S.I.: OR FOR SUSTAINABILITY IN SUPPLY CHAIN MANAGEMENT

Appropriate location for remanufacturing plant towards sustainable supply chain

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Abstract

Confronted with the scarcity of natural resources, increase in product returns and government regulations on protection of environment, firms are implementing remanufacturing operations to achieve growth which is more sustainable and contribute to the millennium sustainable development goals. The challenge before the managers is to decide the appropriate location to establish the remanufacturing facilities in the reverse supply chain. Several conflicting criteria need to be considered before establishing a remanufacturing facility. In this paper, a framework is proposed to evaluate an ideal location for opening a remanufacturing plant, with the aid of ideal solution based multi criteria decision making (MCDM) tools, specifically TOPSIS, GRA and VIKOR. The suitable candidate location is then selected using the veto rule, which helps to overcome the limitation of using a single MCDM tool. An illustrative application in the Indian automotive sector is demonstrated to show the applicability of proposed framework. The approach is useful when there is a lack of quantitative data or the information is incomplete. The developed framework will help industries and economies to impact the use of eco-efficient and socio-economic systems and suggest pathways of transitioning to a more sustainable future.

Keywords Remanufacturing · Location planning · MCDM · TOPSIS · VIKOR · GRA

1 Introduction

Sustainability is "development that meet the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). With increase in industrialization, importance of sustainability has increased considerably (Bulmus et al. 2014). Product returns have also increased due to shortened lifecycles due to advancement in technology (Darbari et al. 2019), and thus consumption of virgin materials has increased, which has resulted in the scarcity of natural resources. Increase in product returns also increases the generation of toxic waste that is detrimental for environment. This has caused governments in many countries to implement regulations on the disposal of waste, use of

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landfills, etc. (Ilgin and Gupta 2010; Lu et al. 2014). These regulations hold manufacturers responsible for the management of products throughout their lifecycle.

Due to the above stated reasons, a number of firms are now implementing closed loop supply chain (CLSC). CLSC is "the design, control and operation of a system to maximize value creation over the entire life cycle of a product with dynamic recovery of value from different types and volumes of returns over time" (Guide Jr. and Van Wassenhove 2009). Implementing CLSC helps to accomplish SDGs by improving environmental and economic performance, simultaneously (Jindal and Sangwan 2017; Prakash et al. 2018). A CLSC involves integration of forward and reverse supply chain (Jayaraman et al. 1999; Kannan et al. 2010; Mehrbod et al. 2012), and aims at product recovery and recovery of materials from the used products (Fattahi and Govindan 2017). Several product recovery options include: reconditioning, reuse, remanufacturing, repair, etc. (Seitz 2007; Rathore et al. 2011).

The reverse part of the CLSC is not a traditional image of the forward supply chain due to collection centers, sorting and recovery facilities (Lu and Bostel 2007). Hence, production, planning and control of remanufacturing operations is much more challenging (Guide Jr. 2000). This is due to uncertainty in timing, quantity and quality of returned products (Jindal and Sangwan 2014; Soleimani et al. 2016; Guide Jr. 2000). It is essential that remanufacturing plants are established at optimal locations, so that overall costs are minimized (Alimoradi et al. 2011), and subsequently firm gets economic benefits from CLSC implementation. The distinct feature of a remanufacturing plant location is that it should be located in the proximity of collection centers, original manufacturing facilities and customers for remanufactured products. Further, there should be availability of skill intensive labor force as remanufacturing operations are skill intensive (Ferrer and Ayres 2000), adequate availability of used products, etc. There are many other factors that need to be considered while establishing a remanufacturing plant. In real situations, many parameters are not known with certainty or the available information is incomplete. Specifically, the biggest challenge arises due to the inherent vagueness in defining and measuring the environmental and social impact.

In our knowledge, none of the studies in the literature has presented a comprehensive framework for deciding an ideal location for establishing a remanufacturing facility. This paper proposes a framework to evaluate an ideal location for establishing a remanufacturing plant, based on the ideal solution based multi criteria decision making (MCDM) techniques, namely, GRA, TOPSIS and VIKOR (Awasthi et al. 2018). Fuzzy theory is integrated with these techniques that helps to model the uncertain parameters. The fuzzy theory also helps to consider the inherent vagueness and imprecision associated with judgements made by experts (Chen and Chiou 1999). Further, crisp values do not capture the vagueness inherent in the real world problems or in many cases, it is not possible to make judgements by crisp values.

The proposed framework is useful for managers involved in the evaluation of an ideal location to establish a remanufacturing facility. The framework is suitable when there is a lack of quantitative data or the available information is incomplete. In a nutshell, we address the following research questions in this paper:

1. Identification of criteria which can be used to evaluate the most suitable location for establishing a remanufacturing facility.
2. Identification of prominent criteria and sub-criteria to select a remanufacturing plant location.

3. Propose a framework to evaluate best alternative location for establishing a remanufacturing plant using selected criteria.

The rest of this paper is organized as follows. Section 2 discusses related literature on facility location & application of MCDM techniques. In Sect. 3, proposed framework, fuzzy set theory and MCDM techniques (GRA, TOPSIS and VIKOR) applied in this paper are explained. Section 4 presents an example that demonstrates practical applicability of proposed approach. In Sect. 5, results are discussed and managerial recommendations are provided. Finally, paper concludes with Sect. 6 that discusses conclusions and provides avenues for future work.

2 Literature review

This section discusses literature on facility location and application of MCDM techniques in facility location problems.

2.1 Introduction to remanufacturing

Remanufacturing is defined as "the process whereby value from old products is recovered by replacing and recovering used components to bring such products to a new or near-new state" (Lund 1983). It involves inspection of used products, disassembly, re-processing and testing, thus ensuring that the products meet the standards of new products (Östlin et al. 2009). Remanufacturing has drawn a lot of attention as it is environmentally sustainable (Guide Jr. 2000; Lu et al. 2014), and is the highest degree of product recovery method. It helps to reduce waste generation and extend product lifecycles (Kovach et al. 2018). Remanufacturing also has the potential for economic advantages and enhances the brand image of an organization (Martin et al. 2010). A number of original equipment manufacturers (OEMs) have started remanufacturing of products, owing to the potential competitive advantage that can be gained from its implementation. Many firms have started to implement remanufacturing operations to promote sustainability (Olugu and Wong 2012; Lu et al. 2014). Few firms that have implemented remanufacturing include Xerox, Caterpillar, HP, etc. (Akan et al. 2013). A number of products such as engines, cell phones, cameras, copiers, etc. are remanufactured (Guide Jr. and Van Wassenhove 2001; Demirel and Gökçen 2008) in North America. However, the concept of remanufacturing is new in developing nations such as India.

2.2 Facility location problem

Selection of the appropriate location for establishing a facility is a strategic decision (Tabari et al. 2008). The location decision of a remanufacturing plant can be categorized as a special case of facility location problem. It involves a set of alternatives that are evaluated against a set of criteria (Tabari et al. 2008; Awasthi et al. 2011). The alternative which performs the best with respect to all the criteria is finally chosen. A number of methods have been used in literature to handle facility location problems (Aikens 1985; Daskin 1997; Hamacher and Nickel 1998; Klose and Drexl 2005). A hybrid Taguchi–immune approach is proposed to optimize a supply chain design problem that involves multi shipping (Tiwari et al. 2010). A bilevel

programming model is used to decide the location of logistics distribution centers (Sun et al. 2008).

Few authors have considered multi criteria facility location models (Lee et al. 1981; Puerto and Fernandez 1999; Ross and Soland 1980; Erkut et al. 2008). Yoon and Hwang (1985a) employed five MCDM methods to select a site for a manufacturing plant location, with quantitative and qualitative data. In the extension of this work, the authors' presented techniques for location decision of multiple plant selection, when there are constraints on budget (Yoon and Hwang 1985b).

2.3 Facility location problem in fuzzy environment

It should be noted that above mentioned studies analyze the location problem in a certain scenario, i.e. a situation when parameters are known. However, parameters are not known with certainty during decision making. Fuzzy theory is integrated into process during such as situation (Carlsson and Fullér 1996; Anagnostopoulos et al. 2008). The authors have also used fuzzy theory to account for uncertainty and vagueness in information, for planning of location of facilities. Kahraman et al. (2003) used four fuzzy MCDM techniques to evaluate ideal sites for locating a facility. Liang and Wang (1991) proposed a decision algorithm for selection of facility site centered on fuzzy theory & hierarchical structure analysis. Chen (2001) proposed a fuzzy MCDM method for selection of suitable alternative for location of distribution center. Chou et al. (2008) proposed a fuzzy multi-attribute approach to select appropriate location of facility, with subjective/objective attributes. Chu (2002) proposed a fuzzy TOPSIS model under group decision making for selection of an appropriate facility. Yong (2006) applied TOPSIS for selection of manufacturing facility site, under uncertain environment. Recently, Temur (2016) proposed a novel cloud-based design optimization approach, that takes into consideration both certain and uncertain attributes, simultaneously.

The remanufacturing facility location problem has been studied by Alimoradi et al. (2011). The authors' applied TOPSIS technique to choose best alternative to establish a remanufacturing plant. However, authors' considered only four criteria in the framework that does not capture all the aspects. The location of a remanufacturing plant involves some distinct criteria such as availability of used products, proximity to collection centres, customer sensitivity to used products, proximity to customers of remanufactured products, proximity to original manufacturing facilities, etc. Besides these criteria, several other attributes need to be considered while deciding the suitable location of a remanufacturing plant, which have not been considered in any of the earlier studies to the best of authors' knowledge. This paper fills the same gap in literature and proposes a framework that considers 17 criteria for deciding the suitable location of a remanufacturing plant. Fuzzy theory is integrated with three ideal based solution MCDM techniques, TOPSIS, GRA and VIKOR, to evaluate the ideal candidate location of a remanufacturing plant. The integration of fuzzy theory helps to capture inherent imprecision and vagueness associated with the information provided by industry experts. An application has been presented in the context of Indian automotive sector to show practical applicability of proposed framework.

3 Methodology

In this section, we present the procedure used to achieve the desired objectives. MCDM techniques are most commonly applied when there are a set of conflicting criteria and the best alternative needs to be selected (Dwivedi et al. 2018). In this study, a combination of GRA, TOPSIS and VIKOR techniques is used to select best alternative for establishing a remanufacturing facility. Fuzzy theory is integrated with each of these techniques to account for the vagueness associated with the information provided by the experts (Wang and Hsu 2010; Han and Trimi 2018). The proposed framework for evaluation of remanufacturing plant location involves the following phases:

1. Identification and validation of evaluation criteria for location of a remanufacturing plant.
2. Evaluation of the alternatives for remanufacturing plant location by applying fuzzy GRA, fuzzy TOPSIS and fuzzy VIKOR techniques, using the inputs from the industry experts.
3. Selection of the best candidate using the veto rule (candidate which is ranked as best by the most number of techniques is selected).
4. Perform sensitivity analysis (Effect of change in weights of criteria on final outcome).

The steps of the proposed framework are discussed in detail below:

3.1 Identification and validation of criteria for location

Firstly, evaluation criteria for selection of a remanufacturing plant location are identified from the comprehensive literature review (Coelho and Mateus 2017; Yang and Lee 1997; Yong 2006; Farahani et al. 2010; Ferdows 1997; Ferrer and Ayres 2000; Guide Jr. 2000; Martin et al. 2010; Lu et al. 2014). In total, 17 criteria are identified and subsequently, discussed with the industry experts. These criteria are: initial investment (A1), governmental financial support (A2), transportation costs (A3), proximity to customers of remanufacturing facility (A4), possibility of expansion (A5), availability of renewable energy source (A6), environmental impact (A7), regulations/Norms to take back used product (A8), customer sensitivity for remanufactured products (A9), logistical capabilities (A10), availability of used products (A11), proximity to suppliers (A12), proximity to original manufacturing facilities (A13), technical feasibility (A14), proximity to collection centers (A15), availability of skilled labor (A16), and connectivity to multimodal transport (A17). The criteria are categorized into the following four categories: economic, environmental, social and resource.

The criteria A1, A3, A7 and A8 are cost (C) criteria, i.e. the lower value of these criteria is beneficial for the location of remanufacturing plant. The criteria, A2, A4–A6 and A9–A17, are beneficial (B) criteria, i.e. the higher value of these criteria is favorable for the location of remanufacturing plant. The list of criteria and sub-criteria is presented in Table 1.

3.2 Evaluation of alternatives for location of remanufacturing plant

This step involves the evaluation of available alternatives for location of a remanufacturing facility. The linguistic ratings are given by experts to criteria and alternatives, and ratings are transformed to triangular fuzzy number (TFN) with the aid of the conversion scale,

Table 1 Criteria for selection of remanufacturing facility location

Criteria	Sub-criteria	Category
Economic	Initial investment (A1)	C
	Governmental financial support (A2)	B
	Transportation costs (A3)	C
	Proximity to customers of remanufactured products (A4)	B
	Possibility of expansion (A5)	B
Environmental	Availability of renewable energy source (A6)	B
	Environmental impact (A7)	C
Social	Regulations/Norms to take back used product (A8)	C
	Customer sensitivity for remanufactured products (A9)	B
Resource	Logistical capabilities (A10)	B
	Availability of used products (A11)	B
	Proximity to suppliers (A12)	B
	Proximity to original manufacturing facilities (A13)	B
	Technical feasibility (A14)	B
	Proximity to collection centers (A15)	B
	Availability of skilled labor (A16)	B
	Connectivity to multimodal transport (A17)	B

C cost criteria, *B* benefit criteria

Table 2 Linguistic terms for alternatives ratings

| Linguistic rating	Membership function
VP—Very poor	(1, 1, 3)
P—Poor	(1, 3, 5)
F—Fair	(3, 5, 7)
G—Good	(5, 7, 9)
VG—Very good	(7, 9, 9)

given in Tables 2 and 3. The alternatives for the location of remanufacturing plant are then evaluated using the following three MCDM techniques: fuzzy GRA, fuzzy TOPSIS and fuzzy VIKOR. The following section describes fuzzy set theory and MCDM techniques applied in this study.

3.2.1 Fuzzy set theory

Fuzzy set theory is applied as it takes into consideration the uncertainty and vagueness that arises due to incomplete information in any decision making process (Zadeh 1965). It uses linguistic terms to signify the inputs provided by the decision makers. Fuzzy theory is useful where appropriate model parameters cannot be judged and requires judgments of experts. For example, the chances that India will win the upcoming game against Australia can be represented as low, high, etc.

Table 3 Linguistic terms for criteria ratings

Linguistic rating	Membership function
VL—Very low	(1, 1, 3)
L—Low	(1, 3, 5)
M—Medium	(3, 5, 7)
H—High	(5, 7, 9)
VH—Very high	(7, 9, 9)

Fig. 1 TFN $\tilde{q}$
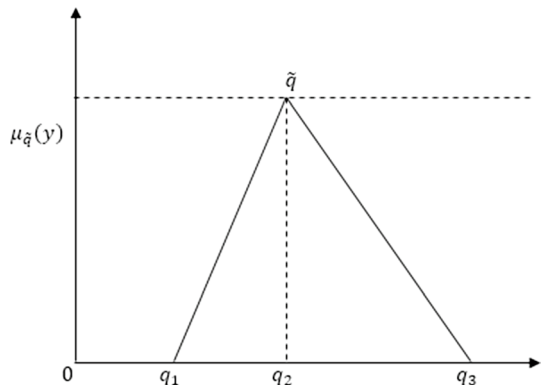
TFNs are widely applied in a number of practical applications, due to their conceptual and computation simplicity (Pedrycz 1994; Klir and Yuan 1995; Yeh and Deng 2004). A TFN is denoted as $\tilde{q} = (q_1, q_2, q_3)$. Figure 1 represents a TFN $\tilde{q}$. The membership function $\mu_{\tilde{q}}(y)$ of a TFN $\tilde{q}$ is given by:

$$\mu_{\tilde{q}} = \begin{cases} 0, & y \leq q_1 \\ \frac{y - q_1}{q_2 - q_1}, & q_1 \leq y \leq q_2 \\ \frac{q_3 - y}{q_3 - q_2}, & q_2 \leq y \leq q_3 \\ 0, & y \geq q_3 \end{cases}$$

q_1, q_2, q_3 are real numbers and, $q_1 < q_2 < q_3$

The value of $\mu_{\tilde{q}}(y)$ is maximum when $y = q_2$, and is equal to 1. The value is minimum at $y = q_1$ and is equal to 0. The values q_1 and q_3 represent the lower and upper values of a TFN. These values indicate fuzziness of the evaluation data (Liang 1999). The following outlines the steps involved.

Firstly, assume that there are p available alternatives (candidate locations for remanufacturing plants), represented as $M = \{M_1, M_2, \ldots, M_p\}$, and a set of q criteria, $N = \{N_1, N_2, \ldots, N_q\}$. The fuzzy ratings given by expert $E_k(k = 1, 2, \ldots, k)$, for each alternative with reference to criteria $N_j(j = 1, 2, \ldots, q)$ are denoted by $\tilde{x}_{ij}^k$.

where

$$\tilde{R}_k = \tilde{x}_{ij}^k = \left(\tilde{a}_{ij}^k, \tilde{a}_{ij}^k, \tilde{a}_{ij}^k \right), \quad i = 1, 2, \ldots, p; k = 1, 2, \ldots, q; \mu_{\tilde{R}_k}(x) : \text{ membership function}$$

The aggregate fuzzy ratings of alternatives are calculated as:

$$\tilde{x}_{ij} = \frac{1}{K} \sum_{k=1}^{K} \tilde{x}_{ij}^k, \quad i = 1, 2, \ldots, p; j = 1, 2, \ldots, q$$

where

$$x_{ij} = \frac{a_{ij} + 4b_{ij} + c_{ij}}{6}.$$

Let $\tilde{w}_j^k = \left(a_j^k, b_j^k, c_j^k\right)$ represents the fuzzy weight given to criteria by expert $E_k(k = 1, 2, \ldots, k)$.

The aggregate fuzzy weight of criteria is calculated as follows:

$$\tilde{w}_j = \frac{1}{K} \sum_{k=1}^{K} \tilde{w}_j^k, \quad j = 1, 2, \ldots, q$$

where $w_j = \frac{a_{ij} + 4b_{ij} + c_{ij}}{6}$.

The decision matrix is given as follows:

$$D = \begin{array}{c} \\ M_1 \\ M_2 \\ \vdots \\ \vdots \\ M_p \end{array} \begin{array}{c} N_1 \ N_2 \ \cdots \ \cdots \ N_q \\ \left[\begin{array}{ccccc} x_{11} & x_{12} & \cdots & \cdots & x_{1q} \\ x_{21} & x_{22} & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ \vdots & \vdots & \cdots & \cdots & \vdots \\ x_{p1} & x_{p2} & \cdots & \cdots & x_{pq} \end{array} \right] \end{array}$$

$W = \left(w_1, w_2, \ldots, w_q\right).$

The next step involves calculation of overall scores of alternatives using the MCDM techniques.

3.2.2 Ideal solution based MCDM techniques

In this paper, ideal solution based MCDM techniques (GRA, VIKOR and TOPSIS) are applied to evaluate best candidate to establish a remanufacturing facility. The techniques vary by the means the total score is calculated. Each of these techniques is discussed in detail below:

3.2.2.1 Fuzzy TOPSIS Fuzzy TOPSIS is a multi-criteria compromise decision technique that uses a distance measure to select the most efficient solution from a set of available alternatives (Hwang and Yoon 1981). It selects that alternative which is at a minimum distance from the positive ideal solution (PIS) and at a maximum distance from the negative ideal solution (NIS) (Prakash and Barua 2015; Singh et al. 2017). The fuzzy TOPSIS technique involves the following steps:

Step 1: Defuzzification of TFN for criteria and alternatives

Step 2: Normalization of decision matrix (R)

$$R = \left[r_{ij}\right]_{m \times n}, \quad i = 1, 2, \ldots, p; j = 1, 2, \ldots, q, \text{ where}$$

$$r_{ij} = \frac{x_{ij} - Min\{x_{ij}, i = 1, 2, \ldots, p\}}{Max\{x_{ij}, i = 1, 2, \ldots, p\} - Min\{x_{ij}, i = 1, 2, \ldots, p\}}, \quad \forall j = 1, 2, \ldots, q$$

$$r_{ij} = \frac{Max\{x_{ij}, i = 1, 2, \ldots, p\} - x_{ij}}{Max\{x_{ij}, i = 1, 2, \ldots, p\} - Min\{x_{ij}, i = 1, 2, \ldots, p\}}, \quad \forall j = 1, 2, \ldots, q$$

Step 3: Computation of weighted normalized matrix

$$V = \left[v_{ij}\right]_{m \times n}, \quad i = 1, 2, \ldots, p; j = 1, 2, \ldots, q \text{ where } v_{ij} = r_{ij}(.)w_j$$

Step 4: Computation of the positive ideal solution (PIS) and the negative ideal solution (NIS) for each criterion:

$$A^* = \left(v_1^*, v_2^*, \ldots, v_q^*\right) \text{ where } v_j^* = \left\{\left(\max\{v_{ij}\}/j \in J^*\right), \left(\min\{v_{ij}\}/j \in J^-\right)/i = 1, 2, \ldots, p\right\}$$

$$A^- = \left(v_1, v_2, \ldots, v_q\right) \text{ where } v_j^- = \left\{\left(\min\{v_{ij}\}/j \in J^*\right), \left(\max\{v_{ij}\}/j \in J^-\right)/i = 1, 2, \ldots, p\right\}$$

J^-: set of cost criteria

J^*: set of benefit criteria

Step 5: Computation of the distance (d_i^*, d_i^-) of each alternative from NIS and PIS:

$$d_i^- = \sum_{j=1}^{q} d_v\left(v_{ij}, v_j^-\right), \quad i = 1, 2 \ldots, p$$

$$d_i^* = \sum_{j=1}^{q} d_v\left(v_{ij}, v_j^*\right), \quad i = 1, 2 \ldots, p$$

$d_v(c, d)$: distance between two crisp numbers y and z

$$d_v\left(\tilde{c}, \tilde{d}\right) = \sqrt{1/3\left[\left(c_1 - d_1\right)^2 + \left(c_2 - d_2\right)^2 + \left(c_3 - d_3\right)^2\right]}$$

Step 6: Calculation of the closeness coefficient $\left(CC_i\right)$ of each alternative

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}, \quad i = 1, 2, \ldots, p$$

Step 7: Ranking of alternatives

Finally, alternatives are ranked in accordance with CC_i values in decreasing order.

3.2.2.2 Fuzzy VIKOR The fuzzy VIKOR approach is a compromise ranking method that "measures the closeness of the alternatives with respect to the positive ideal solution" (Opricovic [1998]). The steps involved in this approach are given in detail below:

Step 1: Defuzzification of fuzzy decision matrix
Step 2: Determining the best f_j^* and the worst values f_j^- of all criteria ratings $j = 1, 2, \ldots, q$

$$f_j^* = \max_i \left\{ x_{ij} \right\}$$

$$f_j^- = \min_i \left\{ x_{ij} \right\}$$

Step 3: Calculate the values of S_i and R_i by:

$$S_i = \sum_{j=1}^{q} w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-}$$

$$R_i = \max_j w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-}$$

Step 4: Calculate the values of Q_i:

$$Q_i = v \frac{S_i - S^*}{S^- - S^*} + (1 - v) \frac{R_i - R^*}{R^- - R^*}$$

where $S^* = \min_i S_i$; $R^* = \min_i R_i$; $S^- = \max_i S_i$; $R^- = \max_i R_i$
v = weight for the strategy of maximum group utility; $(1 - v)$ = weight of the individual regret
Step 5: Ranking of alternatives
In this step, values, S, R and Q are sorted in the ascending order.
Step 6: Propose as a compromise solution the alternative (p′).

3.2.2.3 Fuzzy GRA GRA technique analyzes the similarity between the alternative and the ideal alternative (reference sequence), and generates the alternative rankings (Deng [1982]). The alternative that is closest to the ideal alternative is most preferred. The following outlines the steps involved in fuzzy GRA approach:

Step 1: Normalization of data
Here, raw data is normalized to bring it to a comparable scale. The data is normalized using the following equations:

$$\tilde{r}_{ij} = \frac{x_{ij} - Min\left\{x_{ij}, i = 1, 2, \ldots, m\right\}}{Max\left\{x_{ij}, i = 1, 2, \ldots, m\right\} - Min\left\{x_{ij}, i = 1, 2, \ldots, m\right\}}, \quad \forall j = 1, 2, \ldots, n$$

$$\tilde{r}_{ij} = \frac{Max\{x_{ij}, i = 1, 2, \dots, m\} - x_{ij}}{Max\{x_{ij}, i = 1, 2, \dots, m\} - Min\{x_{ij}, i = 1, 2, \dots, m\}}, \quad \forall j = 1, 2, \dots, n$$

Step 2: Calculation of reference values for normalized criteria.

The reference values $X_0 = (x_{01}, x_{02}, \dots, x_{0j}, x_{0n})$ comprise the ideal value for each criterion. It is the highest value for the benefit criteria and lowest value for the cost criteria. The objective is to find that alternative which has its comparability values closest to reference values.

Step 3: Calculation of grey relational coefficient $(\gamma(x_{0j}, x_{ij}))$

The $\gamma(x_{0j}, x_{ij})$ between x_{ij} and x_{0j} is calculated to determine the closeness of x_{ij} to x_{0j}. The larger the $\gamma(x_{0j}, x_{ij})$, the closer x_{ij} and x_{0j} are. The $\gamma(x_{0j}, x_{ij})$ is calculated as:

$$\gamma(x_{0j}, x_{ij}) = \frac{\Delta_{min} + \xi \Delta_{max}}{\Delta_{ij} + \xi \Delta_{max}} \quad \forall i = 1, 2, \dots, m; \ j = 1, 2, \dots, n$$

where

$$\Delta_{ij} = |x_{oj} - x_{ij}|$$

$$\Delta_{min} = Min\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

$$\Delta_{max} = Max\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

ξ: distinguishing coefficient, $\xi \in [0, 1]$

Step 4: Calculation of the grey relational grade $(\Gamma(X_0, X_i))$

$$\Gamma(X_0, X_i) = \sum_{j=1}^{n} w_j \gamma(x_{0j}, x_{ij}), \quad i = 1, 2, \dots, m$$

w_j: weight of attribute j

$$\sum_{j=1}^{n} w_j = 1$$

Step 5: The alternative with highest value of $\Gamma(X_0, X_i)$ is selected as an ideal candidate.

3.3 Selection of the best alternative

In this phase, applying the veto rule, best alternative is chosen using the rankings obtained by MCDM techniques in step 2 (GRA, TOPSIS and VIKOR), and veto rule. According to the veto rule, the alternative which is rated as the best by the most number of techniques is selected as an ideal alternative for the location of a remanufacturing plant. In case, no majority is found, other measures can be used to select best alternative.

3.4 Sensitivity analysis

Sensitivity analysis answers the following question: "How sensitive is the overall decision to small changes in the individual weights assigned during the pair-wise comparison process?" (Awasthi et al. 2010). It is carried out by doing variation in weights of criteria and analyze the effect on the final outcome. This process is useful in the conditions when there is an uncertainty in the importance of the criteria. In our analysis, we change the weights of criteria used for deciding the remanufacturing plant location and analyze the effect on final location decision of remanufacturing plant. The proposed framework is demonstrated in Fig. 2.
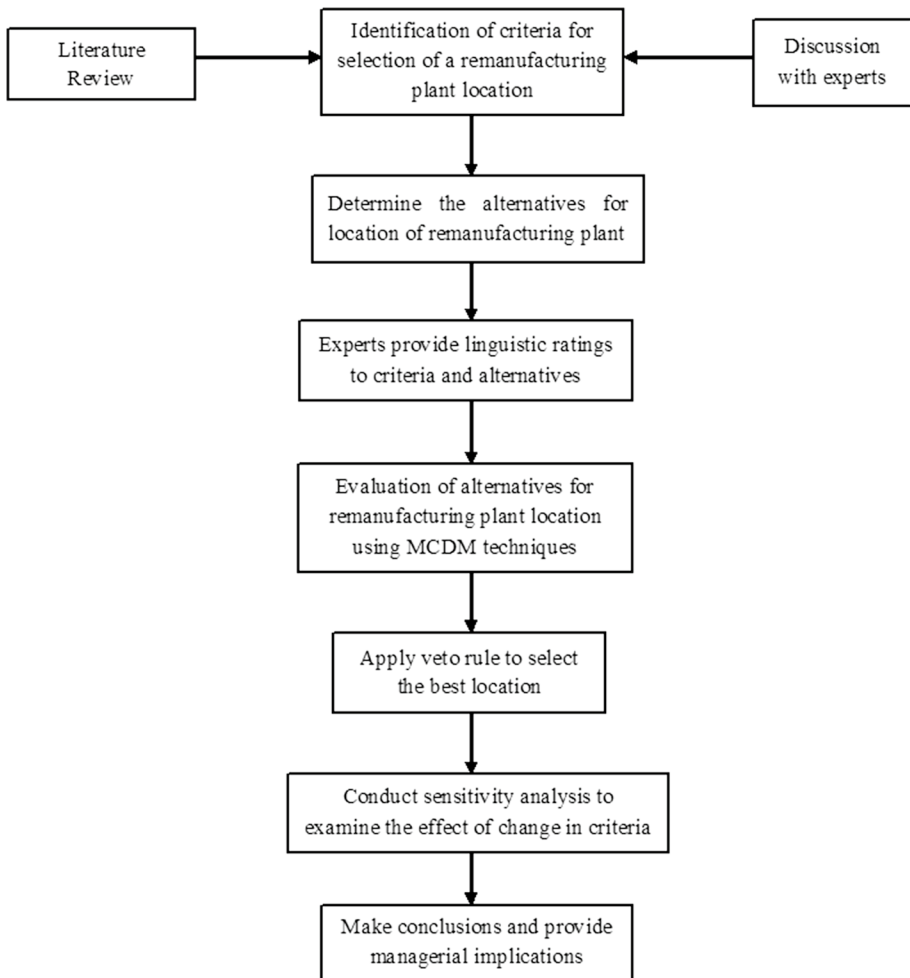

Fig. 2 Proposed framework of our study

4 An application

In this section, an application in the Indian automotive sector is presented using the proposed framework to evaluate the most suitable location to establish a remanufacturing plant.

In India, the quest for ownership of personal vehicles has increased and is expected to double or even triple by year 2030. In year 2017, India was the fourth largest automobile producer in the world. In the financial year (FY) 2018, sales of the passenger vehicles registered a growth of nearly 8% and is expected to grow at the same rate in the coming years. Indian automobile industry is also a major exporter, and exports grew by nearly 17% in the FY 2018. Several organizations are currently investing in the Indian automobile sector. Thus, to keep up the sustainable development, organizations will need to adopt remanufacturing practices and establish remanufacturing plants soon.

In India, the automotive industry is mostly developed in the form of clusters. The reasons for the same as availability of technical know-how, skilled labor and logistical resources at the same place. Moreover, a synergetic association prevails among the component suppliers, manufacturers and related support organizations. Presently there exists three major automotive clusters in India. These are shown in Fig. 3.

Cluster 1: Delhi NCR Region (L1)
Cluster 2: Chennai-Bangalore Region in South India (L2)
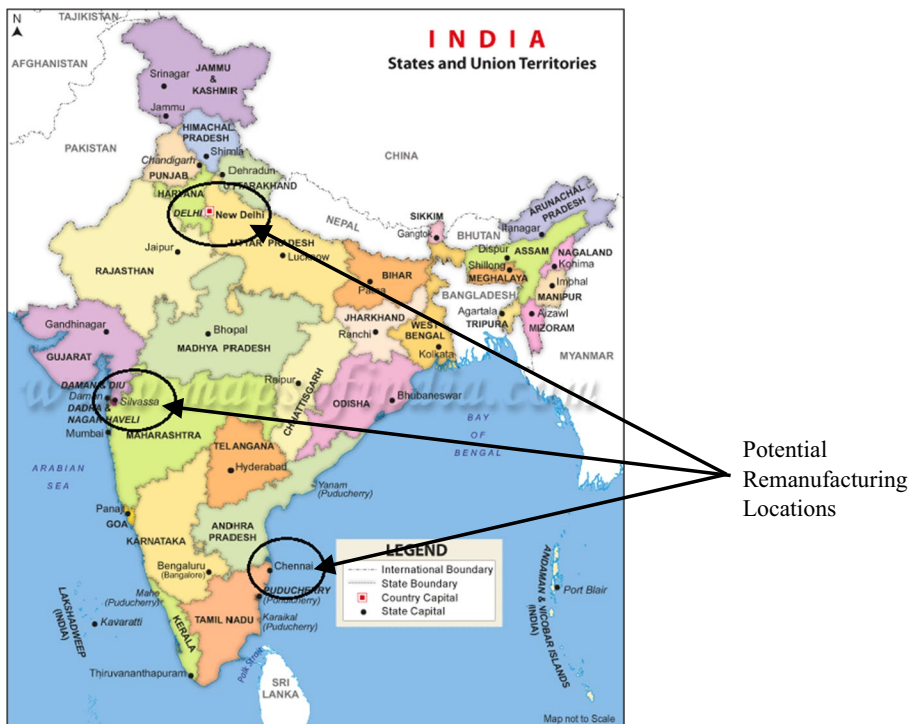*Cluster 3:* Mumbai-Pune-Nasik-Silvassa Region in West India (L3)

Fig. 3 Potential alternatives for establishing a remanufacturing plant

Table 4 Profile of experts

No.	Position	Department	Experience (years)
1	Manager	Maintenance and repair	15
2	Technical engineer	Production	6
3	Product development executive	Design	9
4	Service engineer	Post sales service	7
5	Production executive	Production	14

Cluster 1 is recognized as biggest producer of cars, two wheelers and tractors. It has plants of big manufacturing companies such as Maruti Suzuki (Market leader for passenger cars), largest two-wheeler manufacturer in world Hero Honda, Yamaha and Escorts are also present in this area. There are more than 100 large to medium size component suppliers and manufacturers situated in Cluster 2. It produces more than 30% of four wheelers and 35% of part supplied in India. Cluster 3 enjoys the availability of good logistic infrastructure due to availability of large ports, big highways, uninterrupted power supply and skilled labors. Moreover, it is centrally located and well connected to all parts of the country. As there is symbiotic relationship between original manufacturing and remanufacturing facilities, we have considered three potential remanufacturing locations namely Delhi (L1), Chennai (L2) and Silvassa (L3) at these three respective clusters.

An automobile organization XYZ has three alternatives (L1, L2 and L3) for opening a remanufacturing plant. A committee of five experts (EX1, EX2, EX3, EX4 and EX5) is formed to evaluate the alternatives available for establishing a remanufacturing plant. The experts are from different departments of the organization and have vast experience in their respective fields. The experts are highly knowledgeable about the remanufacturing operations. The profile of experts is provided in Table 4. The linguistic ratings provided by experts to criterion are provided in Table 5.

The final relative weights of each category of criteria and global weights of each sub-criteria are presented in Table 6. Economic criteria hold the highest rank among the category of criteria, with the relative weight of 0.306, followed by resource and environmental criteria. Social criteria hold the least importance among the categories of criteria. Criteria A7 holds the most importance, followed by the criteria A9 and A6.

The final crisp ratings of alternatives for each criterion are shown in Table 7. The final rankings obtained using the three MCDM techniques are demonstrated in Table 8. The first row shows the ranking obtained by using fuzzy TOPSIS method. L2 is the most preferable alternative, followed by L1, based on CC_i value. The second row shows the ranking obtained by applying the fuzzy GRA approach. Based on the values of grey relational grades, L1 is the most preferred location for opening a remanufacturing facility, followed by L3. The third row shows the rankings obtained by applying the fuzzy VIKOR technique. Alternatives L2 and L3 are equally preferred, followed by L1. Using the veto rule, L2 is preferred most number of times and thus, chosen as an ideal location for establishing a remanufacturing facility.

Finally, sensitivity analysis is done to assess the change in final outcomes with variation in the weights of criteria. The results are sensitive if final outcome changes as the weights of criteria are changed, otherwise they are robust. In total, 22 experiments are

Table 5 Linguistic ratings for criteria considered for location of a remanufacturing plant

Criteria		Inputs from experts				
		EX1	EX2	EX3	EX4	EX5
Economic		VH	VH	VH	VH	VH
	A1	H	H	H	M	H
	A2	VH	VH	VH	VH	VH
	A3	M	M	M	M	H
	A4	VH	H	M	M	H
	A5	H	VH	VH	VH	VH
Environmental		H	M	H	H	H
	A6	H	M	H	M	M
	A7	H	H	H	H	H
Social		M	M	M	M	M
	A8	M	M	M	M	M
	A9	VH	VH	VH	H	VH
Resource		VH	H	VH	H	VH
	A10	M	M	H	H	M
	A11	VH	VH	VH	VH	VH
	A12	M	M	L	VL	L
	A13	M	M	M	M	M
	A14	VH	H	VH	H	H
	A15	VH	VH	VH	VH	H
	A16	M	H	H	H	H
	A17	M	H	VH	VH	VH

performed in this phase of research. Table 9 shows the results obtained by performing the sensitivity analysis. Based on the rankings obtained by using three techniques, and subsequently applying veto rule, L3 (14 votes, 64%) is the most preferred location for establishing a remanufacturing facility, followed by L2 (7 votes). L1 is the least preferable location for establishing a remanufacturing facility. Thus, it can be concluded that proposed approach is robust & is relatively insensitive to change in weights of criteria.

5 Discussion and managerial implications

5.1 Discussion of results

There are several key findings that emerge from this study. Firstly, economic category holds the first position among the category of criteria considered for location of a remanufacturing plant. In the economic category, governmental financial support (A2) has the highest importance followed by possibility of expansion (A5). Thus, firms regard financial support from government as a crucial factor as establishing a facility involves huge initial investments. Firms also consider possibility of expansion as crucial because in next few years, as the customers become aware about sustainable development, product return rates may increase and thus remanufacturing facilities may need expansion.

Table 6 Aggregate weights of criteria considered for location of remanufacturing plant

Categories	Relative weights	Criteria	Relative weights	Global weights
Economic	0.306			
		A1	0.186	0.057
		A2	0.244	0.075
		A3	0.152	0.047
		A4	0.184	0.056
		A5	0.234	0.072
Environmental	0.234			
		A6	0.453	0.106
		A7	0.547	0.128
Social	0.177			
		A8	0.375	0.066
		A9	0.625	0.111
Resource	0.283			
		A10	0.109	0.031
		A11	0.163	0.046
		A12	0.065	0.018
		A13	0.094	0.026
		A14	0.144	0.041
		A15	0.157	0.044
		A16	0.124	0.035
		A17	0.143	0.040

Table 7 Aggregate crisp ratings of the alternatives for each criteria

Criteria	Alternatives		
	L1	L2	L3
A1	6.932	8.66	5
A2	5.8	6.2	6.864
A3	6.2	7.664	5.8
A4	8.328	8.328	5
A5	7.332	5	8.328
A6	5	6.6	8.66
A7	7.332	6.6	5.4
A8	5.4	5	5
A9	5.4	7.664	5
A10	5	7.996	7.332
A11	8.66	8.66	5
A12	5	5.4	5.8
A13	5.4	5.8	8.328
A14	5.4	5.8	7.664
A15	7.996	7.664	5
A16	7	6.864	7.996
A17	5.4	8.66	7

Table 8 Rankings of the alternatives

	L1	L2	L3	Alternate ranking	Preferable location
Fuzzy TOPSIS	CC_i	0.490	0.571	0.433	L2 > L1 > L3	L2
Fuzzy GRA	$\Gamma(X_0, X_i)$	0.697	0.545	0.660	L1 > L3 > L2
Fuzzy VIKOR	S_i	0.719	0.467	0.285	L2 = L3 > L1
	R_i	0.128	0.080	0.111
	Q_i	1	0.209	0.323

Table 9 Sensitivity analysis

No.	Experiment	Fuzzy VIKOR	Fuzzy GRA	Fuzzy TOPSIS	Preferred location
1	$W_{A1}=1; W_{A2-A17}=0$	L3 > L1 > L2	L3 > L1 > L2	L2 = L3 > L1	L3
2	$W_{A2}=1; W_{A1, A3-A17}=0$	L3 > L2 > L1	L1 > L2 > L3	L3 > L2 > L1	L3
3	$W_{A3}=1; W_{A1-A2, A4-A17}=0$	L3 > L1 > L2	L3 > L1 > L2	L2 > L1 > L3	L3
4	$W_{A4}=1; W_{A1-A3, A5-A17}=0$	L1 = L2 > L3	L3 > L1 = L2	L1 = L2 > L3	L1 = L2
5	$W_{A5}=1; W_{A1-A4, A6-A17}=0$	L1 = L3 > L2	L2 > L1 > L3	L3 > L1 > L2	L3
6	$W_{A6}=1; W_{A1-A5, A7-A17}=0$	L3 > L2 > L1	L1 > L2 > L3	L3 > L2 > L1	L3
7	$W_{A7}=1; W_{A1-A6, A8-A17}=0$	L3 > L2 > L1	L3 > L2 > L1	L1 > L2 > L3	L3
8	$W_{A8}=1; W_{A1-A7, A9-A17}=0$	L2 = L3 > L1	L2 = L3 > L1	L1 > L2 = L3	L2 = L3
9	$W_{A9}=1; W_{A1-A8, A10-A17}=0$	L2 > L1 > L3	L3 > L1 > L2	L3 > L1 > L2	L3
10	$W_{A10}=1; W_{A1-A9, A11-A17}=0$	L2 = L3 > L1	L1 > L3 > L2	L2 > L3 > L1	L2
11	$W_{A11}=1; W_{A1-A10, A12-A17}=0$	L1 = L2 > L3	L3 > L1 = L2	L1 = L2 > L3	L1 = L2
12	$W_{A12}=1; W_{A1-A11, A13-A17}=0$	L3 > L2 > L1	L1 > L2 > L3	L3 > L2 > L1	L3
13	$W_{A13}=1; W_{A1-A12, A14-A17}=0$	L3 > L2 > L1	L1 > L2 > L3	L3 > L2 > L1	L3
14	$W_{A14}=1; W_{A1-A13, A55-A17}=0$	L3 > L2 > L1	L1 > L2 > L3	L3 > L2 > L1	L3
15	$W_{A15}=1; W_{A1-A14, A16-A17}=0$	L1 = L2 > L3	L3 > L2 > L1	L1 > L2 > L3	L1
16	$W_{A16}=1; W_{A1-A15, A17}=0$	L3 > L1 > L2	L2 > L1 > L3	L3 > L1 > L2	L3
17	$W_{A17}=1; W_{A1-A16}=0$	L2 > L3 > L1	L1 > L3 > L2	L2 > L3 > L1	L2
18	Economic	L3 > L1 > L2	L3 > L1 > L2	L2 > L3 > L1	L3
19	Environmental	L3 > L2 > L1	L3 > L1 > L2	L1 > L2 > L3	L3
20	Social	L2 > L3 > L1	L3 > L1 > L2	L2 > L1 > L3	L2
21	Resource	L2 > L3 > L1	L1 > L3 > L2	L2 > L3 > L1	L2
22	Equal weights	NA	L1 > L3 > L2	L2 > L3 > L1	–

Resource category has the second highest importance among the category of criteria. For smooth running of any manufacturing facility, availability of appropriate resources is must. Our findings show that managers give due importance to availability of resources. Availability of used products (A11) is considered as the most important resource criteria. As remanufacturing operations depend on the availability of used products, there need to be adequate number of used products available, so that firms are able to recover value from used products and earn economic benefits. Proximity to collection centers (A15) and technical feasibility (A14) are the other important resource criteria. If remanufacturing facilities are located closer to collection centers, it is easier and quicker to get the used products.

Further, as remanufacturing operations depend on the condition of used products (Beamon and Fernandes 2004) and skill intensive (Ferrer and Ayres 2000), technical resource feasibility is given due importance.

Environmental category is considered as the third important for location of a remanufacturing plant. In this category, environmental impact (A7) has the highest importance. Social category has the lowest importance among all the categories. In social category, customer sensitivity for remanufactured products (A9) is the most important criteria. If customers have sensitivity for remanufactured products in the region where remanufacturing facility is located, firms can get more number of used products for processing and subsequently, sell the refurbished/remanufactured products. From an overall perspective, environmental impact (A7) is the most important criteria for consideration of location of remanufacturing plant. Customer sensitivity for remanufactured products (A9) holds the second position and availability of renewable energy source (A6) is the third most important criteria.

From economic and environmental perspective, alternative L3 is rated as a better location than L1 and L2, whereas from social and resource perspective, alternative L2 is rated as a superior location over L1 and L3. From an overall perspective (economic, environmental, social and resource category), L3 (14 votes) is the most preferable location for establishing a remanufacturing facility. L2 (7 votes) is the second most preferable location and L1 (2 votes) is least preferable.

5.2 Managerial implications

Several managerial implications emerge from this study. Firstly, the managers can use the framework proposed in this study to evaluate ideal location for establishing a remanufacturing facility. Most often, it is challenging to define & measure environmental and social dimensions of sustainability. The present approach can be of immense help to decision makers as it incorporates vagueness of input data and also considers conflicting criteria.

For holistic evaluation of suitable location of remanufacturing plant, following four categories of criteria should be taken into consideration: economic, environmental, social and resource. The managers can vary the weights of categories of criteria according to their priorities. Since different MCDM techniques may yield different results, proposed approach has applied three MCDM techniques and chosen the alternative suggested by more than one technique, which has helped to overcome the limitation of using a single MCDM method (Awasthi et al. 2018). Hence, this approach yields more reliable results, if not entirely unbiased. Fuzzy theory has been integrated with three MCDM techniques that helps to deal with vagueness associated with information. The proposed approach can be extremely useful when there is lack of quantitative data or incomplete information. Sensitivity analysis can help managers to vary weights of criteria & analyze the stability of model.

6 Conclusions

In this paper, we evaluate the ideal candidate for location of a remanufacturing plant under fuzzy environment. The evaluation is done using three ideal solution based MCDM techniques, GRA, VIKOR and TOPSIS. Fuzzy theory is integrated with these techniques to consider vagueness and uncertainty in available information. The proposed methodology

comprises of three phases. In the first phase, criteria considered in the evaluation of location of remanufacturing plant are identified. The identified criteria are then validated by the industry experts. In the second phase, the experts give linguistic ratings to criteria and to alternatives of remanufacturing locations. Then, rankings of the alternatives are obtained using three MCDM techniques. The final step involves selection of the best alternative by applying the veto rule.

The proposed framework is useful for managers who are involved in the decision of choosing the appropriate location for establishing a remanufacturing facility. The managers who are planning to implement remanufacturing operations can use the criteria and subcriteria proposed in this study to make an informed decision. The benefit of using the proposed methodology is that evaluation of alternatives for location of remanufacturing plant can be done with limited or no quantitative information. Application of veto rule helps to overcome the limitation associated with the use of single MCDM method (Awasthi et al. 2018). The proposed approach can be used by organizations who are in the early phase or planning to implement remanufacturing operations.

The limitation of this approach is that it is based on the input of experts; thus, experts should be carefully chosen. Future research studies can include more number of criteria and results of this study can be compared with results obtained by using other MCDM methods. The model can be validated from results obtained by analyzing real data. This framework provides an example of a sustainable and design making tool with multistakeholder perspectives for industries as well as policy makers for location selection for remanufacturing. By applying appropriate remanufacturing location strategy, the issue of resource scarcity can be addresses and subsequently, advance sustainable development and achieve SDGs.

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