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A novel multiple criteria decision-making approach based on fuzzy DEMATEL, fuzzy ANP and fuzzy AHP for mapping collection and distribution centers in reverse logistics

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A B S T R A C T

The strategic location of reverse logistics facilities enables organizations to obtain optimal performance to collect end-of-line (EOL) products and distribute remanufactured products effectively and efficiently. The planning of facility location entails consideration of multiple essential criteria rather than optimizing a single criterion. This paper develops a methodological framework based on an integrated multiple criteria decision-making (MCDM) approach that captures the complexity of location planning for collection and distribution centers under fuzzy conditions utilizing decision making trial and evaluation laboratory (DEMATEL), analytic network process (ANP), and analytic hierarchy process (AHP). This novel approach aids decision-makers to simultaneously select a separate location for collection and distribution through a holistic assessment of a location's viability for both purposes. It advances the reverse logistics literature by considering multiple criteria and their interrelationships in the location selection process, along with uncertainty and vagueness in decision making. Additionally, the proposed approach allows flexibility for decision-makers as they retain the control in picking a site based on its priority on being a collection or distribution center. Results show that government policies and regulations play a vital role in the facility location decision as they interact mostly with other criteria. Moreover, results also suggest that quantity and quality uncertainties for remanufacturing are significant factors that must be taken into consideration in the collection function, while economic and market-oriented issues are major concerns for a distribution function. This finding was observed through the application of the proposed methodological framework in a case study of the furniture industry in the Philippines. The practical implications of this study focus on being an aid in organizing and improving the operations of the reverse logistics sector of the Philippines. Finally, the proposed approach can be used to address general facility location problems in other industrial applications where tradeoffs among stakeholders or entities are well pronounced and decision-makers find it imperative that such tradeoffs must be carefully considered.

A R T I C L E I N F O

Keywords:
Reverse logistics;
Collection;
Distribution;
Fuzzy environment;
Remanufacturing;
Multiple criteria decision-making (MCDM);
Decision-making and trial evaluation laboratory (DEMATEL);
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1. Introduction

Sustainable practices have become a continual pursuit of manufacturers to address prevalent issues on environmental awareness, resource depletion, consumer awareness of sustainability impacts, legislation, corporate imaging, economic benefits, and government incentives (Mutha and Pokharel, 2009 [1]; Sheu, 2011 [2]; Rashid *et al*., 2013 [3]; Govindan *et al*., 2015 [4, 5]). One chief sustainable practice is the end of life (EOL) strategies which intend to restore goods to its original working condition (USITC, 2012 [6]). Among the extant EOL strategies, the concept of remanufacturing is of growing interest to scholars from domain disciplines (Rashid *et al.*, 2013 [3]). As an industrial process, the goal of remanufacturing is to recover the residual value of used products by reconditioning and reusing components that are still functional and acceptable (Wei *et al.*, 2015 [7]). It is a product recovery technique (PRT) that promotes sustainability as it helps firms achieve closed-loop supply chains. Remanufacturing addresses the environmental, social, and economic dimensions of sustainability by minimizing waste and emission generation, creating jobs, and trimming down production costs by 50 % (Rathore *et al.*, 2011 [8]; Chen and Chang, 2012 [9]; Xiaoyan, 2012 [10]). Several original equipment manufacturers (OEMs) have taken an interest in remanufacturing such as Caterpillar, HP, Xerox, and Kodak to increase profit and improve their social and environmental performances as well. This increased attention can be attributed to remanufacturing's benefits and essential functions in the ever-changing society.

In remanufacturing, one of the crucial aspects is reverse logistics. Reverse logistics is the process of planning, implementing, and controlling efficient, effective inbound flow, inspection, and disposition of returned products and related information for recovering value (Srivastava, 2006 [11]). The collected EOL products are subjected to a detailed inspection, which either ends up remanufactured or disposed. Products that go through the remanufacturing process are distributed in secondary markets; afterward, the cycle of collection and remanufacturing continues. The practice of remanufacturing, however, is rather hindered despite its advantages in terms of sustainability since the receptivity of consumers varies from one region to another, as suggested in the current literature. That is, consumers in well-developed Western countries are more open to remanufactured products compared to those in most developing countries (Nnorom and Osibanjo, 2008 [12]; Zou *et al.*, 2016 [13]).

As critical tasks of reverse logistics, several studies in the literature tackled how these functions can be optimized according to collection rate and sales (Malik *et al.*, 2015 [14]; Pop *et al.*, 2015 [15]), profit and return rate (Hong and Yeh, 2012 [16]), and economies of scale (Atasu *et al.*, 2013 [17]), to name a few. Consequently, dominant mathematical models such as continuous modeling frameworks (Wojanowski *et al.*, 2007 [18]), a mixed-integer nonlinear model (Min and Ko, 2008 [19]), and graph theory and matrix approach (Malik *et al.*, 2015 [14]) are adapted to design such functions.

While prior studies in literature present mathematical models with single objective analyses to optimize collection and distribution decision problems, these methodologies fail to incorporate various aspects and holistic considerations that are necessary for the decision problem involving the location of centers (Malik *et al.*, 2015 [14]). Real-world problems are rarely single objective but are multi-objective; therefore, multi-objective approaches should be given more attention and focus (Govindan *et al.*, 2015 [4, 5]). Additionally, results are expected to be more informed, and better decisions are drawn when an appropriate structure of the problem and evaluation of the multi-criteria nature of the problem is explicitly established. Hence, multi-criteria decision-making (MCDM) approaches are introduced in the current literature. In the field of remanufacturing, pertinent issues are successfully resolved using MCDM approaches such as: identifying a strategic model for distribution channel management using fuzzy analytical hierarchy process (FAHP) and hierarchical fuzzy technique for order of preference and similarity to ideal solutions (HFTOPSIS) (Paksoy *et al.*, 2012 [20]), analyzing the interrelationships between risks faced by third-party logistics service providers (3PLs) using decision-making and trial evaluation laboratory (DEMATEL) (Govindan and Chaudhuri, 2016 [21]), and selecting important criteria in considering factors of reverse logistics implementation using FAHP (Chiou *et al.*, 2012 [22]), to name a few.

Given that the selection of a logistics center can be modeled as a decision problem that involves critical elements and that an integrated approach of simultaneously selecting distribution and collection centers lacks in the current literature, this paper aims to simultaneously identify a location for collection and distribution centers using MCDM approach. With an MCDM model, complexity and uncertainty of the selection process may mimic real-life decision-making with different and contradictory criteria and alternatives. Further, it is imperative to recognize that while the selection of collection and distribution centers are addressed in separate conditions, the need to simultaneously resolve both logistic centers remains relevant in the context of economic and operational sustainability.

Thus, this paper attempts to map both collection and distribution centers simultaneously using an integrated MCDM approach consists of fuzzy DEMATEL, fuzzy analytic network process (FANP), and FAHP. The proposed approach is intended to address the complexity and uncertainty of the selection process in location decision problems. That is, the use of DEMATEL methodology to analyze the causal and effect relations among criteria, ANP to provide criteria priorities, and AHP to rank potential collection and distribution locations. Additionally, fuzzy set theory (FST) is employed to deal with the vagueness, ambiguity, and uncertainty of human judgments (Zadeh, 1965 [23]), prevalent in carrying out the three identified MCDM methodologies (i.e., DEMATEL, ANP, and AHP). The three MCDM methodologies, along with FST, are used as they are suitable to address the following conditions of locating collection and distribution centers for reverse logistics. The problem requires a selection of the best location among possible location sites for collection and distribution functions, subject to multiple and often conflicting criteria. The problem seems to be in a simple hierarchical structure (i.e., goal, criteria, and alternatives); however, real-life conditions suggest that the set of criteria contains interrelationships which must be captured to address the problem holistically. These interrelationships, thus, are identified by fuzzy DEMATEL, and the fuzzy ANP approach is used to address them and generate criteria weights. Finally, to identify the best alternative for each function, the fuzzy AHP methodology is used to generate the relative weights of the possible alternative locations. As opposed to other MCDM approaches for this purpose (e.g., TOPSIS, PROMETHEE, ELECTRE, VIKOR, to name a few) where rankings are directly generated, the fuzzy AHP method which produces priority weights of the alternatives provides a meaningful scheme for allowing tradeoffs of a location between collection and distribution functions. Such a tradeoff is instrumental for operational viability.

The gap that is advanced in this paper is twofold: (a) the use of evaluation criteria to identify collection and distribution centers in the literature is found to be only a few and limited and is focused on single-objective-based mathematical models; this paper seeks to consider critical elements of logistics infrastructure and its relations among one another to determine collection and distribution centers using an integrated MCDM model, and (b) the concept of remanufactured products by consumers in developing countries, such as the Philippines, is relatively unwelcome; this paper pursues to address issues in remanufacturing particularly with that of limited and ill-informed policies, cultural preferences, and assessment of actual benefits.

2. Literature review

The collection of used products is one of the most important tasks of reverse logistics and also the first task that affects all the other activities in remanufacturing. EOL product collection is accompanied by uncertainty, especially in terms of quantity that must be taken into consideration in establishing collection centers (Serrano *et al*., 2013 [24]). On the other hand, distribution of goods involves the transportation of both finished and raw materials; its objective is to make sure that the products delivered are in good condition and will arrive at the right destination. In distribution systems, distribution centers are sometimes required to connect manufacturers and customers for supporting and improving the product flow (Langevin *et al*., 1996 [25]; Yang, 2013 [26]). Due to uncertainties related to returns (e.g., timing, quality, quantity, disassembly and reassembly, homogeneity of product range), the collection function is challenged (Mukherjee and Mondal, 2009 [27]). In the same manner, the distribution function can potentially be affected when end users do not support remanufactured goods due to negative user perception and unawareness of its quality and price, to name a few (Choudhary and Singh, 2011 [28]; Serrano *et al*., 2013 [24]; Sharma *et al*., 2016 [29]).

To address such issues on the collection and distribution process related to remanufacturing, collection and distribution centers are utilized (Malik *et al*., 2015 [14]; Pop *et al*., 2015 [15]). These two logistics functions may be performed in a center altogether or separately. In an ideal situation, a collection of EOL products and distribution of remanufactured products must be optimized; that is, the collection rate and sales must be maximized. It is, however, significant to note that the type of collection model likewise affects this situation. For instance, a recent study conducted by Hong and Yeh (2012) [16] compared non-retailer collection model and retailer collection model and found that the latter is superior to the other model under certain aspects such as profit and return rate. Also, when there is a consideration on operating channels involved (i.e., retailer-managed collection, manufacturer-managed collection, and third-party-managed collection), a retailer-managed collection is believed to be optimal when there are economies of scale; otherwise, the manufacturer-managed collection becomes an optimal option (Atasu *et al*., 2013 [17]).

Furthermore, collection points in a reverse logistics system location have also been a focus of relevant studies. Wojanowski *et al*. (2007) [18] proposed combining a collection of used products with retail activities. A continuous modeling framework is presented for designing a drop-off facility network. They determined that a primary factor for an organization to be involved in the collection of used products is the net value that can be reacquired from a returned product. On the other hand, a mixed-integer nonlinear model is presented by Min and Ko (2008) [19] in determining the optimal number and locations of collection points as well as its centralized return centers. It is proposed to enhance customer convenience by reducing travel time and effort to return used products, thereby, improving the efficiency of product returns. Therefore, an adequate number of collection facilities need to be situated proximate to that of the customers. Similarly, Malik *et al*. (2015) [14] presented other techniques such as graph theory and matrix approach to determine viable locations for collection centers based on ten key factors, comparative significance, and its availabilities. Other authors have also developed mathematical models for the design of reverse logistics network design, considering the location and allocation of facilities (Mutha and Pokharel, 2009 [1]; Yi *et al*., 2016 [30]).

As for the distribution centers, determining practical locations are considered an essential problem as that of collection centers which have also served as the focal point of studies in remanufacturing for the past few decades (Owen and Daskin, 1998 [31]). Two problems of the most highly studied problems for facility location are the *p*-median problem and the maximal covering location problem. The *p*-median problem concerns on locating *p* facilities to minimize the total demand-weighted distance between each customer to the nearest facility around. For the maximal covering location problem, its objective is to locate a fixed number of distribution facilities to make sure that the number of covered demands is maximized. The two models share a common objective; that is, to be able to get the attention of customers to maximize revenue (Zhang *et al*., 2016 [32]). Furthermore, the total relevant cost for the whole distribution process can be minimized when the proper selection of facility location is made (Kuo *et al*., 2011 [33]).

Reverse logistics studies for developing countries are unsurprisingly scarce as it is still in a state of infancy (Sarkis *et al*., 2010 [34]; Zhang *et al*., 2011 [35]). In fact, there are still many aspects that need to be considered and explored in the strategic planning of collection centers location. At a broader scope, remanufacturing is popular in developed economies considering its advantages (Sharma *et al*., 2016 [29]). Developed economies have a more mature foundation on remanufacturing as it is practiced as a means to deal with EOL issues. In developed economies, a well-established understanding and perception of environmental issues exist (Nunes *et al*., 2009 [36]). Additionally, governments in developed countries implement policies that promote the growth of remanufacturing (Govindan *et al*., 2016 [37, 38]). Consequently, more research regarding sustainability approaches like reverse logistics has been focused on developed countries (Sarkis *et al*., 2010 [34]; Zhang *et al*., 2011 [35]). Consumers in well-developed Western countries are more receptive of remanufactured products, while the opposite situation is observed in most developing countries (Nnorom and Osibanjo, 2008 [12]; Zou *et al*., 2016 [13]).

Poor knowledge, limited consumer acceptance, scarcity of remanufacturing tools and techniques, poor remanufacturability of many products, and quality concerns hinder and significantly limit the potential for developing countries from practicing remanufacturing. OEM practices such as patents and intellectual property rights are also hindrances to remanufacturing as they limit possible remanufacturing operations only to the OEM (Ijomah *et al*., 2007 [39]). Sustainable development in developing countries is relatively lower, as is evident in some countries like Thailand, Vietnam, India, Malaysia, and the Philippines (Xu *et al*., 2013 [40]). Complete legislation systems in the context of remanufacturing in these countries are not yet fully developed since there is no recognition of the importance of remanufacturing in most firms in developing countries. Hence, empirical data, specifically in the Philippines, is deficient (Saavedra *et al*., 2013 [41]).

3. Methodology

The following subsections present the MCDM methodologies to be integrated into this work for determining a location for collection and distribution centers.

3. 1 Fuzzy set theory

The fuzzy set theory was developed to deal with uncertainty and impreciseness of human decision (Zadeh, 1965 [23]). In a set of collection of objects $x \in X$ where X is the universe of discourse and $A \subseteq X$, the classical set theory defines the membership of $x \in A$ or $x \notin A$ with truth values defined in a membership function in Eq. 1. A is a crisp set if $\mu_A(x): X \to \{0,1\}$.

$$\mu_A(x) = \begin{cases} 1 & x \in A \\ 0 & x \notin A \end{cases} \tag{1}$$

A is a standard fuzzy set if $\exists$ a membership function $\mu_A(x)$ such that $\mu_A(x): X \to [0,1]$. The set of 2-tuple $A = \{x, \mu_A(x): x \in X, \mu_A(x) \in [0,1]\}$ is a fuzzy set where $x \in A$ and $\mu_A(x)$ is the membership function of $x \in A$.

Fuzzy numbers are fuzzy subsets of $\mathbb{R}$. Fuzzy number foundations and their arithmetic operations were first introduced by Zadeh (1965) [23]. Commonly used in fuzzy set theory applications, a fuzzy number is defined as a convex normalized fuzzy set in $\mathbb{R}$ with membership function which is piecewise continuous.

In MCDM applications, a left-right (L-R) fuzzy number is commonly adopted. A fuzzy number A is of L-R type if $\exists$ membership functions for left and for right with

$$l, r \in \mathbb{R}, \text{ and} \tag{2}$$

$$l, r \geq 0 \text{ with} \tag{3}$$

$$\mu_A(x) = \begin{cases} L((M-x)/l) & x \leq M \\ R((x-M)/r) & x \geq M \end{cases} \tag{4}$$

where $M \in \mathbb{R}$ is the modal value of A and $l, r \in \mathfrak{R}$ are the left and right spreads of A.

In this work, an L-R type triangular fuzzy number (TFN) was adopted because of its popularity and ease of implementation (Promentilla *et al.*, 2008 [42]).

A triangular fuzzy number expresses the strength of each pair of elements in the same group and can be denoted as

$$A = (l, m, u) \tag{5}$$

where $l \leq m \leq u$; l, m, and u represents smallest possible value, modal value, and largest possible value, respectively.

Fig. 1 shows these parameters in a triangular fuzzy scale graph. Table 1 demonstrates a pairwise comparison with fuzzy numbers.

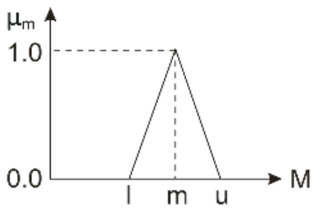

Fig 1 Fuzzy triangular scale graph

Table 1 Sample pairwise comparison matrix

	Criteria 1	Criteria 2	Criteria 3
Criteria 1	(1,1,1)	(5/2,3,7/2)	(9/2,5,11/2)
Criteria 2	(2/7,1/3,2/5)	(1,1,1)	(13/2,7,15/2)
Criteria 3	(2/11,1/5,2/9)	(2/15,1/7,2/13)	(1,1,1)

In the graph shown in Fig. 1, the membership function $\mu_A(x)$ can be defined in Eq. 6.

$$\mu_A(x) = \begin{cases} 0 & x < l \\ (x-l)/(m-l) & l \leq x \leq m \\ (u-l)/(u-m) & m \leq x \leq u \\ 0 & x > u \end{cases} \tag{6}$$

where $l, m, r \in \mathbb{R}$, $\mu_A(x) \to [0,1]$ and X is the universe of discourse.

The arithmetic operations of two TFNs denoted by (a_1, a_2, a_3) and (b_1, b_2, b_3) are shown in Eqs. 7 to 10.

$$A + B = (a_1 + b_1, a_2 + b_2, a_3 + b_3) \tag{7}$$

$$A - B = (a_1 - b_1, a_2 - b_2, a_3 - b_3) \quad (8)$$

$$A \otimes B = (a_1 b_1, a_2 b_2, a_3 b_3) \quad (9)$$

$$A \div B = (a_1/b_3, a_2/b_2, a_3/b_1) \quad (10)$$

Linguistic scales may be used to help decision-makers compare criteria or elements. Scales used by Tseng (2011) [43] and Tseng *et al.* (2008) [44], presented in Tables 2 and 3, were adopted in this study. The linguistic scales are assigned to numbers in a triangular fuzzy scale (i.e., for both Table 2 and Table 3), as well as its reciprocals in the pairwise comparison matrix (i.e., as shown only in Table 3). These tables have an ascending order for the triangular fuzzy numbers along with the degree of importance for each scale. This scale helps address vagueness in decision making by allowing qualitative answers to be quantified. Further, the concept of the fuzzy set theory is integrated into the conventional DEMATEL, ANP, and AHP methodologies to obtain a more comprehensive judgment of decision-makers.

3.2 Fuzzy DEMATEL methodology

The DEMATEL methodology roots from the need to enable analyses and solve problems utilizing pragmatic visualization method specifically directed graphs (Gabus and Fontela, 1972, 1973 [45, 46]; Herrera *et al.*, 2000; Wang and Chuu, 2004 [47]; Tsai and Chou, 2009 [48]). These directed graphs, also known as digraphs, are believed to be more useful compared to directionless graphs because digraphs illustrate directed relations (i.e., causal and effect relations) of sub-systems. When directed relations are established well, it can provide a better understanding of system elements in a complex setting. While conventional DEMATEL methodology is proven effective in evaluating factor relations, human judgment on decision variables remains subjective; thus, crisp values become inadequate (Büyüközkan and Çifçi, 2012 [49]). Hence, the fuzzy set theory is applied to the conventional DEMATEL methodology. Fuzzy DEMATEL has been widely applied in various areas such as air transportation system (Bongo and Ocampo, 2017 [50]), supplier evaluation problems (Büyüközkan and Çifçi, 2012 [49]), green supply chain management practices (Lin, 2013 [51]), truck selection problem (Baykasoğlu *et al.*, 2013 [52]), firm environmental knowledge management (Tseng, 2011) [43], and monitoring of paint utilization (Kumar *et al.*, 2017 [53]), to name a few.

3.3 Fuzzy analytic hierarchy process (AHP) and fuzzy analytic network process (ANP)

Saaty (1977) [54] developed the analytic hierarchy process (AHP) to simplify complex decision problems by structuring the decision attributes and alternatives in a hierarchical manner using a series of pairwise comparisons. AHP models are best used in a decision problem where there are unidirectional hierarchical relations among levels. When the relationships between levels do not merely signify higher or lower, dominant or subordinate, direct or indirect interactions, the analytic network process (ANP) may be used instead. ANP is also introduced by Saaty (1996) [55] as an extension of AHP where feedback mechanisms in a network type of structure are utilized to illustrate better the dependence among alternatives or attributes by obtaining composite weights through a supermatrix (Shyur, 2006) [56].

Both the traditional AHP and ANP methodology are unable to handle imprecise judgments elicited by decision-makers, thus, the enhancement of such methodologies in the being of fuzzy AHP and fuzzy ANP (Tavana *et al.*, 2013) [57]. Instead of a crisp value used in the evaluation process, fuzzy AHP and fuzzy ANP adopt a range of linguistic expressions with a corresponding triangular fuzzy number to improve how decision-makers make qualitative evaluations. Recent applications of fuzzy AHP are, among others, selection of an R&D strategic alliance partner (Chen *et al.*, 2010 [58]), selection of best pricing strategy for new product development (Liao, 2011) [59], resolution of uncertainty and imprecision in the evaluation of airlines' competitiveness (Wu *et al.*, 2013 [60]), selection of a cruise port of call location (Wang *et al.*, 2014 [61]), selection of passenger aircraft type (Dožić *et al.*, 2017 [62]), and various applications in automotive industry (Banduka *et al.*, 2018 [63]). As for fuzzy ANP, it has been widely applied in areas such as evaluation and selection of suppliers (Razmi *et al.*, 2009 [64]), selection of conceptual design in a product development (Ayağ and Özdemir, 2009 [65]), prioritization of strategy (Babaesmailli *et al.*, 2012 [66]), prioritization of advanced-technology projects at the National Aeronautics and Space Administration (NASA) (Tavana *et al.*, 2013 [57]), and evaluation and selection of outsourcing providers for a telecommunication company (Uygun *et al.*, 2014 [67]).

3.4 An integrated MCDM methodology

A detailed procedure on the integrated MCDM approach to determine collection and distribution centers is shown as follows:

Step 1: Apply fuzzy DEMATEL. The interrelationships between criteria are established by decision-makers using linguistic rating scales adopted from Tseng (2011) [43] (see Table 2). This scale helps address vagueness in the decision-making process by allowing qualitative answers to be quantified. Fuzzy DEMATEL is utilized to identify causal and effect criteria. The fuzzy DEMATEL method includes the following steps (Lin and Wu, 2004 [68]). These steps are further applied to both models (e.g., collection and distribution centers) considered in this paper.

Table 2 Linguistic scale for DEMATEL as adopted from Tseng (2011) [43]

Linguistic variable	Code	(TFNs)
No influence	NI	(0.0, 0.1, 0.3)
Very low influence	VLI	(0.1, 0.3, 0.5)
Low influence	LI	(0.3, 0.5, 0.7)
High influence	HI	(0.5, 0.7, 0.9)
Very high influence	VHI	(0.7, 0.9, 1.0)

1.1 *Compute for the fuzzy initial direct-relation matrix.* The fuzzy initial direct-relation matrix $\tilde{Z}$ involves fuzzy numbers represented as $\tilde{Z}_{ijK} = (l_{ijK}, m_{ijK}, u_{ijK})$ as shown in Eq. 11 where k represents the k^{th} decision-maker.

$$(\tilde{Z}_{ijk})_{nxn} = \begin{bmatrix} 0 & \tilde{Z}_{12} & \cdots & \tilde{Z}_{1n} \\ \tilde{Z}_{21} & 0 & \cdots & \tilde{Z}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{Z}_{n1} & \tilde{Z}_{n2} & \cdots & 0 \end{bmatrix} \tag{11}$$

1.2 *Obtain the average judgment of decision-makers.* The average judgment of k decision-makers also referred to as matrix $\tilde{Z}$, is obtained using Eq. 12:

$$\tilde{Z} = \frac{\tilde{Z}_1 \oplus \tilde{Z}_2 \oplus \cdots \oplus \tilde{Z}_k}{k} \tag{12}$$

1.3 *Solve for the fuzzy normalized direct relation matrix* $\tilde{X}$*.* This matrix is obtained using Eq. 13 where $\tilde{X}_{ij} = \frac{\tilde{Z}_{ij}}{r} = \left(\frac{l_{ij}}{r}, \frac{m_{ij}}{r}, \frac{u_{ij}}{r}\right)$ and $r = max_{1\leq i\leq n}\left(\sum_{j=1}^{n} u_{ij}\right)$. According to the authors Lin and Wu (2004) [68], the transformation of linear scale is used as a formula for normalization to transform the criteria scales into its corresponding scales. For instance, $\tilde{a}_i$ represents each triangular fuzzy number in each cell of $\tilde{Z}_{ij}$ and r on the other hand is the maximum summation of the upper bound element of each TFN in every row of Eq. 14.

$$\tilde{X} = \begin{bmatrix} \tilde{X}_{11}\tilde{X}_{12} \dots \tilde{X}_{1n} \\ \tilde{X}_{21}\tilde{X}_{22} \dots \tilde{X}_{2n} \\ \vdots \quad \vdots \quad \ddots \quad \vdots \\ \tilde{X}_{n1}\tilde{X}_{n2} \dots \tilde{X}_{nn} \end{bmatrix} \tag{13}$$

$$\tilde{a}_i = \sum_{j=1}^{n} \tilde{Z}_{ij} = \left(\sum_{j=1}^{n} l_{ij} + \sum_{j=1}^{n} m_{ij} + \sum_{j=1}^{n} u\right), \qquad r = max_{1\leq i\leq n}\left(\sum_{j=1}^{n} u_{ij}\right) \tag{14}$$

1.4 *Define crisp matrix for each element of the matrix* $\tilde{X}$*.* The elements in the matrix $\tilde{X}$ where $\tilde{x}_{ij} = (l'_{ij}, m'_{ij}, u'_{ij})$ are extracted to obtain three crisp matrices, as presented in Eqs. 15, 16, and 17, respectively.

$$X_l = \begin{bmatrix} l'_{11} & l'_{12} & \cdots & l'_{1n} \\ l'_{21} & l'_{22} & \cdots & l'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l'_{n1} & l'_{n2} & \cdots & l'_{nn} \end{bmatrix} (15);\ X_m = \begin{bmatrix} m'_{11} & m'_{12} & \cdots & m'_{1n} \\ m'_{21} & m'_{22} & \cdots & m'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m'_{n1} & m'_{n2} & \cdots & m'_{nn} \end{bmatrix} (16);\ X_u = \begin{bmatrix} u'_{11} & u'_{12} & \cdots & u'_{1n} \\ u'_{21} & u'_{22} & \cdots & u'_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u'_{n1} & u'_{n2} & \cdots & u'_{nn} \end{bmatrix} (17)$$

1.5 *Attain the fuzzy total relation matrix* $\tilde{T}$*.* This matrix is computed using Eq. 18 where the matrix $\tilde{T}$ contains TFNs as in Eq. 19.

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \cdots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \cdots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \cdots & \tilde{t}_{nn} \end{bmatrix} \tag{18}$$

in which $\tilde{t}_{ij} = (l''_{ij}, m''_{ij}, u''_{ij})$, $[l''_{ij}] = X_l \times (I - X_l)^{-1}$, $[m''_{ij}] = X_m \times (I - X_m)^{-1}$, and $[u''_{ij}] = X_u \times (I - X_u)^{-1}$ (19)

1.6 *Defuzzify total relation matrix* $\tilde{T}$. The entries in the total relation matrix $\tilde{T}$ are defuzzified using the center of gravity equation shown in Eq. 20 to obtain matrix $T = (t_{ij})_{n\times n}$.

$$t_{ij} = \frac{l''_{ij} + 4m''_{ij} + u''_{ij}}{6} \tag{20}$$

1.7 *Set threshold value.* The negligible effects are filtered out using a threshold value. This value indicates how one factor affects another. The elements in matrix T that exceed the threshold value are considered of significant relations. The threshold level used in this work is determined by decision-makers. The arithmetic mean of the decision-makers' inputs is computed to determine the threshold.

1.8 *Classify the nature of criteria.* The $D_i + R_i$ and $D_i - R_i$ of each criterion are calculated where D_i and R_i are rows and columns sum of matrix T, respectively. $D_i + R_i$ shows the relative importance of the criteria while $D_i - R_i$ demonstrates a causal relationship. A positive value between the difference of D_i and R_i denotes that a criterion belongs to the causal group. Conversely, negative value denotes that a criterion belongs to the effect group.

1.9 *Construct the impact network relations map.* The relationship of one criterion to another is illustrated through a constructed impact relationship map. A scatter graph is created where a criterion's $D_i + R_i$ value is the abscissa and $D_i - R_i$ value as the ordinate.

Step 2: Apply FANP. The following steps from Ocampo *et al.* (2015) [69] below are adapted to generate the criteria weights. These steps are further applied to both models (e.g., collection and distribution centers) considered in this paper.

2.1 *Attain initial matrix* $\tilde{A}_k$. The elicited judgment of decision-makers on each criterion based on pairwise comparison is gathered using the linguistic scale with TFNs presented in Table 3.

Table 3 FANP linguistic scale from Tseng *et al.*, (2008) [44]

Linguistic Scale	Code	Triangular fuzzy scale	Triangular fuzzy reciprocal scale
Just equal	JU	(1,1,1)	(1,1,1)
Equal importance	EQ	(1/2,1,3/2)	(2/3,1,2)
Moderate importance	MO	(5/2,3,7/2)	(2/7,1/3,2/5)
Strong importance	ST	(9/2,5,11/2)	(2/11,1/5,2/9)
Demonstrated importance	DE	(13/2,7,15/2)	(2/15,1/7,2/13)
Extreme importance	EX	(17/2,9,9)	(1/9,1/9,2/17)

The initial decision per comparison matrix $\tilde{A}_k$is equivalent to $(\tilde{a}_{ijk})_{n\times n}$ represented as $\tilde{a}_{ijk} = (l_{ijk}, m_{ijk}, u_{ijk})$ where k represents the k^{th} decision-maker. The form of this matrix is shown in Eq. 21:

$$(\tilde{a}_{ijk})_{n\times n} = \begin{bmatrix} (1,1,1) & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & (1,1,1) & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & (1,1,1) \end{bmatrix} \tag{21}$$

2.2 *Aggregate the judgments using the geometric mean method.* The judgment of the decision-makers elicited for each matrix type is then aggregated. The geometric mean method is among the most commonly used methods for aggregating individual ratings (Saaty, 2008) [70]. This method generates an aggregate fuzzy pairwise comparison matrix $\tilde{A} = (l_{ij}, m_{ij}, u_{ij})_{n\times n}$, shown in Eq. 22, is used in this paper.

$$l_{ij} = \left[\prod_{k=1}^{K}(l_{ijk})\right]^{\frac{1}{K}}; \quad m_{ij} = \left[\prod_{k=1}^{K}(m_{ijk})\right]^{\frac{1}{K}}; \quad u_{ij} = \left[\prod_{k=1}^{K}(u_{ijk})\right]^{\frac{1}{K}} \tag{22}$$

where l_{ij}, m_{ij}, and u_{ij} represents lower bound, modal value, and upper bound, of the aggregate fuzzy judgment, respectively.

2.3 *Compute for consistency ratio of each pairwise comparison*. Using this approach, the consistency of the initial set of fuzzy judgments made by decision-makers is measured (see Eq. 23). If the optimal value (λ) is positive, all solution ratios completely satisfy the fuzzy judgments, which mean that the initial set of fuzzy judgments is consistent. On the other hand, if the optimal value (λ) is negative, the solution ratios of the fuzzy judgments are strongly inconsistent.

Max λ subject to:

$$\begin{aligned} &(m_{ij} - l_{ij})\lambda w_j - w_i + l_{ij} w_j \leq 0 \\ &(u_{ij} - m_{ij})\lambda w_j + w_i - u_{ij} w_j \leq 0 \\ &\textstyle\sum_{k=1}^{n} w_k = 1 \\ &w_k > 0, k = 1,2, \dots, n \\ &i = 1,2, \dots, n-1, j = 2,3, \dots j > i \end{aligned} \tag{23}$$

where λ represents the degree of satisfaction of fuzzy constraints, l_{ij} is lower bound of the TFN in each element, m_{ij} is the modal value of the TFN in each element, u_{ij} represents the upper bound of the TFN in each element, w_i represents the crisp weight of row element, and w_j is the crisp weight of column element.

Eq. 23 is run in LINGO® Optimization Software, where λ represents the degree of satisfaction of fuzzy constraints, and w_i and w_j are the weights of the elements in the pairwise comparison matrix. This formula is used to defuzzify matrices and to give weight to the criteria compared. Each cell in the pairwise comparison is subjected to the constraints and is added in the formula. As suggested by Mikhailov and Tsvetinov (2004) [71], some cells could be removed in case of inconsistency. Some matrices in this study contain only $n - 1$ cells, the minimum number of cells needed, where n is the number of objects compared.

2.4 *Structure of the initial supermatrix.* Using the local weights obtained in the previous step, the supermatrix is structured as in Eq. 24.

$$S = \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1n} \\ s_{21} & s_{22} & \cdots & s_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ s_{n1} & s_{n2} & \cdots & s_{nn} \end{pmatrix} \tag{24}$$

2.5 *Normalize initial supermatrix.* The supermatrix is normalized to achieve a stochastic column matrix by utilizing the column sum (Eq. 25) and dividing each element in the column by Eq. 26 where C is the column sum.

$$\tilde{T} = \lim_{k\to\infty} (\tilde{X}^1 + \tilde{X}^2 + \cdots + \tilde{X}^k) \tag{25}$$

$$C = \left[\sum_{i=1}^{n} s_{ij}\right]_{i\times n} = [s_j]_{n\times 1} \tag{26}$$

2.6 *Limit matrix to large powers.* The final weights are obtained by raising the matrix to large powers until the elements in the normalized matrix have reached a steady state.

2.7 *Determine normalized weights.* The criterion interactions are divided by the sum of the interactions of the criteria in an arbitrarily chosen column to determine its corresponding normalized weights. The weights of criteria are used to construct the matrix w_c and matrix w_d for collection and distribution function, respectively.

<u>Step 3: Apply FAHP.</u> The weights of each location in terms of its viability as a collection and distribution center with respect to a function's criteria are determined through FAHP. The steps below are adapted from Wang and Chin (2011) [72] and are applied to both models of this paper.

3.1 Decision-makers elicit their judgment on a pairwise comparison matrix among location alternatives with respect to each criterion.

3.2 The results from the pairwise comparison are then utilized and further follow steps 2.1 to 2.3, accordingly.

3.3 The computed weights for each alternative with respect to a certain criterion are plugged into the matrix W_d.

$$W_d = \begin{pmatrix} w_{d_{11}} & w_{d_{12}} & \cdots & w_{d_{1n}} \\ w_{d_{21}} & w_{d_{22}} & \cdots & w_{d_{2n}} \\ \vdots & \vdots & \ddots & \vdots \\ w_{d_{n1}} & w_{d_{n2}} & \cdots & w_{d_{nn}} \end{pmatrix} \tag{27}$$

3.4 The global weights for each alternative are determined by multiplying the matrices in steps 2.7 and 3.3.

3.5 The alternatives are ranked according to the global weights identified in the model. A higher global weight denotes a higher priority.

Step 4: Obtain a satisfactory map. This map which plots alternatives with its global weights for both functions as its coordinates. This graph allows a comparison between a location alternative's satisfaction for collection and distribution. The satisfaction level represents a location's capability to carry out a function.

4. A case study

This section highlights the application of an integrated MCDM approach in the context of identifying the locations for collection and distribution functions of reverse logistics (see Fig. 2). The decision models are tested in a furniture firm as a case study in Cebu, the Philippines, since this industry produce highly remanufacturable products. Moreover, Cebu is considered as one of the emerging industrialized regions in the Philippines that practice remanufacturing.

The MCDM procedure begins with the definition of the decision goal, which is the selection of a viable collection and distribution center location. Then, the location criteria applicable in the Philippine setting for collection and distribution centers are determined through a preliminary survey conducted among experts. A criterion is generally perceived applicable when at least 65 % of the experts agree to have it included in the final roster to be used in the MCDM method (Krishnan and Poulose, 2016 [73]). Applicable criteria are then included in the second level of the framework for collection and distribution centers presented in Figs. 2 and 3, respectively. The next step involves the implementation of fuzzy DEMATEL to determine the interrelationships among criteria. Afterward, FANP is used to obtain the weights of each criterion. Lastly, possible collection and distribution location points are evaluated using FAHP, which results in a final ranking of alternatives. For further analyses and visual purposes, a two-way graph is used to plot the locations points of collection and distribution centers.

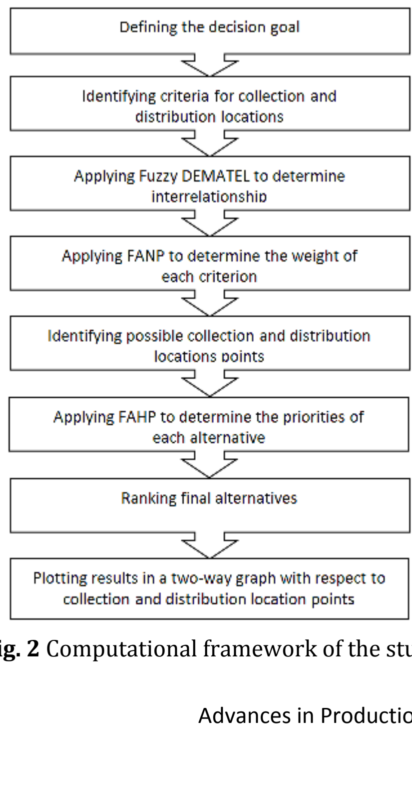

Fig. 2 Computational framework of the study

Selection of experts

It is crucial that the decision-makers involved in any MCDM problem are carefully selected as the accuracy of evaluation among criteria and alternatives significantly relies on their expertise. In this paper, 10 decision-makers (i.e., two decision-makers from the manufacturing firms, two decision-makers from logistics industries, two academics having research interest in the related fields, two decision-makers from government agencies, and two critical consumers) are tapped. Distinct qualifications are set for each decision-maker ranging from minimum educational attainment, years of experience in related fields, working knowledge in remanufacturing/forward and reverse logistics issues, to knowledge in government legislation for manufacturing industries. The choice of respondents is consistent with that of outstanding MCDM applications conducted by several authors (Govindan *et al*., 2009 [74, 75]; Mittal and Sangwan 2014 [76]; and Ocampo and Promentilla 2016 [77]) in various areas of concern.

Decision models

The proposed decision-making models of this paper that pertains to collection and distribution centers are presented in Fig. 3 and Fig. 4, respectively.

A hierarchical structure is utilized to solve the location problem. The structure consists of three levels, and each level represents a particular aspect. The goal of this paper is to determine collection and distribution centers as represented by the first level of the structure. The secondary levels are composed of critical criteria for collection and distribution locations. These criteria are believed to have an interrelationship among one another; thus, fuzzy DEMATEL and FANP are applied in the secondary levels to evaluate the interrelationships and to generate corresponding weights. The location points, as alternatives, are represented in the third level. FAHP is used at this level to determine priorities in terms of an alternative's ranking as a collection or distribution center. The proposed framework is applied through a case study in the furniture industry.

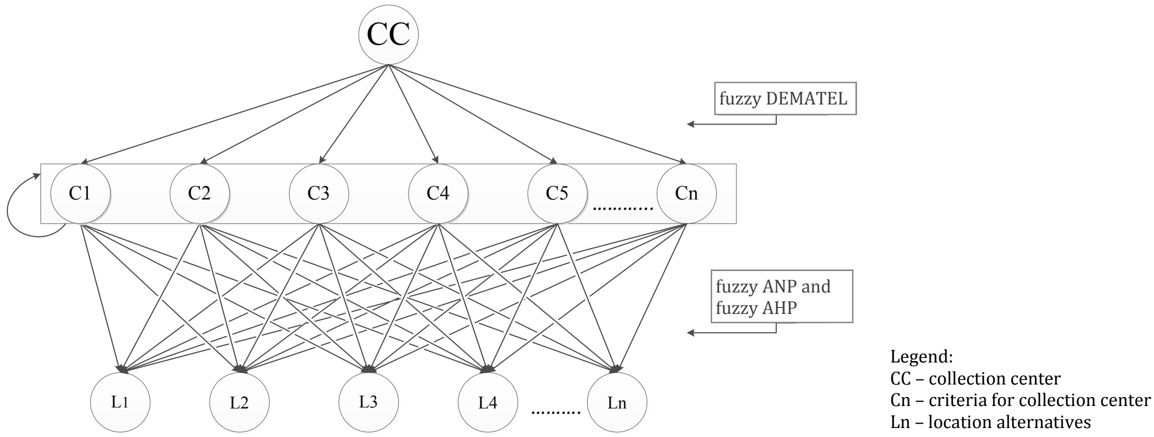

Fig. 3 The decision model for the collection center

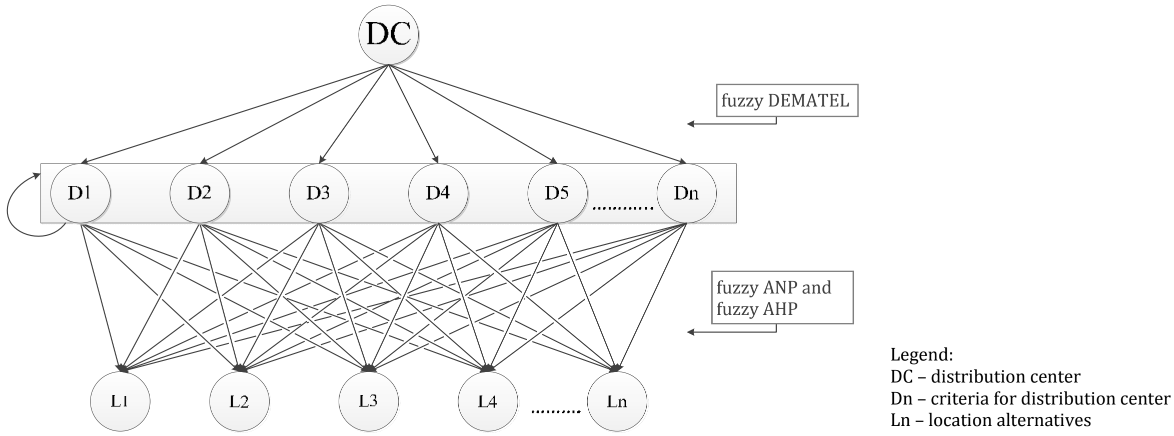

Fig. 4 The decision model for the distribution center

Decision criteria

In the Philippine setting, nine criteria are agreed by decision-makers from the preliminary survey to apply to the decision problem that concerns the selection of locations for collection and distribution centers. These criteria, coded as C1 through C9 for collection center criteria and D1 through D9 for distribution center criteria, are summarized in Tables 4 and 5.

Table 4 Critical criteria for the collection center

Code	Criteria	Description
C1	The capacity of the center	The holding capacity of the facility.
C2	Initial investment	The capability of shareholders' financial support in setting up the facility.
C3	Government policies and regulations	The compliance of requirements given by the government (local regulations on zoning, building codes, among others).
C4	Environmental collaboration with customers	The market's interest and acceptance of the remanufactured product for environmental preservation.
C5	Material availability	The availability of end-of-life products in an area.
C6	Proper disposal	The effective disposal of waste from the facility without any public disturbance.
C7	Land price	The value of the land per square meter.
C8	Supply of product return	The number of EOL products that can be collected.
C9	Quality of product return	The quality of EOL product collected.

Table 5 Critical criteria for the distribution center

Code	Criteria	Description
D1	Distance from facility between competitor	The proximity of competition in a nearby area.
D2	The demand for the second market of the area	The adaptation and acceptance of the remanufactured product by the secondary market in an area.
D3	Initial investment	The capability of shareholders' financial support in setting up the facility.
D4	Government policies and regulations	The compliance of requirements given by the government (local regulations on zoning, building codes, among others).
D5	Environmental collaboration with customers	The market's interest and acceptance of the remanufactured product for environmental preservation.
D6	Distance to suppliers	The accessibility and proximity of facility location from suppliers.
D7	Transportation	The transport of materials and products to and from the location.
D8	Proximity to customers	The proximity of potential customers of the area.
D9	Land price	The value of the land per square meter.

A more concrete illustration of each criterion about its role in the collection and distribution functions of remanufacturing is given as follows:

- *The capacity of the center* (C1)*.* The holding capacity of a facility is an essential factor in setting up a center. This affects the ability of the center to execute its function. For instance, if the facility has reached its maximum capacity, then it is difficult to store additional units.
- *Initial investment* (C2 *and* D3)*.* Investment cost in setting up a facility is a factor to consider in the establishment of both a collection and distribution center. Once a facility is established, it is challenging and costly to revert. Initial investment (C2 and D3) covers the cost for construction, labor, materials, and other activities except for land acquisition.
- *Government policies and regulations* (C3 *and* D4)*.* Government legislation has been identified by Sharma *et al*. (2016) [29] as an important factor in adopting remanufacturing in a developing country. A government's support regarding remanufacturing can either be a major driver for remanufacturing (Xiang and Ming, 2011 [78]), or a major roadblock (Sharma *et al*., 2016 [29]).
- *Environmental collaboration with customers* (C4 *and* D5)*.* Environmental collaboration with customers is achieved when there is support for sustainable practices. The level of acceptance of remanufacturing and support for sustainable practice is directly proportional; when acceptance is high, support is also high (Andel and Aichlmayr, 2002 [79]). This, in turn, creates greater collaboration with the public especially the customers. Cooperation of customers in a distribution function concerns with the support of remanufactured products.
- *Material availability* (C5)*.* The ability to collect is vital in remanufacturing since the raw materials are used products. A lack and insufficient amount of EOL products may hinder the remanufacturing operations as a collection of the used products is the first step that affects all other activities in remanufacturing. With this, material availability (C5) is a significant consideration to assess the viability of a collection center.

- *Proper disposal* (C6). It is necessary to protect the natural environment, and reduce pollution caused by pre-remanufacturing activities. If there is improper waste disposal for facilities, the surrounding area takes a negative impact that affects the community (McAllister, 2015 [80]).
- *Land price* (C7 *and* D9). Similar to investment cost, the price of acquiring land is an essential consideration since it is the foundation for establishing a collection and distribution center.
- *Supply of product return* (C8). Supply of product return is an important criterion since some EOL units that can be collected greatly affects the input cost of materials and components. For instance, organizations would have to acquire new components if there are limited EOL units collected.
- *Quality of product return* (C9). Quality uncertainty must be addressed similarly with quantity uncertainty in which a location with a higher quality level of collected units is preferred. The quality of the EOL units to be collected in an area is also an important consideration since it affects the remanufacturing suitability of the components.
- *The distance of facility between competitor* (D1). It is important to know the distance between competitors to assess how competitive the area is. This enables the organization to know if they can conduct business, perform operations, and penetrate the market.
- *The demand for the secondary market of the area* (D2). The adaptation and acceptance of remanufactured products by the secondary market in an area affect the distribution function of remanufactured goods. For instance, if the end consumers are not supportive of remanufactured goods, then the ability to distribute is negatively affected (Choudhary and Singh, 2011 [28]). As some customers are hesitant in accepting remanufactured products due to its negative perception on its quality (Sharma *et al.*, 2016 [29]), it is of great importance to ensure the consumers' needs are fulfilled upon creating a network supporting the distribution center.
- *Distance to suppliers* (D6). The accessibility and proximity of facility location from suppliers is a significant consideration that affects the lead time of acquiring supplies as it may affect the efficiency of operations if supplies are low.
- *Transportation* (D7). The distribution of remanufactured products as part of the reverse logistics practice involves the transportation of remanufactured products from one location to the other. Transportation (D7) pertains to the ease of product movement, the available alternative routes, and available mode of transportation.
- *Proximity to customers* (D8). The proximity to customers is an important criterion in selecting a location for a distribution center. It is one of the primary considerations as it affects economic performance.

It can be observed that there are criteria applicable for both collection and distribution centers. Some criteria are exclusive to a specific facility. Examples of the limited list of criteria are material availability (C5) for collection centers and proximity to customers (D8) for distribution centers. These criteria are exclusive to a particular facility as they are essential considerations to meet specific objectives. Material availability (C5) is deemed crucial by the decision-makers as applicable only for collection centers as the facility's primary focus is to acquire EOL units. While in the distribution function, this criterion is irrelevant since distribution centers do not deal with EOL unit acquisition. Proximity to customers (D8) is deemed as applicable only for distribution centers since a facility located in the vicinity of customers would significantly minimize costs for delivering products to destinations.

5. Empirical results of the case study

Firstly, the fuzzy DEMATEL methodology is carried out. The aggregate direct relation matrices of the decision-makers are computed using Eq. 12 and are shown in Tables 6 and 7. It is then normalized using Eqs. 13 and 14 which results are presented in Tables 8 and 9. Note that the normalized direct relation matrices are still expressed in fuzzy numbers, therefore, Eq. 20 is used to defuzzify the values and obtain the total defuzzified relation matrices as in Tables 10 and 11. These total defuzzified relation matrices are evaluated by decision-makers further as to which relations are perceived to be significant. The arithmetic average of decision-makers' inputs regarding significant relations among criteria represents the threshold value set. For the case of this paper, a threshold value of 0.47 is established. Then, the next step involves the identification of relations among criteria. Tables 12 and 13 shows the influence and effect of the criteria. The term $(D + R)$ indicates the relative importance of a criterion while $(D - R)$ determines whether a criterion is a dispatcher (net cause) or a receiver (net effect). When a criterion has a positive $(D - R)$ value, it implies that it influences other criteria; otherwise, it is the one influenced. As can be noted from the results, government policies and regulations (C3), environmental collaboration with customers (C4), material availability (C5), land price (C7), supply of product return (C8), and quality of product return (C9) influences the two remaining criteria for collection center whereas demand of the second market of the area (D2), government policies and regulations (D4), environmental collaboration with customers (D5), distance to suppliers (D6), transportation (D7), proximity to customers (D8), and land price (D9) influence the remaining critical criteria for distribution center.

On the other hand, Figs. 5 and 6 show the interdependent relationships of criterion i to criterion j for a collection and distribution center, respectively. The criteria are plotted in a scatter graph where $D_i + R_i$ is its abscissa and $D_i - R_i$ its ordinate. The elements of the deffuzified matrices are compared to the threshold value set. A one and zero representation are developed to distinguish the significant relationship between criteria. A value of one represents a significant relationship between criterion i to criterion j, while a value of zero means no significance between criteria. The arrows denote the influence given and received by one criterion to the other. The arrowhead represents the criteria being affected while the tail corresponds to the influencing criterion.

It can also be noted in Fig. 5 that government policies and regulations (C3), material availability (C5), and of product return (C8) have mostly affected other criteria. However, government policies and regulations (C3) is not affected by any criteria, while material availability (C5) and product return (C8) affect each other. The capacity of the center (C1) and initial investment (C2) are mostly affected by other criteria except for the quality of product return (C9), thus, indicates its dependence on other criteria. In Fig. 6, proximity to customers (D8) has mostly affected other criteria and is affected by the demand of the second market of the area (D2) and environmental collaboration with customers (D5). The demand of the second market of the area (D2) is mostly affected by the other criteria namely: distance of facility between competitor (D1), environmental collaboration with customers (D5), proximity to customers (D8) and land price (D9). The demand for the second market of the area (D2) is mainly dependent on other criteria.

Once the evaluation of criteria using fuzzy DEMATEL approach is completed, FANP and FAHP are correspondingly implemented. These methodologies focus on comparing critical criteria with its significance in a collection and distribution center and identifying interrelationships among criteria. The first step involves aggregating the elicited judgment of decision-makers using Eq. 22. Then, the consistency of each matrix is computed using LINGO® software following through Eq. 23. A positive value of λ indicates that an aggregate matrix has acceptable consistency; conversely, a negative value indicates an inconsistent matrix. In cases of inconsistencies, cells can be deleted (Mikhailov and Tsvetinov, 2004 [71]). Due to some inconsistencies in the judgment of decision-makers, only the first row, being $n - 1$, is considered since $n - 1$ is the minimum solution required in LINGO® to solve Eq. 23.

The initial supermatrices in Tables 14 and 15 are constructed using the generated weights from Eq. 22 and are normalized using Eqs. 25 and 26. Tables 16 and 17 show the normalized matrices for collection and distribution function, respectively. The final weights are obtained by raising these normalized matrices into large powers until a steady-state behavior is observed. The final weights listed in Table 18 are representative of the matrix w_c and matrix w_d of collection and distribution functions, respectively. The furniture firm considered in this paper provided four location alternatives under evaluation. Table 19 summarizes the details of these location alternatives, including lot area, land price, and zoning, to name a few. The location alternatives are evaluated by decision-makers to determine its viability in terms of priorities with respect to each criterion for collection center and distribution center. The elicited judgment of decision-makers is aggregated using the geometric mean method as shown in Eq. 22. Then, using LINGO®, consistency ratios, as well as local weights of the alternative locations, are computed.

The product of matrix w_c and w_d representing the final weights of each criterion (see Table 18) and matrix w_{fc} and w_{fd} (see Tables 20 and 21) is computed to generate the global weights of each alternative (see Table 22). In reference to the global weights, a scatter graph is constructed, as shown in Fig. 7 to map the location alternatives' satisfaction being a collection and distribution center. The satisfaction level represents a location's capability to carry out a function.

Table 6 Aggregated direct relation matrix for the collection center

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	(0.0, 0.1, 0.3)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.4, 0.6, 0.8)	(0.4, 0.5, 0.7)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.7)	(0.3, 0.4, 0.6)
C2	(0.6, 0.8, 0.9)	(0.0, 0.1, 0.3)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.7)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.2, 0.3, 0.5)
C3	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)	(0.5, 0.7, 0.9)	(0.4, 0.5, 0.7)	(0.6, 0.8, 0.9)	(0.6, 0.8, 0.9)	(0.3, 0.5, 0.7)	(0.3, 0.4, 0.6)
C4	(0.5, 0.7, 0.8)	(0.4, 0.6, 0.7)	(0.5, 0.7, 0.9)	(0.0, 0.1, 0.3)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.3, 0.4, 0.6)	(0.5, 0.6, 0.8)	(0.5, 0.6, 0.8)
C5	(0.6, 0.8, 0.9)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.4, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.8)
C6	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.4, 0.6, 0.8)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.4, 0.6, 0.8)	(0.3, 0.5, 0.7)	(0.3, 0.4, 0.6)
C7	(0.6, 0.8, 0.9)	(0.5, 0.7, 0.9)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.2, 0.3, 0.5)
C8	(0.6, 0.8, 0.9)	(0.6, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.8)	(0.5, 0.7, 0.9)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.5, 0.7, 0.9)
C9	(0.4, 0.5, 0.7)	(0.4, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.7)	(0.2, 0.4, 0.6)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)

Table 7 Aggregated direct relation matrix for distribution center

	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	(0.0, 0.1, 0.3)	(0.5 0.7 0.9)	(0.3, 0.5, 0.7)	(0.1, 0.3, 0.5)	(0.2, 0.4, 0.6)	(0.4, 0.6 0.8)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.4, 0.6, 0.8)
D2	(0.5, 0.7, 0.9)	(0.0 0.1 0.3)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)	(0.4, 0.6 0.7)	(0.4, 0.6, 0.8)	(0.6, 0.7, 0.9)	(0.4, 0.6, 0.8)
D3	(0.3, 0.4, 0.6)	(0.4 0.6 0.8)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.4, 0.6, 0.8)	(0.3, 0.4 0.6)	(0.4, 0.5, 0.7)	(0.4, 0.5, 0.7)	(0.5, 0.7, 0.9)
D4	(0.2, 0.4, 0.6)	(0.4 0.6 0.8)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)	(0.5, 0.7, 0.9)	(0.1, 0.3 0.5)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.5, 0.7, 0.9)
D5	(0.4, 0.6, 0.8)	(0.5 0.7 0.9)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)	(0.1, 0.3 0.5)	(0.2, 0.4, 0.6)	(0.5, 0.7, 0.9)	(0.3, 0.5, 0.7)
D6	(0.2, 0.4, 0.6)	(0.3 0.5 0.7)	(0.4, 0.6, 0.8)	(0.1, 0.3, 0.5)	(0.3, 0.4, 0.6)	(0.0, 0.1 0.3)	(0.5, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.3, 0.5, 0.7)
D7	(0.5, 0.7, 0.8)	(0.4 0.6 0.8)	(0.4, 0.6, 0.8)	(0.3, 0.5, 0.7)	(0.3, 0.4, 0.6)	(0.5, 0.7 0.9)	(0.0, 0.1, 0.3)	(0.4, 0.6, 0.8)	(0.3, 0.4, 0.6)
D8	(0.5, 0.7, 0.9)	(0.6 0.8 1.0)	(0.5, 0.7, 0.9)	(0.4, 0.6, 0.8)	(0.5, 0.7, 0.9)	(0.3, 0.4 0.6)	(0.4, 0.6, 0.8)	(0.0, 0.1, 0.3)	(0.4, 0.6, 0.8)
D9	(0.6, 0.8, 0.9)	(0.4 0.6 0.7)	(0.6, 0.8, 0.9)	(0.4, 0.6, 0.8)	(0.4, 0.6, 0.8)	(0.4, 0.6 0.8)	(0.4, 0.6, 0.8)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)

Table 8 Normalized direct relation matrix for collection center

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	(0.000, 0.014, 0.043)	(0.069, 0.098, 0.126)	(0.045, 0.072, 0.098)	(0.056, 0.084, 0.110)	(0.051, 0.078, 0.104)	(0.055, 0.081, 0.108)	(0.059, 0.087, 0.111)	(0.053, 0.081, 0.107)	(0.036, 0.061, 0.088)
C2	(0.081, 0.110, 0.134)	(0.000, 0.014, 0.043)	(0.059, 0.087, 0.113)	(0.056, 0.084, 0.110)	(0.053, 0.081, 0.107)	(0.046, 0.072, 0.101)	(0.077, 0.104, 0.126)	(0.042, 0.069, 0.097)	(0.026, 0.049, 0.078)
C3	(0.056, 0.084, 0.111)	(0.061, 0.090, 0.117)	(0.000, 0.014, 0.043)	(0.072, 0.101, 0.126)	(0.051, 0.078, 0.105)	(0.084, 0.113, 0.134)	(0.081, 0.110, 0.134)	(0.043, 0.069, 0.097)	(0.036, 0.061, 0.088)
C4	(0.068, 0.095, 0.118)	(0.053, 0.081, 0.107)	(0.069, 0.098, 0.124)	(0.000, 0.014, 0.043)	(0.061, 0.090, 0.114)	(0.075, 0.104, 0.130)	(0.036, 0.061, 0.088)	(0.065, 0.092, 0.116)	(0.065, 0.092, 0.117)
C5	(0.084, 0.113, 0.136)	(0.071, 0.098, 0.124)	(0.043, 0.069, 0.098)	(0.051, 0.078, 0.104)	(0.000, 0.014, 0.043)	(0.048, 0.075, 0.104)	(0.058, 0.084, 0.110)	(0.078, 0.107, 0.130)	(0.066, 0.095, 0.121)
C6	(0.062, 0.090, 0.116)	(0.061, 0.090, 0.117)	(0.071, 0.098, 0.123)	(0.058, 0.087, 0.113)	(0.046, 0.072, 0.100)	(0.000, 0.014, 0.043)	(0.059, 0.087, 0.111)	(0.043, 0.069, 0.098)	(0.036, 0.058, 0.085)
C7	(0.081, 0.110, 0.132)	(0.078, 0.107, 0.132)	(0.064, 0.092, 0.118)	(0.056, 0.084, 0.110)	(0.058, 0.087, 0.114)	(0.058, 0.087, 0.114)	(0.000, 0.014, 0.043)	(0.043, 0.069, 0.098)	(0.023, 0.046, 0.075)
C8	(0.084, 0.113, 0.134)	(0.079, 0.107, 0.129)	(0.040, 0.066, 0.094)	(0.071, 0.098, 0.121)	(0.078, 0.107, 0.130)	(0.069, 0.098, 0.124)	(0.048, 0.072, 0.098)	(0.000, 0.014, 0.043)	(0.072, 0.101, 0.126)
C9	(0.051, 0.078, 0.105)	(0.052, 0.078, 0.105)	(0.040, 0.066, 0.095)	(0.061, 0.087, 0.111)	(0.062, 0.090, 0.114)	(0.055, 0.081, 0.105)	(0.029, 0.052, 0.081)	(0.055, 0.084, 0.111)	(0.000, 0.014, 0.043)

Table 9 Normalized direct relation matrix for distribution center

	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	(0.000, 0.015, 0.044)	(0.080, 0.109, 0.133)	(0.044, 0.071, 0.099)	(0.019, 0.044, 0.074)	(0.029, 0.053, 0.083)	(0.063, 0.091, 0.118)	(0.063, 0.091, 0.117)	(0.074, 0.103, 0.127)	(0.062, 0.091, 0.118)
D2	(0.080, 0.109, 0.134)	(0.000, 0.015, 0.044)	(0.075, 0.103, 0.127)	(0.047, 0.074, 0.102)	(0.075, 0.103, 0.127)	(0.055, 0.083, 0.108)	(0.065, 0.091, 0.1170	(0.081, 0.109, 0.130)	(0.056, 0.083, 0.111)
D3	(0.040, 0.065, 0.094)	(0.059, 0.086, 0.111)	(0.000, 0.015, 0.044)	(0.047, 0.074, 0.100)	(0.058, 0.086, 0.112)	(0.041, 0.065, 0.091)	(0.052, 0.077, 0.103)	(0.055, 0.080, 0.103)	(0.074, 0.103, 0.130)
D4	(0.032, 0.059, 0.088)	(0.055, 0.083, 0.111)	(0.065, 0.094, 0.121)	(0.000, 0.015, 0.044)	(0.071, 0.100, 0.127)	(0.021, 0.044, 0.074)	(0.041, 0.068, 0.097)	(0.047, 0.074, 0.102)	(0.071, 0.100, 0.125)
D5	(0.055, 0.083, 0.111)	(0.080, 0.109, 0.133)	(0.060, 0.088, 0.117)	(0.062, 0.091, 0.119)	(0.000, 0.015, 0.044)	(0.021, 0.044, 0.074)	(0.028, 0.053, 0.083)	(0.080, 0.109, 0.131)	(0.050, 0.077, 0.105)
D6	(0.035, 0.062, 0.088)	(0.050, 0.077, 0.103)	(0.058, 0.086, 0.112)	(0.021, 0.044, 0.074)	(0.037, 0.062, 0.091)	(0.000, 0.015, 0.044)	(0.066, 0.094, 0.119)	(0.059, 0.088, 0.115)	(0.044, 0.074, 0.103)
D7	(0.068, 0.097, 0.124)	(0.062, 0.088, 0.114)	(0.063, 0.091, 0.117)	(0.043, 0.071, 0.099)	(0.040, 0.065, 0.093)	(0.071, 0.100, 0.125)	(0.000, 0.015, 0.044)	(0.060, 0.088, 0.115)	(0.038, 0.065, 0.094)
D8	(0.077, 0.106, 0.130)	(0.091, 0.121, 0.140)	(0.075, 0.103, 0.127)	(0.055, 0.083, 0.112)	(0.074, 0.103, 0.128)	(0.038, 0.065, 0.091)	(0.060, 0.088, 0.114)	(0.000, 0.015, 0.044)	(0.059, 0.086, 0.114)
D9	(0.083, 0.112, 0.137)	(0.056, 0.083, 0.108)	(0.088, 0.118, 0.137)	(0.060, 0.088, 0.114)	(0.058, 0.086, 0.112)	(0.056, 0.086, 0.112)	(0.059, 0.088, 0.117)	(0.047, 0.074, 0.100)	(0.000, 0.015 0.044)

Table 10 Total defuzzified direct-relation matrix for collection center

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0.41671423	0.476950149	0.416258116	0.44310584	0.43035511	0.44635719	0.42995474	0.41827428	0.36865124
C2	0.50792484	0.408431607	0.434668408	0.449010277	0.43837842	0.4452388	0.45097947	0.41379572	0.3632351
C3	0.50826854	0.497324253	0.39010564	0.484384238	0.45604524	0.50026838	0.47548591	0.43301991	0.39037429
C4	0.51907261	0.491339845	0.465257725	0.409352809	0.46776876	0.49523275	0.43455459	0.45492889	0.42085009
C5	0.53938017	0.511456226	0.444103289	0.470638663	0.40520224	0.4739281	0.45798685	0.47135091	0.42673748
C6	0.48823607	0.473559814	0.443110971	0.449782541	0.42936429	0.39072474	0.43444987	0.41230093	0.36952385
C7	0.52006556	0.502564809	0.450510473	0.460443193	0.45435602	0.46865441	0.38283735	0.42484289	0.37027334
C8	0.55505298	0.533306792	0.455706833	0.502189978	0.50114104	0.50804831	0.46186805	0.40328363	0.44409374
C9	0.46221839	0.448016535	0.401069165	0.435181448	0.4302822	0.43530698	0.38952752	0.41186065	0.31869023

Table 11 Total defuzzified direct-relation matrix for distribution center

	D1	D2	D3	D4	D5	D6	D7	D8	D9
D1	0.379387623	0.480950052	0.449107005	0.355974857	0.398427846	0.401252967	0.429624918	0.464235289	0.43958904
D2	0.499068063	0.43753611	0.515212253	0.414225485	0.476585747	0.423420219	0.463501764	0.507449492	0.46988036
D3	0.414977178	0.450323629	0.387785617	0.374624169	0.417376406	0.367750928	0.406175131	0.433553207	0.44110393
D4	0.407038664	0.445713958	0.456690076	0.320107297	0.42869193	0.346980264	0.395642264	0.426458008	0.43661605
D5	0.441128257	0.483235613	0.465869892	0.399854848	0.365684239	0.358575917	0.396311756	0.470506148	0.43032409
D6	0.393166800	0.423333127	0.431411076	0.332420986	0.378872918	0.306933531	0.404514398	0.422381271	0.39687451
D7	0.453769553	0.46626574	0.468360931	0.380607821	0.410538757	0.409776064	0.362695127	0.454595803	0.42049414
D8	0.497746937	0.531523108	0.516629772	0.423355486	0.478309318	0.409164549	0.461531792	0.425390001	0.47374084
D9	0.490979166	0.487382806	0.516854466	0.41782285	0.451853632	0.417988269	0.451893605	0.467194462	0.39939782

Table 12 Relative importance and causal relationship of critical criteria for collection center

	D	R	D+R	D-R
C1	3.84662089	4.51693339	8.363554279	-0.6703125
C2	3.91166264	4.342950029	8.254612673	-0.431287385
C3	4.1352764	3.90079062	8.036067022	0.234485783
C4	4.15835806	4.104088986	8.262447048	0.054269077
C5	4.20078393	4.012893321	8.213677246	0.187890604
C6	3.89105308	4.163759646	8.054812727	-0.272706566
C7	4.03454804	3.917644347	7.952192383	0.116903689
C8	4.36469135	3.843657816	8.208349169	0.521033538
C9	3.73215312	3.47242936	7.204582479	0.259723759

Table 13 Relative importance and causal relationship of critical criteria for distribution center

	D	R	D+R	D-R
D1	3.798549593	3.977262239	7.775811833	-0.178712646
D2	4.206879492	4.206264144	8.413143636	0.000615348
D3	3.693670197	4.207921088	7.901591285	-0.514250891
D4	3.663938509	3.418993798	7.082932307	0.244944711
D5	3.811490765	3.806340792	7.617831557	0.005149972
D6	3.489908617	3.441842708	6.931751325	0.04806591
D7	3.827103931	3.771890756	7.598994687	0.055213175
D8	4.217391799	4.071763681	8.289155479	0.145628118
D9	4.101367077	3.908020774	8.009387851	0.193346303

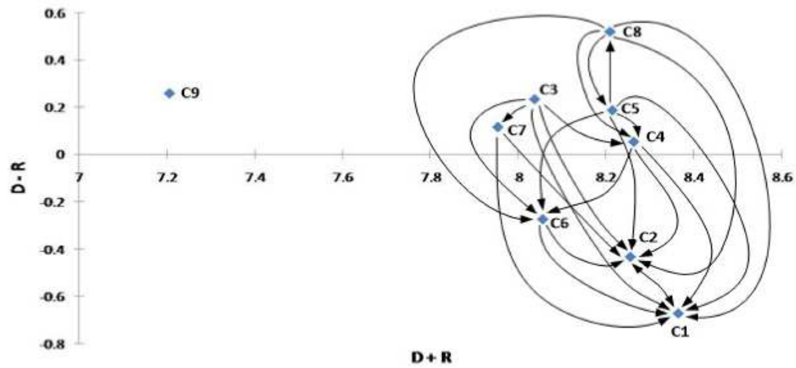

Fig. 5 Impact relationship map for the collection center

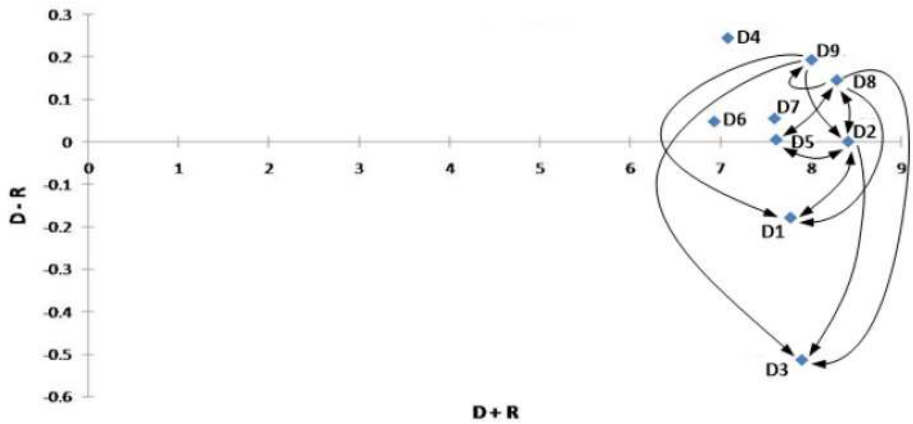

Fig. 6 Impact relationship map for the distribution center

Table 14 Initial supermatrix for collection center

	Goal	C1	C2	C3	C4	C5	C6	C7	C8	C9
Goal		1	1	1	1	1	1	1	1	1
C1	0.051692		0.1657246							
C2	0.204105	0.1599448								
C3	0.083971	0.0699759	0.07244		0.2930341		0.3512969	1		
C4	0.083971	0.0552967	0.05470523				0.3238109			
C5	0.254504	0.2284926	0.3140042		0.2586752		0.3248922		1	
C6	0.069444	0.1183844	0.07667848							
C7	0.02851	0.1693533	0.2157051							
C8	0.156507	0.1985523	0.1007345		0.4482907	1	0.298622			
C9	0.083179									

Table 15 Initial supermatrix for distribution center

	Goal	D1	D2	D3	D4	D5	D6	D7	D8	D9
Goal		1	1	1	1	1	1	1	1	1
D1	0.049747		0.1476923							
D2	0.089082	0.3765877		0.449081		0.4117647			0.5837838	
D3	0.110549									
D4	0.042783									
D5	0.059989		0.3780924	0.305924					0.4162162	
D6	0.092585									
D7	0.196225									
D8	0.151759	0.5130919	0.3893707			0.5882353				1
D9	0.20728	0.1103204	0.0848445	0.2449951						

Table 16 Normalized supermatrix for collection center

	Goal	C1	C2	C3	C4	C5	C6	C7	C8	C9
Goal	0	0.5	0.500001973	1	0.5	0.5	0.4350433	0.5	0.5	1
C1	0.050884	0	0.082862627	0	0	0	0	0	0	0
C2	0.200914	0.0799724	0	0	0	0	0	0	0	0
C3	0.082658	0.0349879	0.036220143	0	0.14651705	0	0.1528293	0.5	0	0
C4	0.082658	0.0276484	0.027352723	0	0	0	0.1408717	0	0	0
C5	0.250525	0.1142463	0.157002719	0	0.1293376	0	0.1413422	0	0.5	0
C6	0.068359	0.0591922	0.038339391	0	0	0	0	0	0	0
C7	0.028064	0.0846767	0.107852975	0	0	0	0	0	0	0
C8	0.15406	0.0992762	0.050367449	0	0.22414535	0.5	0.1299135	0	0	0
C9	0.081878	0	0	0	0	0	0	0	0	0

Table 17 Normalized supermatrix for distribution center

	Goal	D1	D2	D3	D4	D5	D6	D7	D8	D9
Goal	0	0.5	0.500000025	0.499999975	1	0.5	1	1	0.5	0.5
D1	0.049747	0	0.073846154	0	0	0	0	0	0	0
D2	0.089082	0.18829385	0	0.224540489	0	0.20588235	0	0	0.2918919	0
D3	0.110549	0	0	0	0	0	0	0	0	0
D4	0.042783	0	0	0	0	0	0	0	0	0
D5	0.059989	0	0.189046209	0.152961992	0	0	0	0	0.2081081	0
D6	0.092585	0	0	0	0	0	0	0	0	0
D7	0.196225	0	0	0	0	0	0	0	0	0
D8	0.151759	0.25654595	0.19468536	0	0	0.29411765	0	0	0	0.5
D9	0.20728	0.0551602	0.042422252	0.122497544	0	0	0	0	0	0

Table 18 Weights of criteria for collection and distribution center

Collection center		Distribution center	
Criteria	**Weights**	**Criteria**	**Weights**
C1	0.03817	**D1**	0.04272
C2	0.11587	**D2**	0.17471
C3	0.08293	**D3**	0.06626
C4	0.05699	**D4**	0.02564
C5	0.31248	**D5**	0.13016
C6	0.04509	**D6**	0.05549
C7	0.03149	**D7**	0.11761
C8	0.27100	**D8**	0.24528
C9	0.04598	**D9**	0.14212

Table 19 Location alternatives for the furniture industry

Code	Lot area	Cost	Zone	Nearby community population	Accessibility	Other information
F1	302 square meters	PHP 8,500,000 (total contractcost)	Commercial and is surrounded by some residential areas	88,704	The site alternative is accessible by at least 5 five minor roads. These minor roads lead to major roads that surround the site alternative	
F2	156 square meters	PHP 1,200,000 (total contract cost)	Heavily residential area with nearby commercial establishments	112,755	The site alternative is accessible by minor roads leading to subdivisions and other access roads	
F3	45 square meters	PHP 14,400 (monthly rental fee)	Moderate commercial area with residential zones	73,032	The site is located along the road of one of the city's landmark. The street can be accessed through two major roads	An advance rental of two months and a security deposit equivalent to one month is needed
F4	1,800 square meters	PHP 174,000.00 (monthly rental fee)	Industrial zone with residences	99,598	The site is located along a minor road and can be accessed through two alternate roads	An advance rental of three months and a security deposit equivalent to three months is needed; the minimum lease term is one year, and a post-dated check for the succeeding monthly rent is required

Table 20 Local weights of each alternative with respect to a criterion for a collection center

Alternative	C1	C2	C3	C4	C5	C6	C7	C8	C9
F1	0.402238	0.1585758	0.2669257	0.1594486	0.15457	0.1218488	0.161685	0.213737	0.224195
F2	0.212937	0.226141	0.1652397	0.2851311	0.368942	0.4092921	0.38924	0.261059	0.354206
F3	0.103026	0.1914138	0.2852078	0.1649846	0.268178	0.2737234	0.194983	0.180938	0.203212
F4	0.281799	0.4238694	0.2826269	0.3904356	0.20831	0.1951358	0.254092	0.344266	0.218387

Table 21 Local weights of each alternative with respect to a criterion for a distribution center

Alternative	D1	D2	D3	D4	D5	D6	D7	D8	D9
F1	0.2118785	0.1791128	0.1526729	0.1392201	0.1299249	0.1858912	0.3122054	0.1321161	0.2086329
F2	0.2858034	0.2574002	0.3518347	0.2862499	0.213301	0.2353964	0.1801965	0.246009	0.09176981
F3	0.3138274	0.3994122	0.257968	0.3120752	0.4214795	0.2956678	0.1849814	0.1877439	0.5506188
F4	0.1884908	0.1640748	0.2375244	0.2624548	0.2352947	0.2830446	0.3226166	0.434131	0.1489784

Table 22 Global weights of collection and distribution center for the furniture industry

Alternatives	Collection	Ranking	Alternatives	Distribution	Ranking
F1	0.192069	4	F1	0.18003288	4
F2	0.297314	1	F2	0.22323544	3
F3	0.219826	3	F3	0.32561239	1
F4	0.290791	2	F4	0.27111927	2

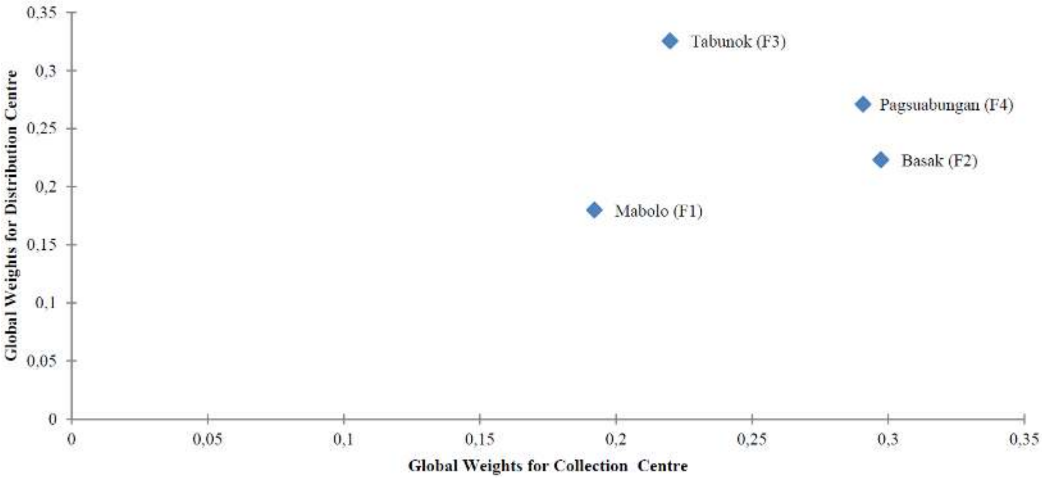

Fig. 7 Furniture industry satisfaction map

6. Discussion and managerial implications

Potential strategic locations of chief logistics functions such as collection and distribution centers are evaluated using the proposed fuzzy MCDM model with key results presented in the previous section. The succeeding sections provide thorough analyses of each aspect considered in selecting a collection and distribution center given the case study in Cebu, Philippines.

6.1 Collection center function

For a collection center, government policies and regulations (C3), material availability (C5) and supply of product return (C8) established the most number of influenced criteria over the other while the quality of product return (C9) has no significance towards other criteria. Moreover, the capacity of the center (C1) and initial investment (C2) are observed as being the most influenced criteria. The results can be viewed and justified as follows:

Government policies and regulations (C3). Government legislation has been identified by Sharma *et al.* (2016) [29] as an important factor in adopting remanufacturing in a developing country. A government's support regarding remanufacturing can either be a major driver for remanufacturing (Xiang and Ming, 2011 [78]), or a major roadblock (Sharma *et al.*, 2016 [29]). The government has a great contributing factor as it can impose legislation that could engage people and organizations in environmentally sustainable activities such as remanufacturing. This shows the dependency of investment (C3), environmental collaboration with consumers (C4) and proper disposal (C6) toward government policies and regulations. Currently, the Philippines does not have specific laws regarding remanufacturing and reverse logistic. Poor implementation, budgetary issues, weak monitoring and implementation, and lack of political will at both local and national level hinder the full effect of the policies and regulations (Magtolis and Indab, 2008 [81]). To make up for the lack of specific laws on remanufacturing, it is ideal that the location of a facility has a proper local implementation of other environmental policies and regulations to increase the efficiency of the collection of EOL units for remanufacturing, and increase the awareness, cooperation, and collaboration of people.

Material availability (C5) *and supply of product return* (C8)*.* It is difficult to predict the quantity of return of materials and products, therefore placing a collection center that has the minimum quantity uncertainty and maximum material availability is a major concern for decision-makers. This is a consideration highlighted by Serrano *et al*. (2013) [24]. The ability to collect sufficient EOL units is considered as a major economic driver of remanufacturing by Toffel (2004) [82] for its economic advantages. When material availability and supply of product return do not have a profitable opportunity for an organization, placing a collection center may not be feasible (Wojanowski *et al*., 2007, [17]). An interdependent relationship is observed between material availability (C5) and supply of product return (C8). Moreover, when material availability (C5) of EOL product is high, the supply of product return (C8) is also high; this implies a directly proportional relationship between both criteria. Material availability (C5) and supply of product return (C8) also affect the capacity of the center (C1), initial investment (C2), environmental collaboration with customers (C4), and proper disposal (C6).

Quality of product return (C9)*.* There are different quality levels of return for each EOL product (Xiaoyan, 2012 [9]). Proper inspection of units should be administered to carefully assess the products' viability for remanufacturing. Aras *et al*. (2008) [83] emphasized that organizations should carefully strategize since a high number of returns may have poor quality creating a challenge as most of the time, quality is unknown and uncertain. This is the reason that quality of product return (C9) does not exhibit any significant relationship with other criteria. The inclusion of this criterion in the framework supports the statement of Aras *et al*. (2008) [83] on the importance of considering quality in collecting EOL units.

The capacity of the center (C1) *and initial investment* (C2)*.* Other criteria must first be assessed in determining the probable capacity and initial investment of the center. The viability of an area in terms of other criteria is evaluated first to ensure that the area is operationally and strategically feasible before considering the required capacity and needed investment to establish a collection center. This shows that capacity is affected by material availability (C5), environmental collaboration with customers (C4), and supply of product return (C8). Additionally, both are interdependent towards one another. These criteria demonstrate a directly proportional relationship, that is, with a greater capacity of a facility, higher investment is needed (Rao *et al*., 2015 [84]).

6.2 Distribution center function

For a distribution center, proximity to customers (D8) established the most number of influences over other criteria while the demand of the second market of the area (D2) is greatly affected by other criteria. Moreover, government policies and regulations (D4), distance to suppliers (D6), and transportation (D7) have no significant influence and are not substantially affected by other criteria.

Proximity to customers (D8)*.* Capturing the interest of customers creates a challenge to support remanufactured products primarily in the Philippine context where remanufactured products are usually associated with inferior quality and are considered as second hand or reused products. This highlights the need to locate a distribution center in the vicinity of customers. By having the facility strategically proximate to customers, awareness, convenience, and increase potential customers may be evident. Consequently, maximized sales and profitability will be attained.

The demand for the secondary market of the area (D2)*.* Attaining a high demand will entail consumers to recognize, accept and be aware of the importance of remanufacturing as the demand of the secondary market of the area (D2) is greatly influenced by environmental collaboration with customers (D5), and proximity to customers (D8). A strategically located facility that captures a high demand would signify a tremendous economic advantage for an organization. Mitra (2007) [85] has stated that the demand to support remanufactured products can be driven by the inherently lower prices of these products. This scenario applies in the context of the Philippines since the market in this country is price-sensitive.

Government policies and regulations (D4)*.* The consideration of government policies for a distribution center is in contrary to the disposition of a collection center. Little emphasis has been given by Philippine legislation regarding the selling and distribution of remanufactured products. As an effect, remanufactured products are not given specific consideration. The little emphasis on the distribution of remanufactured products can be identified as an effect of the lack of legislation and encouragement towards the collection of EOL units. This scenario is contrasting to the effect of policies in India determined by Govindan *et al*. (2016) [37, 38] where regulations towards EOL units restrict the flow of remanufactured products. With the lack of specific legislation towards collecting EOL units, it follows that the distribution aspect is not given importance as well. This is evident in the mathematical results of fuzzy DEMATEL where government policies and regulations (D4) is neither affected nor being affected by other criteria.

Transportation (D7). Most of the time, manufacturers are unwilling to distribute the goods themselves; instead, prefer a third-party logistics provider to perform such operation (Govindan *et al*., 2012 [86]). For this reason, transportation (D7) forms no significant interrelationship with other criteria.

Material availability (C5)*, the supply of product return* (C8)*, and initial investment* (C2)*.* These criteria are deemed by decision-makers to be the most critical considerations in selecting a location for a collection center. A considerable gap is observed between the prioritization of these criteria and the remaining criteria. These criteria are perceived to be the significant drivers that motivate organizations; moreover, this prioritization reveals that economic and profitability concerns are significant considerations to set-up facilities for the collection of EOL units. On the other hand, proximity to customers (D8), the demand of the secondary market (D2) and land price (D9) are perceived to be the most important criteria in choosing a location for a distribution center. Similar to the selection of a location for a collection center, economic and profitability concerns are observed to be more prioritized. Basing on these trends, it can be inferred that economic sustainability is the primary driver for choosing a location alternative for both collection and distribution centers.

6.3 Evaluation of alternative locations

Cebu is a leading exporter in the furniture industry. It accounts for 60 % of the country's total exports of the said sector, making Cebu the furniture capital of the country (PwC Cebu 2017 CEO Survey, 2017 [87]). With this favorable condition of the furniture industry in Cebu, the host company expressed its willingness to expand and improve its operations locally to increase its competitive advantage in the market. The case firm is open to the idea of setting up facilities for reverse logistics to enhance their operations. Four alternatives, F1, F2, F3, and F4 are critically assessed by decision-makers in terms of its viability as a collection and distribution center. The application of FAHP to the viability of locations for both collection and distribution centers in the furniture industry are discussed as follows.

As a potential collection center, F2 exhibits the highest priority. It has been identified that the major contributing factors for this result are material availability (C5), proper disposal (C6), land price (C7), and quality of product returns (C9). From Table 22, it is observed that F2 is given more priority in terms of the proper disposal (C6) criterion. This alternative has a stricter implementation of policies and regulations towards proper waste management as the area is highly industrialized and is more pressured to comply with environmental regulations. The highly urbanized setting of F2 denotes that there is a high EOL unit availability in the area that can be collected. This could be explained in Table 22, as F2 ranked first regarding material availability (C5).

F4 is believed to have the second-highest priority level and is considered as the most important alternative with regards to the initial investment (C2), environmental collaboration with customers (C4), and supply of product returns (C8). F4 ranks first in terms of supply of product returns (C8) since there is also a high priority in environmental collaboration with customers (C4). Notably, there is only a slight difference between the priority levels of F2 and F4. Although F4 ranks first in terms of initial investment (C2) and supply of product return (C8), which are second and third priority for the selection of location for collection center, decision-makers preferred F2 over F4 due to its high material availability (C5) which ranked first in the prioritization on the selection of location for collection center. Comparing the prioritized criteria for F4 and F2, F4 has more important criteria for a collection center. However, considering the remaining criteria, F2 demonstrates more priority. This is then succeeded by F3 and F1 with a high priority for government policies and regulations (C3) and capacity of the center (C1) respectively. In terms of the capacity of the center (C1), while F1 has a lesser lot area compared to F3, decision-makers prefer F1 as it is believed to have sufficient capacity for the operations of a collection center.

With regards to a distribution center, F3 exhibits the highest priority. It has been determined that the key contributing factors in selecting a distribution center are distance of facility between competitor (D1), demand of the second market of the area (D2), government policies and regulations (D4), environmental collaboration with customers (D5), distance to suppliers (D6), and land price (D9). Land price (D9) is considered to be the most significant criterion and is also one of the top priority on the selection of a location for a distribution center, that impacts F3. The expense for the land acquisition of F3 is relatively lower than the other location alternatives making it more preferred by decision-makers. The current operations of the company are currently based in the northern area of Cebu, establishing a distribution center in F3 allows the company to venture in the southern area. Moreover, it allows them to test their profitability of penetrating in a new area. F3 also has the highest ranking of environmental collaboration with customers (D5) and demand of the second market of the area (D2). Exploiting the demand and acceptance of remanufactured products in F3 will be favorable for the company in terms of profitability.

F4 is deemed to have the second-highest priority and is perceived to have the most straightforward transportation and the highest proximity to customers. Although proximity to customers (D8) is the top priority in selecting a location for a distribution center, F3, which has a relatively lower weight for proximity to customers (D8), was still favoured by decision-makers due to the other criteria that have a significant influence in setting up distribution center such as demand of the second market of the area (D2) and environmental collaboration with customers (D5). This is then followed by F2, which is significant in the investment criterion. The least preferred alternative for a distribution center is F1 without significance to any criteria.

In summary, the Philippine furniture industry aims to be a global design innovator using sustainable materials by 2030. The industry intends to focus on factors such as product development where sustainable and environment-friendly materials are being used in manufacturing processes (DTI BOI, 2016 [88]). The government has been collaborating with private sectors to address the roadblock that hinders the growth of the manufacturers and improve policies for consistency and sustainability. The proposed framework of this study gives the government an insight as to the attractiveness of its policies among location alternatives. This allows an evaluation of a location's disposition towards policies for the collection of EOL units and distribution of remanufactured products. The government can impose additional policies or enforce stricter implementation of existing policies should they opt to make regions more supportive of remanufacturing activities. The identification and prioritization of critical criteria allow the government to implement better and more precise legislation that focuses on improving a location's inclination on a specific criterion.

A policy that can be considered by the government is providing incentives to organizations and or consumers through subsidies to organizations. An attractive incentive policy entices organizations to engage in remanufacturing activities and encourages consumers to return EOL units which increase the supply of product return (C8). Another action that can be performed by the government is initiating and enforcing laws that would regulate the remanufacturing sector to standardize their operations. This organizes the remanufacturing sector of the country which is comprised mostly of independent remanufacturers.

Developing countries such as the Philippines lack heuristic research on reverse logistic studies specifically on the branch of remanufacturing. This paper can be considered as a pioneering study that discusses facility location planning supporting remanufacturing. Existing studies on facility location mostly utilizes a single objective criterion and fails to address other critical criteria that would affect the selection location for a collection and distribution center. Since the study is relatively new, it can start an interest among researchers who would like to further supplement the gap in the literature. The criteria determined for a collection and distribution center is applicable in general industry and can be used for future studies.

7. Conclusion

This study proposes a comprehensive approach to solve a facility location problem using fuzzy multiple criteria decision-making (MCDM) techniques. Since the facility location is one of the crucial problems that decision-makers encounter, it is necessary to assess the implications of establishing collection and distribution centers. The proposed approach provides a holistic decision that simultaneously considers multiple criteria that are critical for an EOL product collection center and a remanufactured product distribution center. It is determined in this paper that the government plays a vital role in the decision for the selection of facility locations. Since government policies and regulations (C3 and D4) have a significant interdependent relationship with the other criteria and are evaluated with the alternatives, the government is given an insight as to where locations are most and least preferred for policies. In the field of research in the Philippines, there is a lack of interest and studies on the subject of remanufacturing particularly in the location decision. This study is significant as it supplements this research gap.

This study has identified nine essential criteria for both collection and distribution centers in the context of the Philippines. These criteria can be used by decision-makers as a reference in solving a location problem. The proposed framework provides decision-makers critical evaluation of location alternatives for facilities with consideration to the established criteria. The approach allows decision-makers to address major concerns regarding collecting EOL units and distributing remanufactured products. For example, in the collection function, quantity and quality uncertainties are significant factors that must be taken into consideration; while economic and market-oriented issues are major concerns for a distribution function. The methodology incorporates these various essential criteria that enable decision-makers to perform comprehensive judgment. Moreover, the framework enables decision-makers to assess the suitability of an alternative at strategic, tactical, and operational levels. The location alternatives are ranked based on their viability to perform reverse logistics functions. The decision-makers are given insights and can select a location to perform collection or distribution regardless of ranking as long as it fits the strategic plan of an organization. This allows decision-makers to evaluate specific location that can operate satisfactorily, that is, a location perceived to have sufficient performance to increase economic, social, and environmental opportunities.

Remanufacturing in the Philippines is a mostly unappreciated industrial sector. This can be inferred from the country not having specific laws regarding remanufacturing and reverse logistics. The Philippines still has many issues that must be addressed, such as limited and ill-informed policies, cultural preferences, and assessment of actual benefits. The lack of legislation towards reverse logistic practices particularly in EOL unit collection affects the entire operation of remanufacturing. From the results of the surveys, government policies and regulations (C3 and D4) are seen as an important criterion as it is considered for both collection and distribution centers. Thus, the support of government is essential in improving the overall condition of remanufacturing.

The framework, in general, allows decision-makers to select a location that enables them to exploit the potential of a location as a collection and distribution center. This approach increases the economic and operational viability of reverse logistics operations. Decision-makers retain the control in picking a site based on its priority on being a collection or distribution center. The flexibility of the framework enables decision-makers to select a site as to their preference. For instance, decision-makers can choose to perform collection and distribution on a location for its practicality and applicability instead of its high viability depending on the strategic plan of the organization. Outside the reverse logistic literature, the methodological framework proposed in this work can be used to address general facility location problems where tradeoffs among stakeholders or entities are well pronounced and decision-makers find it imperative that such tradeoffs must be carefully observed. With a different application domain, a few changes in the criteria set, and the interrelationships of these criteria (i.e., other applications could set them as *a priori*) can be implemented. Future work could explore the following: (1) the hierarchical network problem could be better expounded by adding sub-criteria components in the criteria set, (2) the use of other MCDM methodologies, such as data envelopment analysis, best-worst method, multi-objective optimization, in the prioritization of the location alternatives could be carried out as fuzzy AHP imposes limits on the number of alternatives, and (3) the priority of the decision-makers as to the importance of collection and distribution functions is not reflected in the proposed methodological framework which could change the satisfaction trade-off map. Finally, the proposed approach could be set within the context of location-allocation problems.

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