to the sum of the remanufactured flows exiting the respective remanufacturing center toward all redistribution centers. Constraint (16) ensures that, for each product and period, the total flow entering each redistribution center from all remanufacturing centers as well as other redistribution and repair centers is equal to the sum of the flows exiting the respective redistribution center toward second customers and other redistribution centers. Constraint (17) ensures that, in each period, the sum of the flows exiting each remanufacturing center toward all distribution centers does not exceed the manufacturing capacity. Constraint (18) ensures that, in each period, the sum of the flows exiting each remanufacturing center toward all redistribution centers does not exceed the remanufacturing capacity. Constraint (19) ensures that, in each period, the sum of the residual inventory at each distribution center from the previous period and the flow entering the existing period from the manufacturing centers and other distribution centers does not exceed the capacity of the respective distribution center. Constraint (20) ensures that, in first period and each distribution center, the sum of the inventory at the beginning of the first period and the flow entering from the manufacturing centers and other distribution centers does not exceed the capacity of the respective distribution center. Constraint (21) ensures that, in each period, the sum of the flows exiting each collection center toward all remanufacturing, repair, and disposal centers does not exceed the capacity of the respective collection center. Constraint (22) ensures that, in each period, the flow exiting each repair center toward all redistribution centers does not exceed the capacity of the respective repair center. Constraint (23) ensures that, in each period, the sum of the residual inventory at each redistribution center from the previous period and the flow entering the existing period from all the repair and remanufacturing centers as well as other redistribution centers does not exceed the capacity of the respective redistribution center. Constraint (24) ensures that, in the first period and each redistribution center, the sum of the inventory at the beginning of the first period and the flow entering from all the repair and remanufacturing centers as well as other redistribution centers does not exceed the capacity of the respective redistribution center. Constraint (25) ensures that, in each period, the flow entering each disposal center from all collection centers does not exceed the capacity of the respective repair center. Constraints (26)-(40) ensure that shipment between two facilities is possible if both facilities are opened. Constraints (41)-(45) limit the number of activated locations, by which the sum of binary decision variables that indicate the number of activated locations is less than the maximum limit of activated locations (taken equal to the potential number of locations). Constraint (51) ensures that product m is transferred from the client f to the distribution centers if client f produces product m. Constraint (52) ensures that product m is transferred from the collection center to the remanufacturing centers if client f produces product m. Constraints (53)-(62) ensure that there are no links between any locations without actual shipments during all periods for all products. Constraints (63)-(72) ensure that there is no shipping between non-linked locations.

IV. THE PROPOSED SOLUTION METHOD

In this paper, in order to deal with the proposed possibilistic multi-objective model, a two-phase solution approach is used. In the first phase, the original model is converted into an equivalent auxiliary crisp model by applying the efficient possibilistic method used by Pishvaee and Torabi (2010), which is the combination of the methods used by Jiménez et al. (2007) and Parra et al. (2005). Then, in the second phase, we apply the interactive fuzzy multi-objective programming approach proposed by Torabi and Hassini (2008) in order to convert the model into a single objective one and find the final preferred compromise solution. In the following, explanations of the method used to get the equivalent auxiliary crisp model, which is based on the mathematical concepts such as expected interval and expected value of fuzzy numbers, as well as the TH method use to get the single-objective model are given.

A. The Equivalent Auxiliary Crisp Model

The method presented by Jiménez et al. (2007) is based on the definition of the "expected value" and "expected interval" of a fuzzy number. Assume that $\tilde{c}$ is a triangular fuzzy number. The following equation can be defined as the membership function of $\tilde{c}$:

$$\mu_{\tilde{c}(x)} = \begin{cases} f_c(x) = \dfrac{x - c^p}{c^m - c^p} & if \quad c^p \le x \le c^m \\ 1 & if \quad x = c^m \\ g_c(x) = \dfrac{c^o - x}{c^o - c^m} & if \quad c^m \le x \le c^o \\ 0 & if \quad x \le c^p \; or \; x \ge c^o \end{cases} \tag{73}$$

According to Jiménez et al. (2007), the Expected Interval (EI) and Expected Value (EV) of triangular fuzzy number $\tilde{c}$ can be defined as follows:

$$EI(\tilde{c}\,) = [E_1^c, E_2^c] = \left[\int_0^1 f_c^{-1}(x)dx, \int_0^1 g_c^{-1}(x)dx,\right] = \left[\frac{1}{2}(c^p + c^m), \frac{1}{2}(c^m + c^o)\right] \tag{74}$$

$$EV(\tilde{c}) = \frac{E_1^c + E_2^c}{2} = \frac{c^p + 2c^m + c^o}{4} \tag{75}$$

Moreover, according to the ranking method of Jiménez et al. (2007), for any pair of fuzzy numbers $\tilde{a}, \tilde{b}$, the degree to which $\tilde{a}$ is bigger than $\tilde{b}$ is defined as follows:

$$\mu_M(\tilde{a},\tilde{b}) = \begin{cases} 0 & if \;\; E_2^a - E_1^b < 0 \\ \dfrac{E_2^a - E_1^b}{E_2^a - E_1^b - (E_1^a - E_2^b)} & if \;\; 0 \in [E_1^a - E_2^b, E_2^a - E_1^b] \\ 1 & if \;\; E_1^a - E_2^b > 0 \end{cases} \tag{76}$$

When $\mu_M(\tilde{a},\tilde{b}) \geq \alpha$, $\tilde{a}$ is bigger than or equal to $\tilde{b}$ at least at degree α and it will be represented by $\tilde{a} \geq_\alpha \tilde{b}$. Also, according to the definition of fuzzy equations in Parra et al. (2005), for any pair of fuzzy numbers $\tilde{a},\tilde{b}$, $\tilde{a}$ is indifferent (equal) to $\tilde{b}$ at the degree of α if the following relationships hold, simultaneously:

$$\tilde{a} \geq_{\alpha/2} \tilde{b} \quad , \quad \tilde{a} \leq_{\alpha/2} \tilde{b} \tag{77}$$

The above equations can be rewitten as follows:

$$\alpha/2 \leq \mu_M(\tilde{a},\tilde{b}) \leq 1 - \alpha/2 \tag{78}$$

Now, consider the following fuzzy mathematical programming model in which all parameters are defined as triangular or trapezoidal fuzzy numbers:

$$\begin{aligned} &\min Z = \tilde{c}^t x \\ &\text{s.t.} \\ &\quad \tilde{a}_i x \geq \tilde{b}_i \;, i = 1, \dots, l \\ &\quad \tilde{a}_i x = \tilde{b}_i \;, i = l+1, \dots, m \\ &\quad x \geq 0 \end{aligned} \tag{79}$$

According to Dubois et al. (2003), the equations $\tilde{a}_i x \geq \tilde{b}_i$ and $\tilde{a}_i x = \tilde{b}_i$ are equivalent to the following ones, respectively:

$$\frac{E_2^{a_i x} - E_1^{b_i}}{E_2^{a_i x} - E_1^{a_i x} + E_2^{b_i} - E_1^{b_i}} \geq \alpha \qquad , \quad i = 1, \dots, l \tag{80-1}$$

$$\frac{\alpha}{2} \leq \frac{E_2^{a_i x} - E_1^{b_i}}{E_2^{a_i x} - E_1^{a_i x} + E_2^{b_i} - E_1^{b_i}} \leq 1 - \frac{\alpha}{2} \quad , \quad i = l+1, \dots, m \tag{80-2}$$

These equations can be rewritten as follows:

$$\begin{aligned} &\left[(1-\alpha)E_2^{a_i} + \alpha E_1^{a_i}\right]x \geq \alpha E_2^{b_i} + (1-\alpha)E_1^{b_i} && , i = 1, \dots, l \\ &\left[\left(1-\frac{\alpha}{2}\right)E_2^{a_i} + \frac{\alpha}{2}E_1^{a_i}\right]x \geq \frac{\alpha}{2}E_2^{b_i} + \left(1-\frac{\alpha}{2}\right)E_1^{b_i} && , i = l+1, \dots, m \\ &\left[\frac{\alpha}{2}E_2^{a_i} + \left(1-\frac{\alpha}{2}\right)E_1^{a_i}\right]x \leq \left(1-\frac{\alpha}{2}\right)E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i} && , i = l+1, \dots, m \end{aligned} \tag{81}$$

Consequently, using the definitions of EI and EV of a fuzzy number, the equivalent crisp α-parametric model of model (79) can be written as follows:

$$\begin{aligned}
&\min EV(\tilde{c})\,x\\
&s.t.\\
&\left[(1-\alpha)E_2^{a_i}+\alpha E_1^{a_i}\right]x \geq \alpha E_2^{b_i}+(1-\alpha)E_1^{b_i} \qquad ,i=1,\dots,l\\
&\left[\left(1-\frac{\alpha}{2}\right)E_2^{a_i}+\frac{\alpha}{2}E_1^{a_i}\right]x \geq \frac{\alpha}{2}E_2^{b_i}+\left(1-\frac{\alpha}{2}\right)E_1^{b_i} \qquad ,i=l+1,\dots,m\\
&\left[\frac{\alpha}{2}E_2^{a_i}+\left(1-\frac{\alpha}{2}\right)E_1^{a_i}\right]x \leq \left(1-\frac{\alpha}{2}\right)E_2^{b_i}+\frac{\alpha}{2}E_1^{b_i} \qquad ,i=l+1,\dots,m\\
&x \geq 0
\end{aligned} \tag{82}$$

According to the above descriptions, the equivalent auxiliary crisp model of the supply chain network design model can be formulated as follows:

$$\begin{aligned}
Max\,Z_1 = &\sum\nolimits_{r,m,t} Q_{rmt}B_{rm}\left(\frac{Price_{mt}^{p}+2Price_{mt}^{m}+Price_{mt}^{o}}{4}\right)\\
&-\Bigg[\sum\nolimits_{d,h}F_{dh}L_{dh}+\sum\nolimits_{a,h}F_{ah}L_{ah}+\sum\nolimits_{q,h}F_{qh}L_{qh}+\sum\nolimits_{p,h}F_{ph}L_{ph}\\
&+\sum\nolimits_{r,h}F_{rh}L_{rh}+\sum\nolimits_{c,m,t}SC_{mt}SD_{cmt}+\sum\nolimits_{c,a,m,t}Q_{camt}B_{cm}DAC_{amt}\\
&+\sum\nolimits_{f,r,m,t}Q_{frmt}B_{fm}RFCO_{fmt}+\sum\nolimits_{q,r,m,t}Q_{qrmt}B_{qm}RPC_{qmt}\\
&+\sum\nolimits_{a,p,m,t}Q_{apmt}B_{am}PCO_{pmt}+\sum\nolimits_{f,d,m,t}Q_{fdmt}B_{fm}TC_m\,DS_{fd}\\
&+\sum\nolimits_{a,f,m,t}Q_{afmt}B_{am}TC_m\,DS_{af}+\sum\nolimits_{a,p,m,t}Q_{apmt}B_{am}TC_m\,DS_{ap}\\
&+\sum\nolimits_{c,a,m,t}Q_{camt}B_{cm}TC_mDS_{ca}+\sum\nolimits_{a,q,m,t}Q_{aqmt}B_{am}TC_m\,DS_{aq}\\
&+\sum\nolimits_{q,r,m,t}Q_{qrmt}B_{qm}TC_m\,DS_{qr}+\sum\nolimits_{f,r,m,t}Q_{frmt}B_{fm}TC_m\,DS_{fr}\\
&+\sum\nolimits_{r,m,t}Q_{rmt}B_{rm}TC_m\,DS_r+\sum\nolimits_{d,c,m,t}Q_{dcmt}B_{dm}TC_mDS_{dc}\\
&+\sum\nolimits_{d,d',m,t}Q_{dd'mt}B_{dm}TC_m\,DS_{dd'}+\sum\nolimits_{r,r',m,t}Q_{rr'mt}B_{rm}TC_m\,DS_{rr'}\\
&+\sum\nolimits_{d,m,t}ID_{dmt}DH_{dmt}+\sum\nolimits_{r,m,t}IRD_{rmt}RDH_{rmt}+\sum\nolimits_{c,m,t}V_{cmt}Pc_{cmt}\Bigg]
\end{aligned} \tag{83}$$

$$Min\,Z_2 = U \tag{84}$$

s.t.

$$\sum_d Q_{dcmt}B_{dm} \leq \alpha\left(\frac{D^p_{cmt}+D^m_{cmt}}{2}\right)+(1-\alpha)\left(\frac{D^o_{cmt}+D^m_{cmt}}{2}\right)+SD_{cm(t-1)} \qquad \forall c,m,t>1 \qquad (85)$$

$$\sum_d Q_{dcm1}B_{dm} \leq \alpha\left(\frac{D^p_{cm1}+D^m_{cm1}}{2}\right)+(1-\alpha)\left(\frac{D^o_{cm1}+D^m_{cm1}}{2}\right) \qquad \forall c,m,t=1 \qquad (86)$$

$$SD_{cmt} \geq \sum_{i=1}^{t}\left[\frac{\alpha}{2}\left(\frac{D^m_{cmi}+D^o_{cmi}}{2}\right)+\left(1-\frac{\alpha}{2}\right)\left(\frac{D^p_{cmi}+D^m_{cmi}}{2}\right)\right]-\sum_d\sum_{i=1}^{t}Q_{dcmi}B_{dm}$$

$$SD_{cmt} \leq \sum_{i=1}^{t}\left[\left(1-\frac{\alpha}{2}\right)\left(\frac{D^m_{cmi}+D^o_{cmi}}{2}\right)+\frac{\alpha}{2}\left(\frac{D^p_{cmi}+D^m_{cmi}}{2}\right)\right]-\sum_d\sum_{i=1}^{t}Q_{dcmi}B_{dm} \qquad \forall c,m,t \qquad (87)$$

$$\sum_a Q_{camt}B_{cm}+V_{cmt} \geq \left(\sum_d Q_{dcmt}\,B_{dm}\right)\left[\frac{\alpha}{2}\left(\frac{RR^m_m+RR^o_m}{2}\right)+\left(1-\frac{\alpha}{2}\right)\left(\frac{RR^p_m+RR^m_m}{2}\right)\right]$$

$$\sum_a Q_{camt}B_{cm}+V_{cmt} \leq \left(\sum_d Q_{dcmt}\,B_{dm}\right)\left[\left(1-\frac{\alpha}{2}\right)\left(\frac{RR^m_m+RR^o_m}{2}\right)+\frac{\alpha}{2}\left(\frac{RR^p_m+RR^m_m}{2}\right)\right] \qquad \forall c,m,t \qquad (88)$$

$$\sum_c Q_{camt}B_{cm}\left[\left(1-\frac{\alpha}{2}\right)\left(\frac{RRm^m_m+RRm^o_m}{2}\right)+\frac{\alpha}{2}\left(\frac{RRm^p_m+RRm^m_m}{2}\right)\right] \geq \sum_f Q_{afmt}B_{am} \qquad \forall a,m,t \qquad (89)$$

$$\sum_c Q_{camt}B_{cm}\left[\frac{\alpha}{2}\left(\frac{RRm_m^m+RRm_m^o}{2}\right)+\left(1-\frac{\alpha}{2}\right)\left(\frac{RRm_m^p+RRm_m^m}{2}\right)\right] \leq \sum_f Q_{afmt}B_{am}$$

$$\sum_c Q_{camt}B_{cm}\left[\left(1-\frac{\alpha}{2}\right)\left(\frac{RRc_m^m+RRc_m^o}{2}\right)+\frac{\alpha}{2}\left(\frac{RRc_m^p+RRc_m^m}{2}\right)\right] \geq \sum_q Q_{aqmt}B_{am}$$

$$\sum_c Q_{camt}B_{cm}\left[\frac{\alpha}{2}\left(\frac{RRc_m^m+RRc_m^o}{2}\right)+\left(1-\frac{\alpha}{2}\right)\left(\frac{RRc_m^p+RRc_m^m}{2}\right)\right] \leq \sum_q Q_{aqmt}B_{am} \quad \forall a,m,t \tag{90}$$

$$\sum_c Q_{camt}B_{cm}\left[\left(1-\frac{\alpha}{2}\right)\left(\frac{RRp_m^m+RRp_m^o}{2}\right)+\frac{\alpha}{2}\left(\frac{RRp_m^p+RRp_m^m}{2}\right)\right] \geq \sum_p Q_{apmt}B_{am}$$

$$\sum_c Q_{camt}B_{cm}\left[\frac{\alpha}{2}\left(\frac{RRp_m^m+RRp_m^o}{2}\right)+\left(1-\frac{\alpha}{2}\right)\left(\frac{RRp_m^p+RRp_m^m}{2}\right)\right] \leq \sum_p Q_{apmt}B_{am} \quad \forall a,m,t \tag{91}$$

‘’

The written equations are the equivalent crisps of fuzzy objective function (1) and fuzzy constraints (6)-(9) and (11)-(13), respectively.

B. Fuzzy Interactive Programming Approach

Among several approaches that have been developed to solve the multi-objective crisp models, fuzzy interactive methods are one of the most attractive approaches. The main advantage of these methods is the ability of measuring and adjusting the satisfaction degree of each objective function based on priorities of the decision maker (Torabi and Hassini, 2008). In this paper, a two-phase hybrid solution approach is utilized to deal with the fuzzy and the multi-objective mathematical model, which is a combination of the presented possibilistic programming in the previous section and the TH method. In the first phase, the model is converted to the equivalent auxiliary crisp one. Then, in the second phase, the multi-objective crisp model is solved using the Torabi and Hassini (TH) method and converted into a single-objective model based on priorities of the decision maker. In this paper, an interactive fuzzy solution approach is proposed by combining the methods of Jiménez et al. (2007), Parra et al. (2005), and the TH method (Torabi and Hassini, 2008).The steps of the proposed hybrid solution approach can be summarized as follows:

Step 1: Determine the appropriate triangular or trapezoidal possibility distributions for imprecise parameters and formulate the MOPMINLP model for the 3PL closed-loop supply chain network design problem.

Step 2: Convert the imprecise objective functions into the crisp ones using the expected values of the corresponding imprecise parameters.

Step 3: Determine the minimum acceptable feasibility degree of decision vector α and convert the fuzzy constraints into the crisp ones. Then, formulate the equivalent auxiliary crisp MOPMINLP model.

Step 4: Determine the α-Positive Ideal Solution (α-PIS) and α-Negative Ideal Solution (α-NIS) for each objective function and α-feasibility level. To obtain the α-PIS, i.e., $(\mathcal{Z}_1^{PIS}, x_1^{PIS})$ and $(\mathcal{Z}_2^{PIS}, x_2^{PIS})$, the equivalent crisp MOPMINLP model should be solved for each objective function separately and then, the α-NIS for each objective function can be estimated as follows:

$$\mathcal{Z}_1^{NIS} = \mathcal{Z}_1\left(\mathrm{x}_2^{\mathrm{PIS}}\right), \mathcal{Z}_2^{NIS} = \mathcal{Z}_2(x_1^{PIS}) \tag{92}$$

Step 5: Determine a linear membership function for minimization objective functions as relation (93) and for maximation objective functions as relation (94).

$$\mu_{\mathrm{k}}(\mathrm{x}) = \begin{cases} 1 & if\ \mathcal{Z}_{\mathrm{k}} < \mathcal{Z}_{\mathrm{k}}^{PIS} \\ \dfrac{\mathcal{Z}_{\mathrm{k}}^{NIS} - \mathcal{Z}_{\mathrm{k}}}{\mathcal{Z}_{\mathrm{k}}^{NIS} - \mathcal{Z}_{\mathrm{k}}^{PIS}} & if\ \mathcal{Z}_{\mathrm{k}}^{PIS} \leq \mathcal{Z}_{\mathrm{k}} \leq \mathcal{Z}_{\mathrm{k}}^{NIS} \\ 0 & if\ \mathcal{Z}_{\mathrm{k}} > \mathcal{Z}_{\mathrm{k}}^{NIS} \end{cases} \tag{93}$$

$$\mu_{\mathrm{k}}(\mathrm{x}) = \begin{cases} 1 & if\ \mathcal{Z}_{\mathrm{k}} > \mathcal{Z}_{\mathrm{k}}^{PIS} \\ \dfrac{\mathcal{Z}_{\mathrm{k}} - \mathcal{Z}_{\mathrm{k}}^{NIS}}{\mathcal{Z}_{\mathrm{k}}^{PIS} - \mathcal{Z}_{\mathrm{k}}^{NIS}} & if\ \mathcal{Z}_{\mathrm{k}}^{NIS} \leq \mathcal{Z}_{\mathrm{k}} \leq \mathcal{Z}_{\mathrm{k}}^{PIS} \\ 0 & if\ \mathcal{Z}_{\mathrm{k}} > \mathcal{Z}_{\mathrm{k}}^{NIS} \end{cases} \tag{94}$$

where $\mu_{\mathrm{h}}(\mathrm{x})$ denotes the satisfaction degree of the hth objective function.

Step 6: Convert the equivalent crisp MOMINLP model into a single-objective MINLP model using the Torabi and Hassini (2008) aggregation functions. It should be noted that this method ensures obtaining the efficient solutions. The TH aggregation function is as follows:

$$\max\ \psi(x) = \vartheta\lambda_0 + (1-\vartheta)\sum\nolimits_k \varphi_k\mu_k(\mathrm{x}) \tag{95}$$

s.t.

$$\lambda_0 \leq \mu_k(\mathcal{Z}) \qquad k = 1,2 \tag{96}$$

$$x \in \mathrm{F}(x), \lambda_0 \qquad \vartheta \in [0,1] \tag{97}$$

where $\mathrm{F}(x)$ denotes the feasible region involving the constraints of the equivalent crisp model. Also, φ_k and ϑ denote the importance of the hth objective function and the coefficient of compensation, respectively. Notably, the optimal value of variable $\lambda_0 = \min_k\{\mu_k(x)\}$ indicates the minimum satisfaction degree of objective functions and the TH aggregation function in fact seeks a preferred value between the min operator (λ_0) and the weighted sum operator ($\sum_k \varphi_k\mu_k(\mathrm{x})$) based on the value of ϑ. In other words, the decision makers can obtain both balanced and unbalanced compromised solutions via changing the values of parameters φ_k and ϑ based on their own interests and preferences.

Step 7: Specify the value of the coefficient of compensation (ϑ) and relative importance of the fuzzy goals (φ_k), and solve the respective single-objective MINLP model. If the decision maker is satisfied with the current solution, stop; otherwise, provide another compromise solution by changing the values of ϑ and α (and if necessary, the value of φ_k) and go to step 3.

V. COMPUTATIONAL RESULTS

In this section, to validate the presented mathematical model and to illustrate applicability of the proposed solution, the validity of the model will be evaluated based on a numerical experiment. The calculations have been performed using the IBM ILOG CPLEX software in small dimensions. Dimensions of the sample problem are as follows: 3 clients, 3 potential locations of distribution centers, 6 first customers, 2 potential locations of collection centers, 1 potential location of repair center, 1 potential location of redistribution center, 2 potential locations of disposal centers, 3 products, 2 capacity levels, and 3 periods. The parameters in the numerical experiment are given in Table IV.

Table IV. Ranges of parameters for the numerical experiment

Parameter	***Value***
D_{cmt}^{m}-D_{cmt}^{o}-D_{cmt}^{p}	U (50,80)-U (100,130)-U (0,30)
$Price_{mt}^{m}$-$Price_{mt}^{o}$-$Price_{mt}^{p}$	U (1000,2000)-U (2000,3000)-U (500,900)
F_{dh}	U (15000,20000)
F_{ah}	U (70000 ,90000)
F_{qh}	U (50000,60000)
F_{rh}	U (40000,80000)
RC_{qht}	U (6000,7000)
REC_{rht}	U (8000,9000)
RR_{m}^{m}-RR_{m}^{o}-RR_{m}^{p}	(0.15,0.1,0.17)- (0.17,0.2,0.25)- (0.13,0.09,0.14)
RRm_{m}^{m}-RRm_{m}^{o}-RRm_{m}^{p}	(0.21,0.13,0.16)- (0.22,0.14,0.2)- (0.2,0.12,0.13)
RRc_{m}^{m}-RRc_{m}^{o}-RRc_{m}^{p}	(0.56,0.7,0.58)- (0.68 ,0.8,0.6)- (0.55 ,0.6,0.57)
RRp_{m}^{m}-RRp_{m}^{o}-RRp_{m}^{p}	(0.26,0.31,0.34)- (0.27 ,0.32,0.36)- (0.25,0.28,0.3)
Pc_{cmt}	U(100,200)

Table V. The components of the objective functions

$(\boldsymbol{\varphi_1}, \boldsymbol{\varphi_2}) = (\mathbf{0.7}, \mathbf{0.3}) - \boldsymbol{\alpha} = \mathbf{0.9} - \boldsymbol{\vartheta} = \mathbf{0.3}$				
Objective function	***Components of the objective function***	***Values of the components of the objective function***	***Value of the objective function***	***Satisfaction degree of the objective function*** $\mu_k(\mathcal{Z})$
$\mathcal{Z}_1$	Income	466440	222130	0.946
	Fixed cost	221680		
	Collection/inspection cost	1382,9		
	Remanufacturing cost	557,05		
	Repair cost	1542,9		
	Disposal cost	156,22		
	Transportation cost	3672,2		
	Holding cost	0		
	Returned products not-collecting cost	15317		
$\mathcal{Z}_2$	Shortage value	157	157	0.936

We first set the values of φ_1 and φ_2 to 0.7 and 0.3 to validate the model in the numerical experiment of this section. The model is solved with respect to the parameters of the numerical experiment and the values of the objective functions and variables will be reported by setting ϑ in the aggregation function of TH equal to 0.3 and α equal to 0.9 in the possibilistic problem solving. The reason for selecting 0.3 for ϑ is that the first objective function is more important than the second objective function, as indicated by vector φ .Therefore, for the decision maker, the unbalanced solutions with higher degrees of satisfaction for the first objective are more attractive. The components of the objective functions as well as the degrees of their satisfaction in the TH method after running the model with the specified parameters are reported in Table V.

A. Impact of the Amount of Demand of the First Customers and Price

Since the amount of the returned products is a function of the amount of satisfied demand of the first customers and the only source of revenue for 3PL is the sale of returned products to the secondary market, if the amount of demand is low, the amounts of returned products and revenue of 3PL will also be low. Therefore, due to the high cost of network construction, it is likely that the decision to create network in low demand is not economical. Sensitivity analysis of the price of repaired products also seems to be necessary, because at low prices, the network will not be profitable. To this end, we solve the test problem for the different values considered for the average demand and price of repaired products while other parameters are kept unchanged. The results are depicted in Figs. (2) and (3).

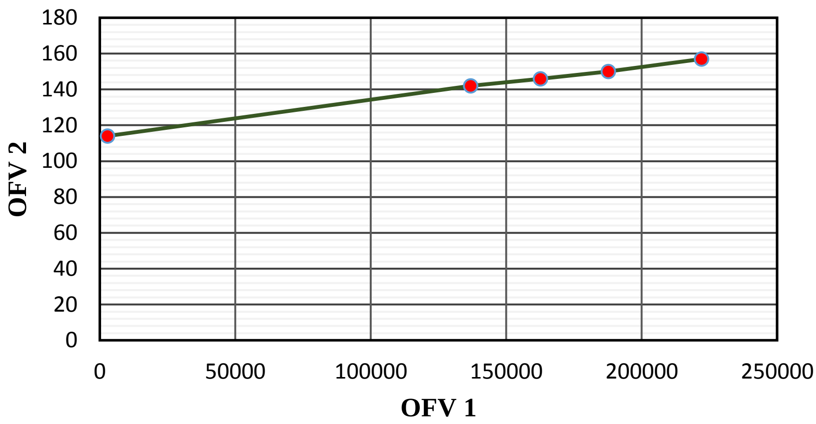

Figure 2. Demand sensitivity analysis

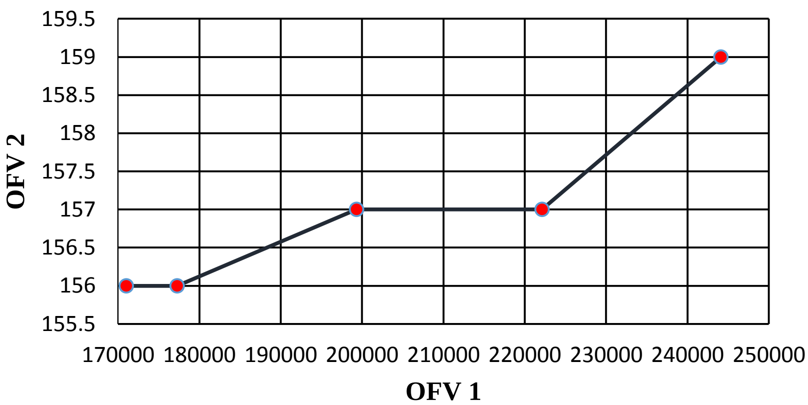

Figure 3. Price sensitivity analysis

Obviously, with increase in prices and demand, 3PL achieves more profitability, as shown in Figs. (2) and (3).

B. Sensitivity Analysis of the Model Based on the TH Aggregation Function Coefficients

A summary of the results of the numerical experiment for different values of ϑ and φ is presented in Table VI. Also, the decision maker provides the relative importance of objectives linguistically. It should be noted that if the number of objectives is more than two, the well-known MCDM techniques such as Analytic Hierarchy Process (AHP) can be used to set the objective weights more precisely.

Table VI. Summary of the values in sensitivity analysis of the parameters of the aggregation objective function in the TH method

Problem	ϑ	φ	$\mathcal{Z}_1$	$\mu_1(\mathcal{Z})$	$\mathcal{Z}_2$	$\mu_2(\mathcal{Z})$
1	0.6	0.2,0.8	209565	0.942	154	0.9475
	0.6	0.5,0.5	210985	0.9435	155	0.9449
	0.6	0.8,0.2	211090	0.944	155	0.9445
	0.4	0.2,0.8	208570	0.941	153	0.949
	0.4	0.5,0.5	209985	0.9429	155	0.9451
	0.4	0.8,0.2	211300	0.9447	156	0.9442

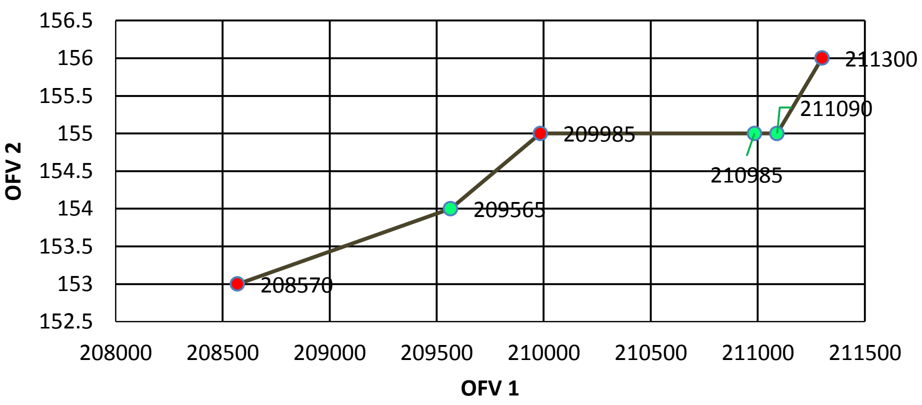

Figure 4. The Pareto-optimal solutions of the numerical experiment with respect to the TH aggregation function coefficients

The proposed formulation for TH aggregation function is able to achieve both acceptable balanced and unbalanced solutions to a sample problem based on preferences of the decision maker by adjusting the value of ϑ. In this method, a larger value of ϑ means that higher attention is paid to the minimum degree of satisfaction of the objective functions or λ_0. Therefore, there will be more balanced solutions. On the other hand, the lower value of ϑ means that, regardless of the satisfaction degree of other objectives, we seek a higher degree of satisfaction for objectives that weigh more (unbalanced solutions). The TH method is appropriate when the decision maker has a tendency to achieve efficient balanced solutions and pays higher attention to the minimum satisfaction degree of objective functions. Based on the results, the values of both objective functions are changed by changing the value of ϑ.

VI. CONCLUSION

In this paper, a mixed-integer nonlinear programming model was developed to formulate a bi-objective 3PL supply chain network design problem. The general structure of the proposed closed-loop supply chain network for 3PL incorporates the option of lateral transportation in the model to improve the performance of the 3PL supply chain. Also, the model considers the issue of distributive justice. These features distinguish the proposed model from the previous research in this area. Based on the results, it was shown that lateral transportation was an improvement factor for both the objectives of profit and service level. Also, the solution method used to the bi-objective problem enabled the decision maker to gain preferential values of objective functions by weight adjustment.

Examining heuristic and metaheuristic methods to solve large-scale problems, extending the model by incorporating different modes of transportation, and developing it by considering a hybrid facility for the entities of distribution and collection centers are some directions for future studies in this area.

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