A New Fuzzy Mathematical Model in Recycling Collection Networks: A Possibilistic Approach

B. Vahdani, R. Tavakkoli-Moghaddam, A. Baboli, and S. M. Mousavi

***Abstract*—**Focusing on the environmental issues, including the reduction of scrap and consumer residuals, along with the benefiting from the economic value during the life cycle of goods/products leads the companies to have an important competitive approach. The aim of this paper is to present a new mixed nonlinear facility location-allocation model in recycling collection networks by considering multi-echelon, multi-suppliers, multi-collection centers and multi-facilities in the recycling network. To make an appropriate decision in reality, demands, returns, capacities, costs and distances, are regarded uncertain in our model. For this purpose, a fuzzy mathematical programming-based possibilistic approach is introduced as a solution methodology from the recent literature to solve the proposed mixed-nonlinear programming model (MNLP). The computational experiments are provided to illustrate the applicability of the designed model in a supply chain environment and to help the decision makers to facilitate their analysis.

***Keywords*—**Location-allocation model; recycling collection networks; fuzzy mathematical programming.

I. INTRODUCTION

BY increasing globalization and making a movement to concentration on competition among networks of companies, numerous industries have gained the new experiences. Supply chain management (SCM) has been regarded as an important competitive approach for the organizations in the real-life situations. The global networks of suppliers have been established by multi-national companies that benefit from country-industry specific features in order to create the competitive advantage [1–3]. Logistics, recycling activities and supply chain managers should balance their attempts to reduce costs and innovate while trying to keep appropriate environmental and ecological performance [4]. Making attempts through recycling activities and logistics have forced companies to focus on closing the supply chain loop, namely closed-loop supply chains (CLSCs) [5,6]; thus, CLSCs have an extensive importance in recent two decades, which contains both the forward supply chain and the reverse supply chain at the same time. The forward supply chain basically considers the movement of goods/products from the upstream suppliers to the downstream customers. The reverse supply chain considers the movement of used/unsold products from the customer to the upstream supply chain, for possible recycling and reuses. Regarding the configuration of both forward and reverse supply chain networks has high impacts on the performance of each other. Hence, to avoid the sub-optimality obtained by the separated design, these forward and reverse networks should be combined concurrently [7].

A high degree of uncertainty in supply chain planning decisions is forced and the overall performance of the supply chain network is affected remarkably due to the dynamic and complex nature of supply chain [8]. Ho [9] categorized the uncertainty impacting on the real-world production systems into two main groups: 1) uncertainty about environmental issues, 2) uncertainty about system issues. The strategic horizon of supply chain network design decisions has crucial impacts on uncertainty in this problem. Furthermore, Fleischmann, et al. [10] stated that since controlling and estimating the quantity and quality of returned products is so difficult, the issue of uncertainty in the context of reverse supply chains is so important. Hence, taking in to account the significance of uncertainty, the researchers focused on uncertain parameters and considered them in the network design of supply chain [8]. To handle this issue, in the recent years many researchers have made attempts to model the uncertainty of supply chain by using probability distributions that are usually provided from historical data [11,12]. However, designing the stochastic models may not be the best approach because of the unreliability or unavailability of the required data in real-life problems and applications.

To solve the above mentioned difficulties, fuzzy sets theory [13] can deal with various kinds of uncertainty, particularly fuzzy coefficients for the lack of knowledge or epistemic uncertainty along with flexibility in constraints and objectives (i.e., fuzziness) simultaneously [14]. The limited attempts have been made to utilize this fuzzy approach for forward supply chain network design [15].

The aim of this paper is to design a functional possibilistic mathematical programming model under uncertainty regarding both environmental and system issues that involves in uncertain demands, returns, capacities, costs and distances. The concerned objective contains transportation costs and fixed opening costs of collection centers. The rest of this paper is organized as follows. The relevant literature review is

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reviewed in Section II. The concerned problem is defined in Section III. Model formulation is described in Section IV in detail; then in Section V, solution methodology is proposed based on a possibilistic mixed nonlinear programming model. Computational experiments are provided in Section VI. Finally, in Section VII, conclusions are given.

II. Literature Review

Kroon and Vrijens [16] proposed a quantitative mixed-integer linear program (MILP) model for the planning of a return logistics system for reusable containers. Schultmann et al. [17] designed a model for the planning of vehicle routing in the product-recovery networks. Jayaraman et al. [18] presented an MILP model for finding the optimal locations of remanufacturing and distribution facilities as well as the transshipment, production and stocking of the optimal quantities of remanufactured products and cores. Barros et al. [19] considered a case study on the design of a logistics network for recycling and provided by processing construction waste. Krikke et al. [20] presented an MILP model for a two-stage reverse supply chain network for a copier manufacturer. In this study, the objective function contains both the processing costs of returned products and inventory costs in order to minimize the total cost. Jayaraman et al. [21] made an attempt to solve the single product two-level hierarchical location problem by considering the reverse supply chain operations of hazardous products based on their prior work. In addition, they proposed a heuristic to deal with relatively large-sized problems. Min et al. [22] presented a mixed-integer nonlinear programming (MINLP) model and a genetic algorithm that could solve a multi-period reverse logistics network design problem regarding both spatial and temporal consolidation of returned products. Aras et al. [23] designed an MINLP model for establishing the locations of collection centers in a simple reverse supply chain network. The model considered in this study has the capability of determining the optimal buying price of used products with the objective of maximizing profit. Also, they presented a heuristic approach based on a meta-heuristic algorithm (i.e., tabu search) to solve the model. Pati et al. [24] considered a mixed-integer goal programming (MIGP) model for paper recycling logistics network design, in which the goals included: (1) minimizing the positive deviation from the planned budget allocated for reverse logistics activities, (2) minimizing the positive deviation from the maximum limit of non-relevant wastepaper, and (3) minimizing the negative deviation from the minimum desired waste collection

Du and Evans [25] proposed a bi-objective optimization model to evaluate reverse logistic networks that could handle the returns-requiring-repair service. The two objectives are minimization of the overall costs and minimization of the total tardiness of cycle time. Uster et al. [26] provided a CLSC network in which the forward network was existed and only collection and recovery centers should be located. The direct and reverse flows are optimized in this model concurrently. Also, an exact solution method is extended on the basis of Benders decomposition procedure. Min and Ko [27] designed a multi-period MILP model considering a closed-loop multi-commodity logistics network for third party logistics providers (3PLs) for determining the number and location of repair facilities, where returned products from retailers or end-customers were inspected, repaired, and refurbished for redistribution. Pishvaee and Torabi [15] investigated a bi-objective possibilistic optimization model in order to minimize the total cost of logistics network and to minimize the total tardiness of delivered products in a logistics network design. Franca et al. [28] developed a bi-objective model under uncertainty in order to maximize the profit and minimize the total number of defective raw material parts in a supply chain network design. Vahdani et al. [29] proposed a bi-objective interval fuzzy possibilistic chance-constraint mixed integer linear programming model for designing a reliable network of facilities in logistics network under uncertainty. Zeballos et al. [30] developed a two-stage scenario-based approach for integrating the uncertainty in the quality and quantity of returned products in the design and planning problem of logistics system. Vahdani et al. [31] presented a fuzzy multi-objective robust optimization model to configure a reliable logistics network.

III. Problem Definition and Proposed Model

Fuzzy mathematical programming is often divided into main groups as follows [32]:

- *Flexible programming*: Fuzzy mathematical programming with imprecision by expressing the flexibility in the target values of objective functions and the elasticity of constraints [33].
- *Possibilistic programming*: Fuzzy mathematical programming with uncertain coefficients in objective functions and constraints [34].

Our proposed fuzzy programming model is addressed in the second group, in which parameters in the objective function, technological coefficients and right hand sides are uncertain in nature. The concerned CLSC network in this paper is a multi-echelon network as depicted in Fig. 1. This paper considers a fuzzy mixed nonlinear programming (MNLP) model for scrap steel recycling network. This scrap steel recycling network discussed involving three providers, namely customer zones, metal manufacturing facility and iron and steel facility. Home scrap steel and prompt scrap steel will be sent directly in the recycling network by “metal manufacturing” and “iron and steel facility”, while customer zones supply obsolete scrap steel by using collection centers [35]. As it can be seen in Fig. 1, the considered network in this paper is a general structure, which can support both collection and recycling processes. Thus, it can be applied to various kinds of industries.

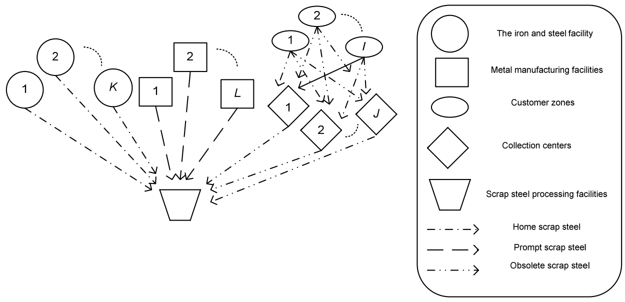

Fig. 1 Structure of scrap steel recycling network design

The main assumptions considered in problem formulation are as follows:

- All demands of scrap steel facility should be satisfied by three providers (i.e., customer zones, metal manufacturing facility and the iron and steel facility).
- Locations of scrap steel facility, customer zones, metal manufacturing facilities and iron and steel facilities are fixed and predefined.
- Locations of collection centers are changeable and undefined.
- Multiple types of scrap steels (i.e., home scrap steel, prompt scrap steel and obsolete scrap steel) are moved through the network.
- Duo to the unavailability or incompleteness of data in real-world situations, particularly in long-term horizon, most of the parameters embedded in such recycling network design problem are imprecise in nature. Hence, in order to model the lack of knowledge regarding the ill-known parameters, appropriate possibility distributions are utilized.
- Capacities of collection centers are limited.

IV. Model Formulation

The following notation is utilized in the formulation of the possibilistic mixed nonlinear facility location-allocation model in recycling collection networks.

Parameters

I: Number of customer zones $(i = 1,2, \dots, I)$
J: Number of potential collection centers $(j = 1,2, \dots, J)$
K: Number of the Iron and steel facilities$(k = 1,2, \dots, K)$
L: Number of Metal manufacturing facilities $l = (1,2, \dots, L)$
O: Scrap steel processing facility
$\tilde{a}$: Transportation cost of obsolete scrap steel per unit of weight and per unit of distance between each pair of customer zone and collection center
$\tilde{b}$: Transportation cost of obsolete scrap steel per unit of weight and per unit of distance between each collection center and scrap steel processing facility
$\tilde{f}$: Transportation cost of obsolete scrap steel per unit of weight and per unit of distance between each pair of the Iron and steel facility and scrap steel processing facility
$\tilde{g}$: Transportation cost of obsolete scrap steel per unit of weight and per unit of distance between each pair of Metal manufacturing facility and scrap steel processing facility
$\tilde{c}_j$: Opening cost of collection center j
$\tilde{d}_{ij}$: Distance between customer zone i and collection center j
$\tilde{e}_{jo}$: Distance between collection center j and scrap steel processing facility
$\tilde{l}_{ko}$: Distance between iron and steel facility k and scrap steel processing facility
$\tilde{u}_{lo}$: Distance between metal manufacturing facility l and scrap steel processing facility
$\tilde{\propto}_i$: Total quantities of obsolete scrap steel generated by customer zone i in a time period
$\tilde{\gamma}_k$: Total quantities of obsolete scrap steel generated by iron and steel facility k in a time period
$\tilde{\varepsilon}_l$: Total quantities of obsolete scrap steel generated by metal manufacturing facility l in a time period
$\tilde{\beta}$: Total demand of scrap steel processing facility for obsolete scrap steel
$\tilde{H}_j$: Maximum storage capacity of collection center j
M: Big enough number

Decision variables

p_{ij}: Total quantities of obsolete scrap steel transported from customer zone i to collection center j
q_{jo}: Total quantities of obsolete scrap steel transported from collection center j to scrap steel processing facility
s_{ko}: Total quantities of obsolete scrap steel transported from Iron and steel facility k to scrap steel processing facility
r_{lo}: Total quantities of obsolete scrap steel transported from Metal manufacturing facility l to scrap steel processing facility

$$x_j = \begin{cases} 1; \text{if collection center } j \text{ is open} \\ 0; \text{otherwise} \end{cases}$$

$$y_{ij} = \begin{cases} 1; \text{if customer zone } i \text{ and collection center } j \text{ have business} \\ 0; \text{otherwise} \end{cases}$$

$$z_{jo} = \begin{cases} 1; \text{if collection center } j \text{ and scrap steel processing facility have business} \\ 0; \text{otherwise} \end{cases}$$

$$t_{ko} = \begin{cases} 1; \text{if iron and steel facility } k \text{ and scrap steel processing facility have business} \\ 0; \text{otherwise} \end{cases}$$

$$w_{lo} = \begin{cases} 1; \text{if metal manufacturing facility } l \text{ and scrap steel processing facility have business} \\ 0; \text{otherwise} \end{cases}$$

Model:

$$\text{Min} Z = \sum_{i=1}^{I} \sum_{j=1}^{J} \tilde{a} \tilde{d}_{ij} p_{ij} y_{ij} + \sum_{j=1}^{J} \tilde{b} \tilde{e}_{jo} q_{jo} z_{jo} + \sum_{k=1}^{K} \tilde{f} \tilde{l}_{ko} s_{ko} t_{ko} + \sum_{l=1}^{L} \tilde{g} \tilde{u}_{lo} r_{lo} w_{lo} + \sum_{j=1}^{J} \tilde{c}_j x_j \quad (1)$$

s.t.

$$\sum_{j=1}^{J} p_{ij} y_{ij} = \tilde{\propto}_i \ \forall i \in (1,2, \dots, I) \quad (2)$$

$$s_{ko} t_{ko} = \tilde{\gamma}_k \forall k \in (1,2, \dots, K) \quad (3)$$

$$r_{lo} w_{lo} = \tilde{\varepsilon}_l \forall l \in (1,2, \dots, L) \quad (4)$$

$$\sum_{k=1}^{K} s_{ko} t_{ko} + \sum_{l=1}^{L} r_{lo} w_{lo} + \sum_{j=1}^{J} q_{jo} z_{jo} \geq \tilde{\beta} \quad (5)$$

$$\sum_{i=1}^{I} p_{ij} y_{ij} = q_{jo} z_{jo} \forall j \in (1,2,\dots,J) \quad (6)$$

$$\sum_{i=1}^{I} p_{ij} y_{ij} \leq \tilde{H}_j x_j \, \forall j \in (1,2,\dots,J) \quad (7)$$

$$\sum_{j=1}^{J} x_j \geq 1 \quad (8)$$

$$\sum_{j=1}^{J} y_{ij} = 1 \forall i \in (1,2,\dots,I) \quad (9)$$

$$\sum_{i=1}^{I} y_{ij} \geq 1 \forall j \in (1,2,\dots,J) \quad (10)$$

$$\sum_{k=1}^{K} t_{ko} \geq 1 \quad (11)$$

$$\sum_{l=1}^{L} w_{lo} \geq 1 \quad (12)$$

$$\sum_{j=1}^{J} z_{jo} \geq 1 \quad (13)$$

$$y_{ij} \leq x_j \forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J) \quad (14)$$

$$z_{jo} \leq x_j \forall j \in (1,2,\dots,J) \quad (15)$$

$$\frac{1}{M} y_{ij} \leq p_{ij} \leq \tilde{\alpha}_i y_{ij} \forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J) \quad (16)$$

$$\frac{1}{M} t_{ko} \leq s_{ko} \leq \tilde{\gamma}_k t_{ko} \forall k \in (1,2,\dots,K) \quad (17)$$

$$\frac{1}{M} w_{lo} \leq r_{lo} \leq \tilde{\varepsilon}_l w_{lo} \forall l \in (1,2,\dots,L) \quad (18)$$

$$\frac{1}{M} t_{ko} \leq s_{ko} \leq \tilde{\beta} t_{ko} \forall k \in (1,2,\dots,K) \quad (19)$$

$$\frac{1}{M} w_{lo} \leq r_{lo} \leq \tilde{\beta} w_{lo} \forall l \in (1,2,\dots,L) \quad (20)$$

$$\frac{1}{M} z_{jo} \leq q_{jo} \leq \tilde{\beta} z_{jo} \forall j \in (1,2,\dots,J) \quad (21)$$

$$p_{ij} \geq 0, q_{jo} \geq 0, s_{ko} \geq 0 \; and \; r_{lo} \geq 0 \forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J), \forall k \in (1,2,\dots,K) \quad (22)$$

$$x_j, y_{ij}, z_{jo}, t_{ko}, w_{lo} = \{0,1\} \forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J), \forall k \in (1,2,\dots,K), \forall l \in (1,2,\dots,L) \quad (23)$$

The objective function expresses the cost structure of the obsolete scrap steel recycling network, which consists of transportation costs and fixed opening costs. Constraint (2) ensures all obsolete scrap steel generated by each customer zone will be collected by collection centers. Constraint (3) ensures all obsolete scrap steel generated by each iron and steel facility will be collected by scrap steel processing facility. Constraint (4) ensures all obsolete scrap steel generated by each metal manufacturing facility will be collected by scrap steel processing facility. Constraint (5) guarantees that demand of scrap steel processing facility for obsolete scrap steels will be satisfied from Iron and steel facilities, Metal manufacturing facilities and collection centers. Constraint (6) ensures that the output of each collection center must equal to the input of it. Constraint (7) is capacity constraint; it ensures that the storage capacity of each collection center cannot be exceeded. Constraint (8) ensures that there must be at least one collection center existing in the network to collect scrap steel from customer zones. Constraint (9) ensures that each customer zone should be assigned to one and only one collection center. Constraint (10) ensures that collection center will have at least one customer zone to supply scrap steel for it. Constraint (11) guarantees that scrap steel processing facility will have at least one iron and steel facility to supply scrap steel for it. Constraint (12) ensures scrap steel processing facility will have at least one Metal manufacturing facility to supply scrap steel for it. Constraint (13) guarantees that scrap steel processing facility will have at least one collection center to supply scrap steel for it. Constraints (14-23) are logical constraints. They express that any two depots in the network have business should found on the basis that the two depots are open.

V. Solution Methodology

There exist some imprecise natures in the recycling network because some information is incomplete or unavailable, including demands, returns, capacities, costs and distances in the objective function and constraints. Consequently, the classical optimization method that needs well-defined and precise information cannot be competent for the recycling network problem. With respect to above mentioned objective function and constraints, this paper is dealing with a PMNLP.

In general, transportation costs, capacity of collection center and etc. are often estimated by experts or decision makers. Moreover, the demands are determined by forecasting which is usually inaccurate. These imprecise natures are regarded as fuzzy numbers which can be expressed by possibility distributions. Possibility distributions in the conventional fuzzy set can be categorized in to several groups. Among the different kinds of possibility distributions, the triangular distribution is utilized most often to represent imprecise data for solving possibilistic mathematical problems because of its simplicity as well as flexibility, though other patterns may be suited in specific applications [36]. Thus, to solve the presented model, an original model is converted into an equivalent auxiliary crisp model. The approach is on the basis of two novel methods, which proposed by [37]. Finally, GAMS software is utilized in this paper to find the best solution of the model.

The equivalent auxiliary crisp model: Assume that $\tilde{c}$ is a triangular fuzzy number, the Eq. (2) can be found as the membership function of $\tilde{c}$:

$$\mu_{\tilde{c}}(x) = \begin{cases} f_c(x) = \frac{x - c^p}{c^m - c^p} \text{if} c^p \leq x \leq c^m \\ 1 \qquad \text{if} \quad x = c^m \\ g_c(x) = \frac{c^o - x}{c^o - c^m} \text{if} c^m \leq x \leq c^o \\ 0 \qquad \text{if} \;\; x \leq c^p \text{or} \;\; x \geq c^o \end{cases} \quad (24)$$

The following fuzzy mathematical programming model is considered, in which all parameters are defined as triangular or trapezoidal fuzzy numbers:

$$min \;\; z = \tilde{c}^t x$$

s.t.

$$\tilde{a}_i x \geq \tilde{b}_i, i = 1,\dots,l$$

$$\tilde{a}_i x = \tilde{b}_i, \qquad i = l+1,\dots,m$$

$$x \geq 0 \tag{25}$$

The equivalent crisp ∝-parametric model of the model (1) can be written as follows [37,15]:

$$min \;\; z = EV(\tilde{c})x$$

s.t.

$$\left[(1-\alpha)E_2^{a_i} + \alpha E_1^{a_i}\right]x \geq \alpha E_2^{b_i} + (1-\alpha)E_1^{b_i}, \quad i = 1,2 \ldots, l$$

$$\left[\left(1-\frac{\alpha}{2}\right)E_2^{a_i} + \frac{\alpha}{2}E_1^{a_i}\right]x \geq \frac{\alpha}{2}E_2^{b_i} + \left(1-\frac{\alpha}{2}\right)E_1^{b_i}, \quad i = l+1, \ldots, m$$

$$\left[\frac{\alpha}{2}E_2^{a_i} + \left(1-\frac{\alpha}{2}\right)E_1^{a_i}\right]x \leq \left(1-\frac{\alpha}{2}\right)E_2^{b_i} + \frac{\alpha}{2}E_1^{b_i}, \quad i = l+1, \ldots, m$$

$$x \geq 0 \tag{26}$$

where $EV(\tilde{c}) = \frac{c^p+2c^m+c^o}{4}$, $E_1^a = \frac{1}{2}(a^p + a^m)$, $E_2^a = \frac{1}{2}(a^m + a^o)$, $E_1^b = \frac{1}{2}(b^p + b^m)andE_2^b = \frac{1}{2}(b^m + b^o)$. For details of the method, the reader can refer to [37].

According to above descriptions, the equivalent auxiliary crisp model of the MNLP model can be formulated as follows:

$$\text{Min } Z = \sum_{i=1}^{I}\sum_{j=1}^{J}\left(\frac{a^p+2a^m+a^o}{4}\right)\left(\frac{d_{ij}^p+2d_{ij}^m+d_{ij}^o}{4}\right)p_{ij}y_{ij} + \sum_{j=1}^{J}\left(\frac{b^p+2b^m+b^o}{4}\right)\left(\frac{e_{jo}^p+2e_{jo}^m+e_{jo}^o}{4}\right)q_{jo}z_{jo} + \sum_{k=1}^{K}\left(\frac{f^p+2f^m+f^o}{4}\right)\left(\frac{l_{ko}^p+2l_{ko}^m+l_{ko}^o}{4}\right)s_{ko}t_{ko} + \sum_{l=1}^{L}\left(\frac{g^p+2g^m+g^o}{4}\right)\left(\frac{u_{lo}^p+2u_{lo}^m+u_{lo}^o}{4}\right)r_{lo}w_{lo} + \sum_{j=1}^{J}\left(\frac{c_j^p+2c_j^m+c_j^o}{4}\right)x_j \tag{27}$$

s.t.

$$\sum_{j=1}^{J} p_{ij}y_{ij} \geq \frac{\alpha}{2}\left(\frac{\alpha_i^m+\alpha_i^o}{2}\right) + \left(1-\frac{\alpha}{2}\right)\left(\frac{\alpha_i^p+\alpha_i^m}{2}\right) \; ; \quad \forall i \in (1,2,\ldots,I) \tag{28}$$

$$\sum_{j=1}^{J} p_{ij}y_{ij} \leq \left(1-\frac{\alpha}{2}\right)\left(\frac{\alpha_i^m+\alpha_i^o}{2}\right) + \frac{\alpha}{2}\left(\frac{\alpha_i^p+\alpha_i^m}{2}\right) \; ; \quad \forall i \in (1,2,\ldots,I) \tag{29}$$

$$s_{ko}t_{ko} \geq \frac{\alpha}{2}\left(\frac{\gamma_k^m+\gamma_k^o}{2}\right) + \left(1-\frac{\alpha}{2}\right)\left(\frac{\gamma_k^p+\gamma_k^m}{2}\right) \; ; \quad \forall k \in (1,2,\ldots,k) \tag{30}$$

$$s_{ko}t_{ko} \leq \left(1-\frac{\alpha}{2}\right)\left(\frac{\gamma_k^m+\gamma_k^o}{2}\right) + \frac{\alpha}{2}\left(\frac{\gamma_k^p+\gamma_k^m}{2}\right) \; ; \quad \forall k \in (1,2,\ldots,K) \tag{31}$$

$$r_{lo}w_{lo} \geq \frac{\alpha}{2}\left(\frac{\varepsilon_l^m+\varepsilon_l^o}{2}\right) + \left(1-\frac{\alpha}{2}\right)\left(\frac{\varepsilon_l^p+\varepsilon_l^m}{2}\right) \; ; \quad \forall l \in (1,2,\ldots,L) \tag{32}$$

$$r_{lo}w_{lo} \leq \left(1-\frac{\alpha}{2}\right)\left(\frac{\varepsilon_l^m+\varepsilon_l^o}{2}\right) + \frac{\alpha}{2}\left(\frac{\varepsilon_l^p+\varepsilon_l^m}{2}\right) \; ; \quad \forall l \in (1,2,\ldots,L) \tag{33}$$

$$\sum_{k=1}^{K} s_{ko}t_{ko} + \sum_{l=1}^{L} r_{lo}w_{lo} + \sum_{j=1}^{J} q_{jo}z_{jo} \geq \alpha\left(\frac{\beta^m+\beta^o}{2}\right) + (1-\alpha)\left(\frac{\beta^p+\beta^m}{2}\right) \tag{34}$$

$$\sum_{i=1}^{I} p_{ij}y_{ij} = q_{jo}z_{jo} \; ; \quad \forall j \in (1,2,\ldots,J) \tag{35}$$

$$\sum_{i=1}^{I} p_{ij}y_{ij} \leq [(1-\alpha)\left(\frac{H_j^m+H_j^o}{2}\right) + \alpha\left(\frac{H_j^p+H_j^m}{2}\right)]x_j \; ; \quad \forall j \in (1,2,\ldots,J) \tag{36}$$

$$\sum_{j=1}^{J} x_j \geq 1 \tag{37}$$

$$\sum_{j=1}^{J} y_{ij} = 1 \; ; \quad \forall i \in (1,2,\ldots,I) \tag{38}$$

$$\sum_{i=1}^{I} y_{ij} \geq 1 \; ; \quad \forall j \in (1,2,\ldots,J) \tag{39}$$

$$\sum_{k=1}^{K} t_{ko} \geq 1 \tag{40}$$

$$\sum_{l=1}^{L} w_{lo} \geq 1 \tag{41}$$

$$\sum_{j=1}^{J} z_{jo} \geq 1 \tag{42}$$

$$y_{ij} \leq x_j \; ; \quad \forall i \in (1,2,\ldots,I), \forall j \in (1,2,\ldots,J) \tag{43}$$

$$z_{jo} \leq x_j \; ; \quad \forall j \in (1,2,\ldots,J) \tag{44}$$

$$\frac{1}{M}y_{ij} \leq p_{ij} \leq \left[(1-\alpha)\left(\frac{\alpha_i^m+\alpha_i^o}{2}\right) + \alpha\left(\frac{\alpha_i^p+\alpha_i^m}{2}\right)\right]y_{ij} \; ; \quad \forall i \in (1,2,\ldots,I), \forall j \in (1,2,\ldots,J) \tag{45}$$

$$\frac{1}{M}t_{ko} \le s_{ko} \le \left[(1-\alpha)\left(\frac{\gamma_k^m+\gamma_k^o}{2}\right)+\alpha\left(\frac{\gamma_k^p+\gamma_k^m}{2}\right)\right]t_{ko}\;;\;\;\forall k \in (1,2,\dots,K) \quad (46)$$

$$\frac{1}{M}w_{lo} \le r_{lo} \le \left[(1-\alpha)\left(\frac{\varepsilon_l^m+\varepsilon_l^o}{2}\right)+\alpha\left(\frac{\varepsilon_l^p+\varepsilon_l^m}{2}\right)\right]w_{lo}\;;\;\;\forall l \in (1,2,\dots,L) \quad (47)$$

$$\frac{1}{M}t_{ko} \le s_{ko} \le \left[(1-\alpha)\left(\frac{\beta^m+\beta^o}{2}\right)+\alpha\left(\frac{\beta^p+\beta^m}{2}\right)\right]t_{ko}\;;\;\;\forall k \in (1,2,\dots,K) \quad (48)$$

$$\frac{1}{M}w_{lo} \le r_{lo} \le [(1-\alpha)\left(\frac{\beta^m+\beta^o}{2}\right)+\alpha\left(\frac{\beta^p+\beta^m}{2}\right)]w_{lo}\forall l \in (1,2,\dots,L) \quad (49)$$

$$\frac{1}{M}z_{jo} \le q_{jo} \le \left[(1-\alpha)\left(\frac{\beta^m+\beta^o}{2}\right)+\alpha\left(\frac{\beta^p+\beta^m}{2}\right)\right]z_{jo}\;;\;\;\forall j \in (1,2,\dots,J) \quad (50)$$

$$p_{ij} \ge 0, q_{jo} \ge 0, s_{ko} \ge 0 \; and \; r_{lo} \ge 0\;;\;\;\forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J), \forall k \in (1,2,\dots,K) \quad (51)$$

$$x_j, y_{ij}, z_{jo}, t_{ko}, w_{lo} = \{0,1\}\;;\;\;\forall i \in (1,2,\dots,I), \forall j \in (1,2,\dots,J), \forall k \in (1,2,\dots,K), \forall l \in (1,2,\dots,L) \quad (52)$$

VI. Computational Experiments

To illustrate the validity and suitability of the proposed PMNLP model, several numerical experiments are considered and the related results are provided in this section. For this purpose, three test problems are designed that their sizes are given in Table I.

TABLE I
THE SIZE OF TEST PROBLEMS

Problem no.	No. of customer zones (I)	No. of potential collection centers (J)	No. of the iron and steel facilities(K)	No. of metal manufacturing facilities (L)
1	3	3	3	3
2	4	4	4	4
3	5	4	5	4

To generate the triangular fuzzy parameters according to [38], the three prominent points (i.e., the most likely, the most pessimistic and the most optimistic values) are obtained for each imprecise parameter. To do so, the most likely (C^m) value of each parameter is first provided randomly by utilizing the uniform distributions which is specified in Table II. The corresponding crisp value is equal to the most likely value for all parameters when the proposed crisp model is applied. Thus, without loss of generality two random numbers (r_1, r_2) are generated between 0.2 and 0.8 by applying uniform distribution, and the most pessimistic (C^p)and optimistic (C^o) values of a fuzzy number ($\tilde{C}$)are calculated by:

$$C^o = (1 + r_1)C^m$$
$$C^p = (1 - r_2)C^m$$

To compare the possibilistic and crisp models, all the mathematical models are coded in the optimization software (i.e., GAMS 8.0). The summary of test results on the basis of different $\propto$-levels are provided in Tables III to V.

The computational results illustrates that the proposed model can effectively support the development of a location-allocation model in recycling collection networks for the companies in supply chain environment. It considers the demands, returns, capacities, costs and distances under uncertainty in our objective and constraints by efficient mathematical programming approach because of its fuzzy and imprecise nature and the simplicity of its solution procedure besides its flexibility and applicability. These values and parameters are defined and expressed as the fuzzy numbers via possibilistic approach for the real-life situations. In addition, the proposed model can be provided various solutions by considering different values of α-level according to the specific applications in supply chain environment.

TABLE II
SOURCES OF RANDOM GENERATION

Parameters	Corresponding random distribution		
	Problem 1	Problem 2	Problem 3
a	~Uniform (18,30)	~Uniform (23,36)	~Uniform (30,85)
b	~Uniform (28,32)	~Uniform (45,75)	~Uniform (55,75)
f	~Uniform (32,44)	~Uniform (48,65)	~Uniform (50,75)
g	~Uniform (42,55)	~Uniform (53,78)	~Uniform (62,90)
c_j	~Uniform (60,125)	~Uniform (68,160)	~Uniform (55,155)
d_{ij}	~Uniform (4,20)	~Uniform (4,30)	~Uniform (5,35)
e_{jo}	~Uniform (4,15)	~Uniform (6,21)	~Uniform (6,25)
l_{ko}	~Uniform (5,18)	~Uniform (7,20)	~Uniform (9,24)
u_{lo}	~Uniform (6,20)	~Uniform (8,24)	~Uniform (10,22)
$\propto_i$	~Uniform (45,85)	~Uniform (55,100)	~Uniform (50,125)
γ_k	~Uniform (70,125)	~Uniform (65,155)	~Uniform (40,185)
ε_l	~Uniform (100,210)	~Uniform (110,275)	~Uniform (140,295)
β	~Uniform (450,600)	~Uniform (650,810)	~Uniform (750,920)
H_j	~Uniform (185,320)	~Uniform (290,385)	~Uniform (350,625)

TABLE III
SUMMARY OF TEST RESULTS BASED ON DIFFERENT α-LEVELS FOR TEST PROBLEM 1

Variables	α-level				
	0	0.1	0.2	0.3	0.4 -1
Z^*	619460	639840	631680	638540	No feasible solution was found
p_{ij}	$\begin{pmatrix} 0 & 67.5 & 0 \\ 49.5 & 0 & 0 \\ 0 & 0 & 54 \end{pmatrix}$	$\begin{pmatrix} 0 & 80.325 & 0 \\ 50.05 & 0 & 0 \\ 0 & 0 & 54.6 \end{pmatrix}$	$\begin{pmatrix} 0 & 69 & 0 \\ 0 & 0 & 50.6 \\ 55.2 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 69.75 & 0 \\ 0 & 0 & 51.15 \\ 55.8 & 0 & 0 \end{pmatrix}$	
q_{jo}	$(49.5 \quad 67.5 \quad 54)$	$(50.05 \quad 80.325 \quad 54.6)$	$(55.2 \quad 69 \quad 50.6)$	$(55.8 \quad 69.75 \quad 51.15)$	
s_{ko}	$(72 \quad 85.5 \quad 99)$	$(72.8 \quad 86.45 \quad 100.1)$	$(73.6 \quad 87.4 \quad 101.2)$	$(74..4 \quad 88.35 \quad 102.3)$	
r_{lo}	$(112.5 \quad 157.5 \quad 180)$	$(113.75 \quad 159.25 \quad 182)$	$(115 \quad 161 \quad 184)$	$(116.25 \quad 162.75 \quad 186)$	
x_j	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	
y_{ij}	$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}$	
z_{jo}	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	
t_{ko}	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	
w_{lo}	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1)$	

TABLE IV
SUMMARY OF TEST RESULTS BASED ON DIFFERENT α-LEVELS FOR TEST PROBLEM 2

Variables	α-level					
	0	0.1	0.2	0.3	0.4	0.5-1
Z^*	171550	170100	164780	176760	172580	No feasible solution was found
p_{ij}	$\begin{pmatrix} 64 & 0 & 0 & 0 \\ 0 & 0 & 0 & 48 \\ 0 & 0 & 56 & 0 \\ 0 & 72 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 65.6 & 0 \\ 49.2 & 0 & 0 & 0 \\ 0 & 57.4 & 0 & 0 \\ 0 & 0 & 0 & 73.8 \end{pmatrix}$	$\begin{pmatrix} 0 & 67.2 & 0 & 0 \\ 50.4 & 0 & 0 & 0 \\ 0 & 0 & 58.8 & 0 \\ 0 & 0 & 0 & 75.6 \end{pmatrix}$	$\begin{pmatrix} 0 & 68.8 & 0 & 0 \\ 0 & 0 & 0 & 51.6 \\ 0 & 0 & 60.2 & 0 \\ 77.4 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 70.4 & 0 & 0 \\ 52.8 & 0 & 0 & 0 \\ 0 & 0 & 61.6 & 0 \\ 0 & 0 & 0 & 79.2 \end{pmatrix}$	
q_{jo}	$(64 \quad 72 \quad 56 \quad 48)$	$(49.2 \quad 57.4 \quad 65.6 \quad 73.8)$	$(50.4 \quad 67.2 \quad 58.8 \quad 75.6)$	$(77.4 \quad 68.8 \quad 60.2 \quad 51.6)$	$(52.8 \quad 70.4 \quad 61.6 \quad 79.2)$	
s_{ko}	$(60 \quad 68 \quad 96 \quad 112)$	$(61.5 \quad 69.7 \quad 98.4 \quad 114.8)$	$(63 \quad 71.4 \quad 100.8 \quad 117.6)$	$(64.5 \quad 73.1 \quad 103.2 \quad 120.4)$	$(66 \quad 74.8 \quad 105.6 \quad 123.3)$	
r_{lo}	$(92.5 \quad 124 \quad 168 \quad 200)$	$(94.5 \quad 127.1 \quad 172.2 \quad 205)$	$(96.5 \quad 130.2 \quad 176.4 \quad 210)$	$(98.5 \quad 133.3 \quad 180.6 \quad 215)$	$(100.5 \quad 136.4 \quad 184.8 \quad 220)$	
x_j	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	
y_{ij}	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$	
z_{jo}	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	
t_{ko}	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	
w_{lo}	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	

TABLE V
SUMMARY OF TEST RESULTS BASED ON DIFFERENT α-LEVELS FOR TEST PROBLEM 3

Variables	α -level					
	0	0.1	0.2	0.3	0.4	0.5-1
Z^*	1536300	1569500	1751600	169850	186900	No feasible solution was found
p_{ij}	$\begin{pmatrix} 0 & 45.5 & 0 & 0 \\ 0 & 0 & 0 & 54.6 \\ 56.7 & 0 & 0 & 0 \\ 0 & 0 & 38.5 & 0 \\ 80.5 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 47.45 & 0 & 0 \\ 0 & 0 & 56.94 & 0 \\ 59.13 & 0 & 0 & 0 \\ 0 & 0 & 0 & 40.15 \\ 83.95 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 49.4 \\ 59.28 & 0 & 0 & 0 \\ 0 & 61.56 & 0 & 0 \\ 0 & 0 & 41.8 & 0 \\ 0 & 87.4 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 51.35 & 0 & 0 \\ 0 & 0 & 61.62 & 0 \\ 63.99 & 0 & 0 & 0 \\ 0 & 0 & 0 & 43.45 \\ 90.85 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 53.3 & 0 & 0 & 0 \\ 0 & 63.96 & 0 & 0 \\ 0 & 0 & 0 & 66.42 \\ 0 & 0 & 45.1 & 0 \\ 94.3 & 0 & 0 & 0 \end{pmatrix}$	
q_{jo}	$(137.2 \quad 45.5 \quad 38.5 \quad 54.6)$	$(143.08 \quad 47.45 \quad 56.94 \quad 40.15)$	$(59.28 \quad 148.96 \quad 41.8 \quad 49.4)$	$(154.84 \quad 51.35 \quad 61.62 \quad 43.45)$	$(147.6 \quad 63.96 \quad 45.1 \quad 66.42)$	
s_{ko}	$(31.5 \quad 66.5 \quad 112 \quad 84 \quad 70)$	$(32.85 \quad 69.35 \quad 116.8 \quad 87.6 \quad 73)$	$(34.2 \quad 72.2 \quad 121.6 \quad 91.2 \quad 76)$	$(35.55 \quad 75.05 \quad 126.4 \quad 94.8 \quad 79)$	$(36.9 \quad 77.9 \quad 131.2 \quad 98.4 \quad 82)$	
r_{lo}	$(105 \quad 87.5 \quad 154 \quad 189)$	$(109.5 \quad 91.25 \quad 160.6 \quad 197.1)$	$(114 \quad 95 \quad 167.2 \quad 205.2)$	$(118.5 \quad 98.75 \quad 173.8 \quad 213.3)$	$(123 \quad 102.5 \quad 180.4 \quad 221.4)$	
x_j	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	$(1 \quad 1 \quad 1 \quad 1)$	
y_{ij}	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$	

z_{jo}	(1 1 1 1)	(1 1 1 1)	(1 1 1 1)	(1 1 1 1)	(1 1 1 1)
t_{ko}	(1 1 1 1 1)	(1 1 1 1 1)	(1 1 1 1 1)	(1 1 1 1 1)	(1 1 1 1 1)
w_{lo}	1536300	1569500	1751600	169850	186900

VII. CONCLUSIONS

This paper aimed at designing and developing a new mathematical programming model under uncertainty that could cope with both environmental and economic concerns in the recycling network design. We addressed a general network structure that supports the cooperation collection and recycling processes, and thus it could be applied to the various kinds of industrial fields in a supply chain environment. Unlike the previous studies, in which all suppliers were similar, considering various suppliers was lead to different ways to gather scraps. In addition, the proposed model had the ability to determine used capacity and location of each collocation center. All types of scraps separately had specified, which was needed for recycling process; consequently, the required information transferred to managers in order to decide from which supplier and its quantity scraps should be gathered. Also, the constraint of capacity of collection centers was considered in the model. Moreover, a possibilistic mathematical programming approach was applied that was able to cope with both kinds of uncertainty affecting recycling network by considering the unavailability or incompleteness as well as imprecise nature of data concurrently.

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