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Evaluation of Production Facilities in a Closed-Loop Supply Chain: A Fuzzy TOPSIS Approach

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ABSTRACT

It has become common for manufacturing facilities involved in production of new products to also carry out collection and re-processing of used products. While environmental consciousness has become an obligation to the facilities in the production of new products due to governmental regulations and public perspective on environmental issues, potentiality of the facilities to re-process used products directly affects the profitability of the facilities. Although many papers in the literature deal with performance evaluation of facilities, none of them address these two factors. To this end, a TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) approach, which evaluates production facilities in terms of both environmental-consciousness and potentiality, is proposed. Furthermore, since most of the criteria that fall under these two factors are intangible, triangular fuzzy numbers (TFNs) are employed to rate them in the evaluation process. A numerical example demonstrates the feasibility of the proposed method.

Keywords: Closed-Loop Supply Chain, Fuzzy Sets, TOPSIS, Environmental Consciousness and Potential.

1. MOTIVATION

Development of methods for producing new products from conceptual design to final delivery such that the environmental standards and requirements are satisfied, is what is suggested by environmental consciousness (EC). In the last decade, EC has become an obligation to many facilities in a forward supply chain (series of activities required to produce and distribute new products to customers), enforced primarily by governmental regulations and customer perspective on environmental issues [7]. At the same time, many of these facilities are driven, mainly by profitability [6], to administer another series of activities required to retrieve used products from consumers and re-process (recycle/remanufacture) them to recover their left-over market value. This second series is called a reverse supply chain. The combination of forward and reverse supply chains is called a closed-loop supply chain. A generic closed-loop supply chain is shown in Figure 1.

There are many papers in the literature, which propose how to design a supply chain [1], [6], [12], [13]. However, none of these papers address the issue of environmental consciousness in the forward supply chain. Furthermore, every model assumes that all the facilities that are engaged in the reverse supply chain have sufficient potential to efficiently re-process the incoming used products. Motivated by the risk of re-processing used products in facilities of insufficient potentiality, Pochampally and Gupta [9] and Pochampally et al. [10] proposed approaches that employ Analytic Hierarchy Process (AHP) [11] and Charnes-Cooper-Rhodes (CCR) model [3] respectively, to evaluate the potentiality of recovery facilities operating in a region where a reverse supply chain is to be designed. However, these approaches have two limitations:

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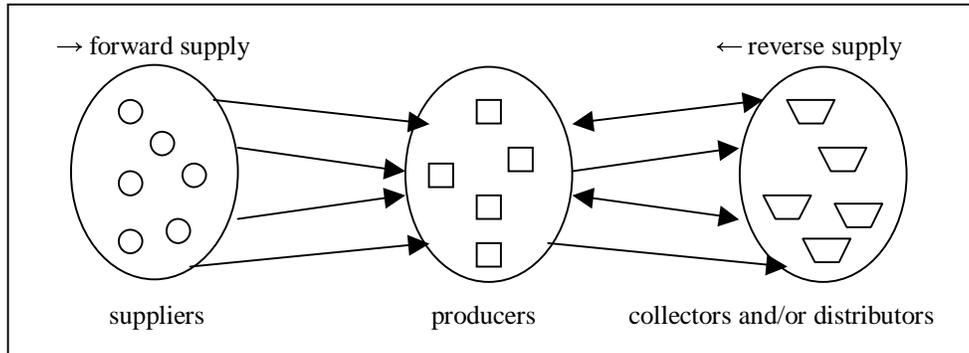


Figure 1. A Generic Closed-Loop Supply Chain

1. The facilities considered for evaluation, participate in only a reverse supply chain. (In practice, collection and re-processing of used-products are often carried out by the same parties that are involved in a forward supply chain [7]. So, it is obviously more desirable to develop an integrated model that evaluates production facilities dealing with both forward and reverse flows of products.)
2. It is assumed that the ratings assigned to the criteria for evaluation of facilities, are correct and certain. (In practice, instead of assumed-as-certain ratings, linguistic expressions – for example, “fair”, “satisfied”, “medium” – are regarded as the natural representation of the preference or judgment. This indicates the necessity for application of fuzzy set theory [17].)

In this paper, we take off with the above limitations in mind and propose a fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) approach [5], [15] to evaluate production facilities in a closed-loop supply chain, in terms of both EC (mainly associated with the forward supply chain) and potentiality (mainly associated with the reverse supply chain).

For the convenience of the reader, we first introduce the TOPSIS method [8] in Section 2. In Section 3, we introduce the basic concepts of fuzzy set theory [17], which we use in the TOPSIS method. Then, in Section 4, we present all the criteria that we consider for comparison of candidate facilities, and in Section 5, we present a numerical example to demonstrate the feasibility of the approach. Section 6 concludes the paper.

2. TOPSIS METHOD

The basic concept of the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method [14] is that the rating of the alternative selected as the best from a set of different alternatives, should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution in a geometrical (i.e., Euclidean) sense.

The TOPSIS method evaluates the following decision matrix, which refers to m alternatives that are evaluated in terms of n criteria:

Alternatives	Criteria				
	C_1	C_2	C_3	.....	C_n
	w_1	w_2	w_3	.....	w_n
A_1	z_{11}	z_{12}	z_{13}	.....	z_{1n}
A_2	z_{21}	z_{22}	z_{23}	.....	z_{2n}
A_3	z_{31}	z_{32}	z_{33}	.....	z_{3n}
.
.
.
A_m	z_{m1}	z_{m2}	z_{m3}	.....	z_{mn}

where A_i is the i th alternative, C_j is the j th criterion, w_j is the weight assigned to the j th criterion, and z_{ij} is the performance measure of the i th alternative in terms of the j th criterion.

The following steps are performed [14]:

Step 1: Construct the normalized decision matrix. This step converts the various dimensional measures of performance into non-dimensional attributes. An element r_{ij} of the normalized decision matrix R is calculated as follows:

$$r_{ij} = \frac{z_{ij}}{\sqrt{\sum_{i=1}^m z_{ij}^2}} \quad (1)$$

Step 2: Construct the weighted normalized decision matrix. A set of weights $W = (w_1, w_2, \dots, w_n)$ (such that $\sum w_j = 1$), specified by the decision-maker, is used in conjunction with the normalized decision matrix R to determine the weighted normalized matrix V defined by $V = (v_{ij}) = (r_{ij}w_j)$.

Step 3: Determine the ideal and the negative-ideal solutions. The ideal (A^*) and the negative-ideal (A^-) solutions are defined as follows:

$$A^* = \left\{ \left(\max_i v_{ij} \mid j \in J \right), \left(\min_i v_{ij} \mid j \in J' \right) \quad \text{for } i = 1, 2, 3, \dots, m \right\} \quad (2)$$

$$= \{p_1, p_2, p_3, \dots, p_n\}$$

$$A^- = \left\{ \left(\min_i v_{ij} \mid j \in J \right), \left(\max_i v_{ij} \mid j \in J' \right) \quad \text{for } i = 1, 2, 3, \dots, m \right\} \quad (3)$$

$$= \{q_1, q_2, q_3, \dots, q_n\}$$

where

$$J = \{j = 1, 2, \dots, n \mid j \text{ associated with benefit criteria}\} \text{ and}$$

$$J' = \{j = 1, 2, \dots, n \mid j \text{ associated with cost criteria}\}$$

With respect to benefit criteria, the decision maker desires to choose the alternative with the maximum rating. With respect to cost criteria, however, he desires to choose the alternative with the minimum rating. Obviously, A^* indicates the most preferable (ideal) solution. Similarly, A^- indicates the least preferable (negative-ideal) solution.

Step 4: Calculate the separation distances. In this step, the concept of the n -dimensional Euclidean distance is used to measure the separation distances of the rating of each alternative from the ideal solution and the negative-ideal solution. The corresponding formulae are

$$S_{i^*} = \sqrt{\sum (v_{ij} - p_j)^2} \quad \text{for } i = 1, 2, 3, \dots, m \quad (4)$$

where S_{i^*} is the separation (in the Euclidean sense) of the rating of alternative i from the ideal solution, and

$$S_{i^-} = \sqrt{\sum (v_{ij} - q_j)^2} \quad \text{for } i = 1, 2, 3, \dots, m \quad (5)$$

where S_{i^-} is the separation (in the Euclidean sense) of the rating of alternative i from the negative-ideal solution.

Step 5: Calculate the relative closeness to the ideal solution. The relative closeness of the rating of alternative A_i with respect to the ideal solution A^* is defined as follows:

$$C_{i^*} = \frac{S_{i^-}}{S_{i^*} + S_{i^-}} \quad (6)$$

Step 6: Rank the preference order. The best alternative can now be decided according to preference rank order of C_{i^*} . It is the one with the rating that has the shortest distance to the ideal solution. The way the alternatives are processed in the previous steps reveals that if an alternative has the rating with the shortest distance to the ideal solution, then that rating is guaranteed to have the longest distance to the negative-ideal solution.

3. FUZZY SET THEORY

The terms of expression like “not very clear”, “probably so” and “very likely” can be heard very often in daily life. The commonality in such terms is that they are more or less tainted with imprecision. This imprecision or vagueness of human decision-making is called “fuzziness” in the literature. With different decision-making problems of diverse intensity, the results can be misleading if fuzziness is not taken into account. However, since Zadeh [17] first proposed fuzzy set theory, an increasing number of studies have dealt with imprecision (fuzziness) in problems by applying the fuzzy set theory. Our paper too makes use of this theory in the employment of the TOPSIS method to evaluate production

facilities in a closed-loop supply chain. The concepts of the fuzzy set theory, which we utilize in this paper, are as follows:

3.1. Linguistic Values and Fuzzy Sets

When dealing with imprecision, decision-makers may be provided with information characterized by vague language such as: high risk, low profit and good customer service. By using *linguistic* values like “high”, “low”, “good”, “medium”, “cheap”, etc., people are usually attempting to describe factors with uncertain or imprecise values. For example, “weight” of an object may be a factor with an uncertain or imprecise value and so, its linguistic value can be “very low”, “low”, “medium”, “high”, “very high”, etc. The fuzzy set theory is primarily concerned with quantifying the vagueness in human thoughts and perceptions. The transition from vagueness to quantification is performed by applying the fuzzy set theory as depicted in Figure 2.

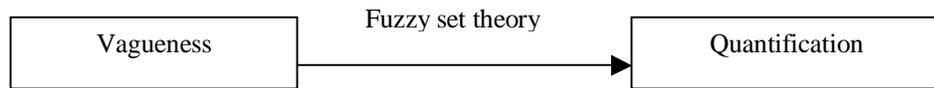


Figure 2. Application of Fuzzy Set Theory

To deal with quantifying vagueness, Zadeh proposed a membership function which associates with each quantified linguistic value a grade of membership belonging to the interval [0, 1]. Thus, a fuzzy set is defined as:

$$\forall x \in X, \mu_A(x) \in [0,1]$$

where $\mu_A(x)$ is the degree of membership, ranging from 0 to 1, of a quantity x of the linguistic value, A , over the universe of quantified linguistic values, X . X is essentially a set of real numbers. The more x fits A , the larger the degree of membership of x . If a quantity has a degree of membership equal to 1, this reflects a complete fitness between the quantity and the vague description (linguistic value). Whereas, if the degree of membership of a quantity is 0, then that quantity does not belong to the vague description.

The membership function can be viewed as an expert’s opinion. We use the term “expert” because an expert usually holds some required knowledge about relative problems while a layperson may not. For example, when a financial manager is asked what a “high annual interest rate” is, the possibility of 20% being “high annual interest rate” would be higher than that of 3%, 5% or 9%. Thus, the membership function, here, can be explained as the possibility of an interest rate being considered as “high”. A reasonable mapping from interest rate to its degree of membership about the fuzzy set “high annual interest rate” is depicted in Figure 3. This membership function looks like a typical cumulative probability function; however, here, the value of the membership function represents the possibility of a fuzzy event, while the value of a cumulative probability function represents the cumulative probability of a statistical event.

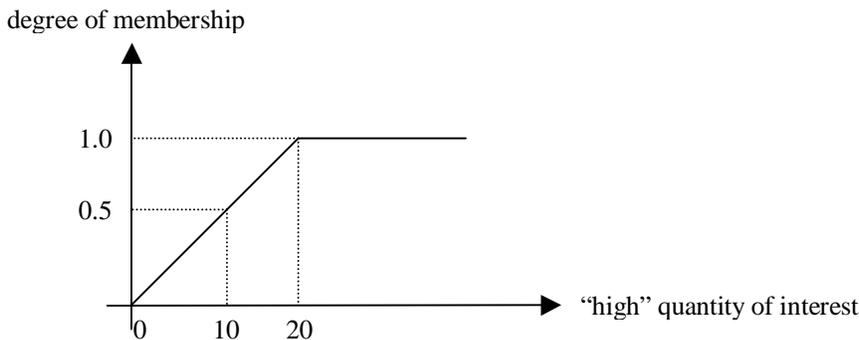


Figure 3. Mapping of Quantified “High” Interest Values to their Degrees of Membership

3.2. Triangular Fuzzy Numbers

A triangular fuzzy number (TFN) [16] is a fuzzy set with three parameters, each representing a quantity of a linguistic value associated with a degree of membership of either 0 or 1. It is graphically depicted in Figure 4. The parameters a , b and c respectively denote the smallest possible quantity, the most promising quantity and the largest possible quantity that describe the linguistic value.

Each TFN, P , has linear representations on its left and right side such that its membership function can be defined as:

$$\mu_P = 0, \quad x < a \quad (7)$$

$$= (x-a) / (b-a) \quad a \leq x \leq b \quad (8)$$

$$= (c-x) / (c-b) \quad b \leq x \leq c \quad (9)$$

$$= 0, \quad x \geq c. \quad (10)$$

For each quantity x increasing from a to b , its corresponding degree of membership linearly increases from 0 to 1. While x increases from b to c , its corresponding degree of membership linearly decreases from 1 to 0. The membership function is a mapping from any given x to its corresponding degree of membership.

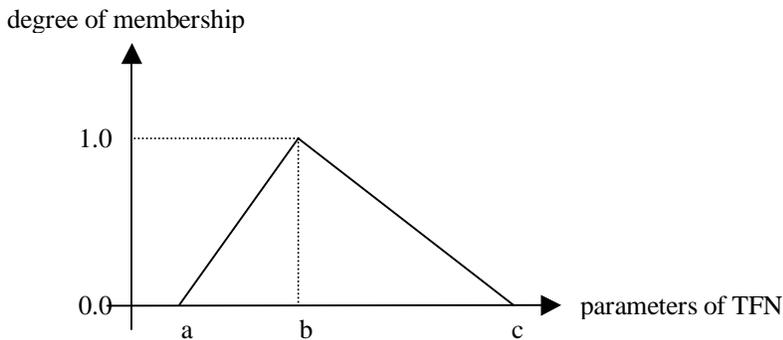


Figure 4. Triangular Fuzzy Number

The TFN is mathematically easy to implement, and more importantly, it represents the rational basis for quantifying the vague knowledge in most decision-making problems. Hence, we use TFNs only to quantify the vagueness of the performance measures, z_{ij} , in our TOPSIS approach (hence the name – fuzzy TOPSIS approach) to evaluate production facilities in a closed-loop supply chain. If a performance measure is precise, for consistency, we still represent that as a TFN whose all parameters are equal ($a = b = c$).

The basic operations on triangular fuzzy numbers are as follows [2], [4], [16]:

For example, $P_1 = (a, b, c)$ and $P_2 = (d, e, f)$.

$$P_1 + P_2 = (a+d, b+e, c+f) \quad \text{addition;} \quad (11)$$

$$P_1 - P_2 = (a-f, b-e, c-d) \quad \text{subtraction;} \quad (12)$$

$$P_1 * P_2 = (a*d, b*e, c*f) \text{ where } a \geq 0 \text{ and } d \geq 0 \quad \text{multiplication;} \quad (13)$$

$$P_1 / P_2 = (a/f, b/e, c/d) \text{ where } a \geq 0 \text{ and } d > 0 \quad \text{division.} \quad (14)$$

3.3. Defuzzification

Defuzzification is a technique to convert a fuzzy number into a crisp real number. There are several methods to serve this purpose [15]. For example, the Centre-of-Area method [18] converts a fuzzy number $P = (a, b, c)$ into a crisp real number Q where

$$Q = \frac{(c-a) + (b-a)}{3} + a \quad (15)$$

Defuzzification might become necessary in two situations: (i) When comparison between two or more fuzzy numbers is difficult to perform, and (ii) When a fuzzy number to be operated on, has negative parameters (for example, squaring TFN $(-1, 0, 1)$ using Equation 13 will lead to $(1, 0, 1)$ that is not a fuzzy number).

4. CRITERIA FOR EVALUATION OF PRODUCTION FACILITIES

In order to facilitate our implementation of the TOPSIS method, we frame the problem of evaluation of production facilities in a closed-loop supply chain, as a four-level hierarchy that is similar to the hierarchy in the Analytic Hierarchy Process [11]. The first level in the hierarchy contains our objective, i.e., evaluation of each production facility in the supply chain, the second level contains the main criteria for evaluation, the third level contains the sub-criteria under each main criterion, and the fourth (last) level contains all the production facilities operating in the supply chain. Figure 5 illustrates these hierarchy levels.

The following sub-sections give brief descriptions of the main criteria on the second level in the hierarchy and their corresponding sub-criteria on the third level (see [7] for detailed descriptions of some of the criteria):

4.1. Environmentally Conscious Design (ECD)

ECD is concerned with designing products with certain environmental considerations. The following sub-criteria fall under ECD.

4.1.1. *Design for Disassembly* (DD)

Disassembly is used both in recycling and remanufacturing to increase the recovery rate by allowing selective separating of parts and materials. Thus, DD initiatives lead to the correct identification of design specifications to minimize the complexity of the structure of the product by minimizing the number of parts, increasing the use of common materials, and choosing the fastener and joint types which are easily removable.

4.1.2. *Design for Recycling* (DC)

DC suggests making better choices for material selection such that the processes of material selection and material recovery become more efficient. Some important characteristics of DC are: long product life with the minimized use of raw materials (source reduction), more adaptable materials for multi-product applications, and fewer components within a given material in an engineered system.

4.1.3. *Design for Remanufacturing* (DR)

DR suggests the use of reusable parts and packaging in the design of new products, for source reduction.

4.2. Environmentally Conscious Manufacturing (ECM)

In addition to environmentally friendly product designs, issues involving manufacturing must also be addressed to have a complete concept of environmentally conscious production. These issues (we place them on the third level in the hierarchy) include the following:

- Selecting low pollution energy sources for manufacturing (ES)
- Designing cooling systems such that the coolant can be reused and the heat collected by it can be utilized as an energy source (CS)
- Monitoring waste generation as a result of manufacturing (WM)

4.3. Attitude of Management (AMT)

The attitude of the decision-makers (managers) in the facility matters a great deal when it comes to implementing the above practices (ECD and ECM). All the managers in the facility must have the following credentials (we place them on the third level in the hierarchy):

- Environmentally friendly thoughts (EF)
- Flexibility to handle uncertainties in the supply and quality of used products (FU)

- Readiness to usage of automated disassembly systems (AD) to avoid high lead time, expensive labor use, and possible human exposure to hazardous by-products

4.4. Potentiality (POT)

We evaluate a facility, also in terms of its potentiality to efficiently re-process the incoming used products. The following factors (we place them on the third level in the hierarchy) serve as potentiality measures:

4.4.1. *Throughput (TP) / Supply (SU)*

The only driver to administer a forward supply chain is the demand for new products and so if there is low demand for new products, there is practically no forward supply chain. However, this is not the case in some reverse supply chains where even if there is a low supply (and/or low demand) of used products (SU), reverse flow of goods (used products) must be administered due to environmental regulations. In supply-driven cases like these, it is unfair to judge a facility without considering SU in the hierarchy. Though throughput (TP) is a criterion that can evaluate a facility, it is not justified to use TP as an independent criterion because TP depends on SU. However, SU must not be taken as an independent criterion too because it cannot evaluate the facility. Furthermore, a low SU might lead to a low TP and a high SU might lead to a high TP. So, the idea is to take $(TP)/(SU)$ as a criterion in the hierarchy. Thus, we compensate for the effect of a low TP by dividing TP with a possibly low SU, in order not to underestimate the facility under consideration. Similarly, we dampen the effect of a high TP by dividing TP with a possibly high SU, in order not to overestimate the facility under consideration.

4.4.2. *Throughput (TP) * Disassembly time (DT)*

Disassembly time (DT) is not exactly the inverse of TP because TP takes into account the whole re-processing (disassembly plus recovery) time. Unlike in the forward supply chain, components of incoming goods (used products) in the reverse supply chain are likely to be deformed and/or broken and/or different in number even for the same type of products. Hence, incoming products of the same type might have different re-processing times, unlike in the forward supply chain where manufacturing time and assembly time are pre-determined and equal for products of the same type. Since TP of a facility depends upon DT, it is unfair to not consider DT in the hierarchy. However, DT must not be taken as an independent criterion because it cannot evaluate the facilities. Furthermore, a high DT might lead to a low TP and a low DT might lead to a high TP. So, the idea is to take $(TP)(DT)$ as a criterion in the hierarchy. Thus, we compensate for the effect of a low TP by multiplying TP with a possibly high DT, in order not to underestimate the facility under consideration. Similarly, we dampen the effect of a high TP by multiplying TP with a possibly low DT, in order not to overestimate the facility under consideration.

4.4.3. *Increment in quality of products (QO – QI)*

Unlike in the forward supply chain, components of incoming goods (used products) of even the same type in the reverse supply chain are likely to be of varied quality (worn-out, low-performing, etc). Though the average quality of re-processed goods (QO) is a criterion that can evaluate a facility, it is not justified to use QO as an independent criterion for evaluation because QO depends on average quality of incoming products (QI). However, QI must not be taken as an independent criterion too because it cannot evaluate the facilities. So, the idea is to take the difference between QO and QI as a criterion in the hierarchy.

4.5. Cost (COS)

Cost incurred by a production facility can be divided into the following types (we place them on the third level in the hierarchy):

- Fixed cost (FC), which is the sum of space cost, machinery cost, personnel cost, etc.
- Operational cost (OC), which is the sum of rent, salaries, maintenance cost, etc.

4.6. Customer Service (CSE)

Customer service basically gives an idea about how well a facility is

- Giving incentives to the collection centers supplying used products (IC)
- Giving incentives to the customers buying re-processed goods (IS)
- Utilizing incentives provided by the government (UG)
- Meeting environmental regulations laid by the government (ER)

(Note that the term ‘customer service’ is used here because, in our opinion, any beneficiary is a customer, be it the government or the collection center or the actual customer buying re-processed goods.)

5. NUMERICAL EXAMPLE

In our example, all the criteria on the second level in the hierarchy are given linguistic ratings (“high”, “medium”, etc) by three experts. Similarly, all sub-criteria but (TP/SU), (TP*DT), (QO-QI), FC and OC on the third level in the hierarchy are given linguistic ratings by the same three experts. TFNs in Table 1 are employed to quantify these different linguistic ratings.

Table 1. Linguistic Rating Conversion Table for Criteria and Sub-Criteria

Linguistic Rating	Triangular Fuzzy Number
Very high (VH)	(0.7, 0.9, 1.0)
High (H)	(0.5, 0.7, 0.9)
Medium (M)	(0.3, 0.5, 0.7)
Low (L)	(0.1, 0.3, 0.5)
Very low (VL)	(0.0, 0.1, 0.3)

The linguistic ratings given to the main criteria by each expert and the average quantified rating of each criterion are shown in Table 2. Also, the relative ratings obtained by normalizing the average ratings are shown.

Table 2. Relative Ratings of Main Criteria

Criterion	Expert E1	Expert E2	Expert E3	Average Rating	Relative Rating
ECD	H	H	M	(0.43, 0.63, 0.83)	(0.09, 0.18, 0.36)
ECM	VH	H	VH	(0.63, 0.83, 0.97)	(0.14, 0.24, 0.42)
AMT	L	L	VL	(0.07, 0.23, 0.43)	(0.02, 0.07, 0.19)
POT	H	H	H	(0.50, 0.70, 0.90)	(0.11, 0.20, 0.39)
COS	M	H	H	(0.43, 0.63, 0.83)	(0.09, 0.18, 0.36)
CSE	M	L	M	(0.23, 0.43, 0.63)	(0.05, 0.12, 0.28)

Similarly, linguistic ratings, average quantified ratings and relative ratings of sub-criteria of ECD, ECM, AMT, POT, COS and CSE are shown in Tables 3, 4, 5, 6, 7 and 8 respectively.

Table 3. Relative Ratings of Sub-Criteria of ECD

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
DD	H	H	M	(0.43, 0.63, 0.83)	(0.21, 0.42, 0.89)
DC	L	L	VL	(0.07, 0.23, 0.43)	(0.03, 0.15, 0.46)
DR	M	H	H	(0.43, 0.63, 0.83)	(0.21, 0.42, 0.89)

Table 4. Relative Ratings of Sub-Criteria of ECM

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
ES	H	H	H	(0.50, 0.70, 0.90)	(0.21, 0.40, 0.78)
CS	M	H	H	(0.43, 0.63, 0.83)	(0.18, 0.36, 0.72)
WM	M	L	M	(0.23, 0.43, 0.63)	(0.10, 0.24, 0.54)

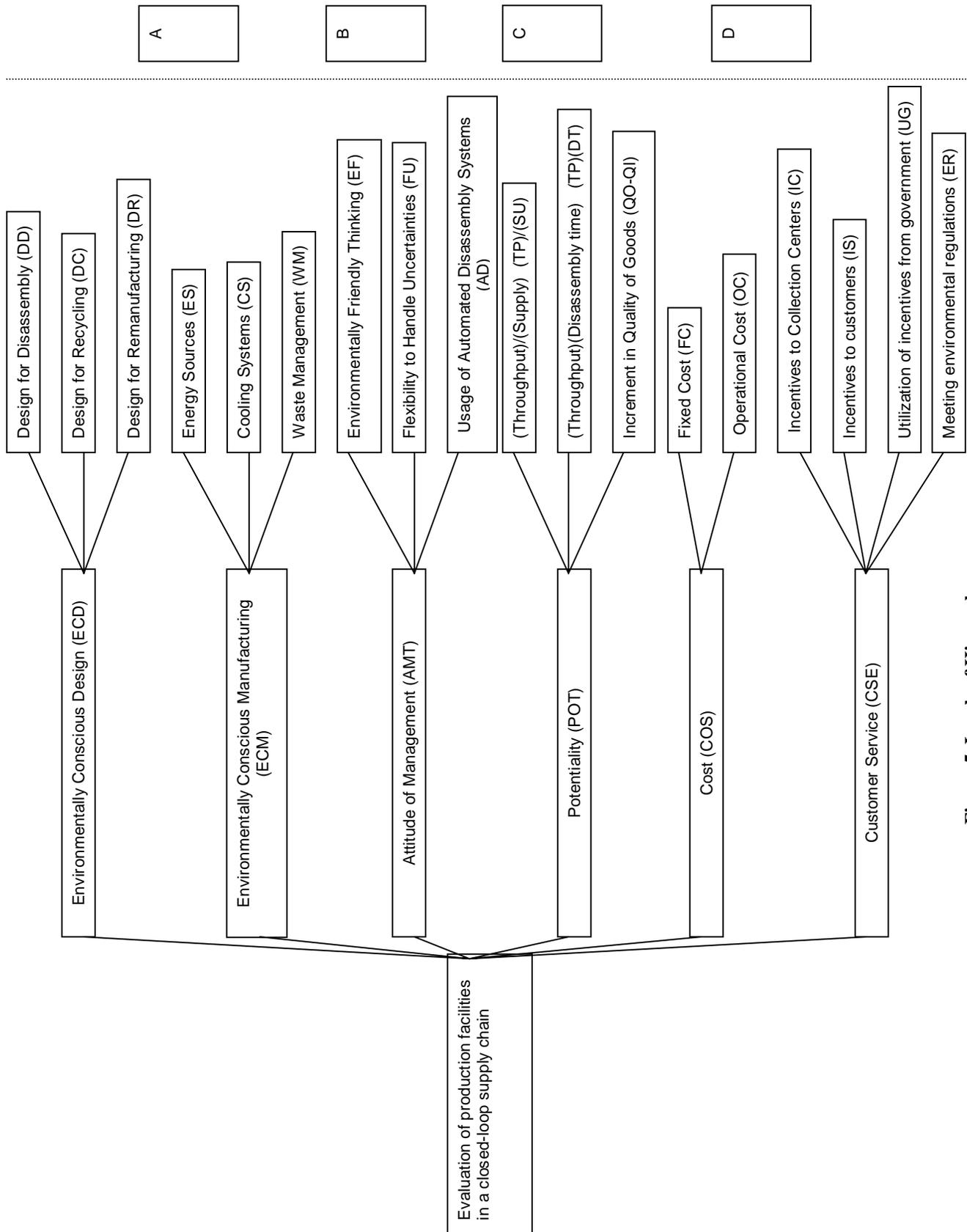


Figure 5. Levels of Hierarchy

Table 5. Relative Ratings of Sub-Criteria of AMT

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
EF	L	L	VL	(0.07, 0.23, 0.43)	(0.04, 0.18, 0.59)
FU	M	H	H	(0.43, 0.63, 0.83)	(0.23, 0.49, 1.14)
AD	M	L	M	(0.23, 0.43, 0.63)	(0.12, 0.33, 0.86)

Table 6. Relative Ratings of Sub-Criteria of POT

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
TP/SU	H	H	M	(0.43, 0.63, 0.83)	(0.21, 0.42, 0.89)
TP*DT	L	L	VL	(0.07, 0.23, 0.43)	(0.03, 0.15, 0.46)
QO-QI	M	H	H	(0.43, 0.63, 0.83)	(0.21, 0.42, 0.89)

Table 7. Relative Ratings of Sub-Criteria of COS

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
FC	H	H	M	(0.43, 0.63, 0.83)	(0.34, 0.73, 1.66)
OC	L	L	VL	(0.07, 0.23, 0.43)	(0.06, 0.27, 0.86)

Table 8. Relative Ratings of Sub-Criteria of CSE

Sub-Criterion	E1	E2	E3	Average Rating	Relative Rating
IC	M	H	H	(0.43, 0.63, 0.83)	(0.17, 0.35, 0.78)
IS	L	L	VL	(0.07, 0.23, 0.43)	(0.03, 0.13, 0.40)
UG	H	H	H	(0.50, 0.70, 0.90)	(0.19, 0.39, 0.84)
ER	L	L	VL	(0.07, 0.23, 0.43)	(0.03, 0.13, 0.40)

Since the ratings considered in the TOPSIS methods must all sum up to unity, we multiply the rating of each sub-criterion on the third level in the hierarchy with the rating of its corresponding main criterion on the second level in the hierarchy. The ratings of the criteria on the third level in the hierarchy, which are ready for being used in the TOPSIS method, are shown in Table 9.

Table 9. Ratings of Sub-Criteria for the TOPSIS Method

Sub-Criterion	Rating for the TOPSIS Method (Relative Rating of Sub-Criterion * Relative Rating of Corresponding Criterion)
DD	(0.02, 0.08, 0.32)
DC	(0.00, 0.03, 0.17)
DR	(0.02, 0.08, 0.32)
ES	(0.03, 0.10, 0.33)
CS	(0.03, 0.09, 0.30)
WM	(0.01, 0.06, 0.23)
EF	(0.00, 0.01, 0.11)
FU	(0.00, 0.03, 0.22)
AD	(0.00, 0.02, 0.16)
TP/SU	(0.02, 0.08, 0.35)
TP*DT	(0.00, 0.03, 0.18)
QO-QI	(0.02, 0.08, 0.35)
FC	(0.03, 0.13, 0.60)
OC	(0.00, 0.05, 0.31)
IC	(0.01, 0.04, 0.22)
IS	(0.00, 0.02, 0.11)
UG	(0.01, 0.05, 0.24)
ER	(0.00, 0.02, 0.11)

Table 10 shows the linguistic ratings and their corresponding TFNs used to evaluate the production facilities with respect to each sub-criterion.

Table 10. Linguistic Rating Conversion Table for Production Facilities

Linguistic Rating	Triangular Fuzzy Number
Very Good (VG)	(7, 10, 10)
Good (G)	(5, 7, 10)
Fair (F)	(2, 5, 8)
Poor (P)	(1, 3, 5)
Very Poor (VP)	(0, 0, 3)

Table 11 shows the sub-criteria with crisp (non-fuzzy) values. For consistency in the TOPSIS method, we convert each such value into a TFN whose all parameters are equal to that value.

Table 11. Crisp Values of Sub-Criteria for Evaluation

Sub-Criterion	Production Facilities			
	A	B	C	D
TP/SU	0.9	0.7	0.9	0.5
TP*DT	25	30	15	40
QO-QI	0.6	0.7	0.3	0.5
FC (\$)	100000	150000	70000	200000
OC (\$)	500	300	450	400

Now, we are ready to perform the six steps in the TOPSIS method.

Step 1: Construct the normalized decision matrix. Table 12 shows our decision matrix for the fuzzy TOPSIS approach and Table 13 shows the corresponding normalized decision matrix. The elements in the normalized decision matrix are calculated using Equation 1.

Step 2: Construct the weighted normalized decision matrix. Table 14 shows the weighted normalized decision matrix. This is constructed using the weights of the sub-criteria listed in Table 9 and the normalized decision matrix in Table 13.

Step 3: Determine the ideal and the negative-ideal solution. Each row in the decision matrix shown in Table 14 has a maximum rating (found using Equation 2) and a minimum rating (found using Equation 3). They are nothing but, the ideal and the negative-ideal solutions respectively, for the corresponding sub-criterion. For arithmetic simplicity, we assume here that the rating with the highest “most promising quantity” (second parameter in the TFN) is the maximum and the rating with the lowest “most promising quantity” is the minimum.

Step 4: Calculate the separation distances. In this step of our example, since we obtain some TFNs with negative “smallest possible quantities” and/or negative “most promising quantities”, we defuzzify those TFNs using Equation 15, before squaring them in the process of calculating separation distances. The separation distances of each production facility, which are calculated using Equations 4 and 5, are shown in Table 15.

Step 5: Calculate the relative closeness to the ideal solution. Using Equation 6, we calculate the relative closeness coefficient for each facility in the supply chain. These coefficients are shown in Table 16.

Step 6: Rank the preference order. It is clear from Table 16 that facilities A and C are much better than facilities B and D. If the cut-off value of the relative closeness coefficient decided by the decision-maker is say, 0.45, he will be happy with the performance of facilities A and C and might recommend improvements for facilities B and D.

6. CONCLUSIONS

None of the papers in the literature, which propose methods for performance evaluation of production facilities, address either environmental consciousness in the forward supply chain, or potentiality in the reverse supply chain. Keeping in mind - the growing participation of the facilities in the closed-loop supply chain, in this paper, we identified all the important criteria that ought to be considered for evaluation. Furthermore, we proposed a fuzzy TOPSIS approach for evaluation of the facilities with respect to those criteria.

Table 12. Decision Matrix for the TOPSIS Method

Sub-Criterion	Production Facilities			
	A	B	C	D
DD	(7, 10, 10)	(2, 5, 8)	(1, 3, 5)	(5, 7, 10)
DC	(5, 7, 10)	(0, 0, 3)	(5, 7, 10)	(5, 7, 10)
DR	(2, 5, 8)	(7, 10, 10)	(2, 5, 8)	(5, 7, 10)
ES	(1, 3, 5)	(5, 7, 10)	(1, 3, 5)	(1, 3, 5)
CS	(0, 0, 3)	(5, 7, 10)	(1, 3, 5)	(0, 0, 3)
WM	(1, 3, 5)	(0, 0, 3)	(2, 5, 8)	(2, 5, 8)
EF	(1, 3, 5)	(5, 7, 10)	(5, 7, 10)	(7, 10, 10)
FU	(5, 7, 10)	(7, 10, 10)	(2, 5, 8)	(7, 10, 10)
AD	(0, 0, 3)	(7, 10, 10)	(1, 3, 5)	(0, 0, 3)
TP/SU	(0.9, 0.9, 0.9)	(0.7, 0.7, 0.7)	(0.9, 0.9, 0.9)	(0.5, 0.5, 0.5)
TP*DT	(25, 25, 25)	(30, 30, 30)	(15, 15, 15)	(40, 40, 40)
QO-QI	(0.6, 0.6, 0.6)	(0.7, 0.7, 0.7)	(0.3, 0.3, 0.3)	(0.5, 0.5, 0.5)
FC	(10, 10, 10)	(15, 15, 15)	(7, 7, 7)	(20, 20, 20)
OC	(5, 5, 5)	(3, 3, 3)	(4.5, 4.5, 4.5)	(4, 4, 4)
IC	(0, 0, 3)	(0, 0, 3)	(5, 7, 10)	(1, 3, 5)
IS	(1, 3, 5)	(2, 5, 8)	(7, 10, 10)	(5, 7, 10)
UG	(2, 5, 8)	(0, 0, 3)	(1, 3, 5)	(0, 0, 3)
ER	(1, 3, 5)	(5, 7, 10)	(5, 7, 10)	(2, 5, 8)

Table 13. Normalized Decision Matrix

Sub-Criterion	Production Facilities			
	A	B	C	D
DD	(0.41, 0.74, 1.13)	(0.12, 0.37, 0.90)	(0.06, 0.22, 0.56)	(0.29, 0.52, 1.13)
DC	(0.28, 0.58, 1.15)	(0, 0, 0.35)	(0.28, 0.58, 1.15)	(0.28, 0.58, 1.15)
DR	(0.11, 0.35, 0.88)	(0.39, 0.71, 1.1)	(0.11, 0.35, 0.88)	(0.28, 0.50, 1.1)
ES	(0.11, 0.58, 2.89)	(0, 0, 1.73)	(0.11, 0.58, 2.89)	(0.11, 0.58, 2.89)
CS	(0, 0, 0.59)	(0.42, 0.92, 1.96)	(0.08, 0.39, 0.98)	(0, 0, 0.59)
WM	(0.08, 0.39, 1.67)	(0, 0, 1)	(0.16, 0.65, 2.67)	(0.16, 0.65, 2.67)
EF	(0.06, 0.21, 0.5)	(0.28, 0.49, 1)	(0.28, 0.49, 1)	(0.39, 0.7, 1)
FU	(0.26, 0.42, 0.89)	(0.37, 0.6, 0.89)	(0.1, 0.3, 0.71)	(0.37, 0.6, 0.89)
AD	(0, 0, 0.42)	(0.59, 0.96, 1.41)	(0.08, 0.29, 0.71)	(0, 0, 0.42)
TP/SU	(0.59, 0.59, 0.59)	(0.46, 0.46, 0.46)	(0.59, 0.59, 0.59)	(0.33, 0.33, 0.33)
TP*DT	(0.43, 0.43, 0.43)	(0.52, 0.52, 0.52)	(0.26, 0.26, 0.26)	(0.69, 0.69, 0.69)
QO-QI	(0.55, 0.55, 0.55)	(0.64, 0.64, 0.64)	(0.28, 0.28, 0.28)	(0.46, 0.46, 0.46)
FC	(0.36, 0.36, 0.36)	(0.54, 0.54, 0.54)	(0.25, 0.25, 0.25)	(0.72, 0.72, 0.72)
OC	(0.6, 0.6, 0.6)	(0.36, 0.36, 0.36)	(0.54, 0.54, 0.54)	(0.48, 0.48, 0.48)
IC	(0, 0, 0.59)	(0, 0, 0.59)	(0.42, 0.92, 1.96)	(0.08, 0.39, 0.98)
IS	(0.06, 0.22, 0.56)	(0.12, 0.37, 0.90)	(0.41, 0.74, 1.13)	(0.29, 0.52, 1.13)
UG	(0.19, 0.86, 3.58)	(0, 0, 1.34)	(0.1, 0.51, 2.24)	(0, 0, 1.34)
ER	(0.06, 0.26, 0.67)	(0.29, 0.61, 1.35)	(0.29, 0.61, 1.35)	(0.12, 0.44, 1.08)

Table 14. Weighted Normalized Decision Matrix

Sub-criterion	Production Facilities			
	A	B	C	D
DD	(0.01, 0.06, 0.36)	(0, 0.03, 0.29)	(0, 0.02, 0.18)	(0.01, 0.04, 0.36)
DC	(0, 0.02, 0.20)	(0, 0, 0.06)	(0, 0.02, 0.20)	(0, 0.02, 0.20)
DR	(0, 0.03, 0.28)	(0.01, 0.06, 0.35)	(0, 0.03, 0.28)	(0.01, 0.04, 0.35)
ES	(0, 0.06, 0.95)	(0, 0, 0.57)	(0, 0.06, 0.95)	(0, 0.06, 0.95)
CS	(0, 0, 0.18)	(0.01, 0.08, 0.59)	(0, 0.03, 0.29)	(0, 0, 0.18)
WM	(0, 0.02, 0.38)	(0, 0, 0.23)	(0, 0.04, 0.61)	(0, 0.04, 0.61)
EF	(0, 0, 0.06)	(0, 0, 0.11)	(0, 0, 0.11)	(0, 0.01, 0.11)
FU	(0, 0.01, 0.20)	(0, 0.02, 0.20)	(0, 0.01, 0.16)	(0, 0.02, 0.20)
AD	(0, 0, 0.07)	(0, 0.02, 0.23)	(0, 0.01, 0.11)	(0, 0, 0.07)
TP/SU	(0.01, 0.05, 0.20)	(0.01, 0.04, 0.16)	(0.01, 0.05, 0.20)	(0.01, 0.03, 0.11)
TP*DT	(0, 0.01, 0.08)	(0, 0.02, 0.09)	(0, 0.01, 0.05)	(0, 0.02, 0.12)
QO-QI	(0.01, 0.04, 0.19)	(0.01, 0.05, 0.22)	(0.01, 0.02, 0.10)	(0.01, 0.04, 0.16)
FC	(0.01, 0.05, 0.22)	(0.02, 0.07, 0.32)	(0.01, 0.03, 0.15)	(0.02, 0.09, 0.43)
OC	(0, 0.03, 0.18)	(0, 0.02, 0.11)	(0, 0.03, 0.17)	(0, 0.02, 0.15)
IC	(0, 0, 0.13)	(0, 0, 0.13)	(0, 0.04, 0.43)	(0, 0.02, 0.22)
IS	(0, 0, 0.06)	(0, 0.01, 0.10)	(0, 0.01, 0.12)	(0, 0.01, 0.12)
UG	(0, 0.04, 0.86)	(0, 0, 0.32)	(0, 0.03, 0.54)	(0, 0, 0.32)
ER	(0, 0.01, 0.07)	(0, 0.01, 0.15)	(0, 0.01, 0.15)	(0, 0.01, 0.12)

Table 15. Separation Measures of Facilities

Production Facility	Positive Distance S*	Negative Distance S-
A	0.239	0.288
B	0.320	0.208
C	0.200	0.290
D	0.305	0.233

Table 16. Relative Closeness Coefficients of Facilities

Production Facility	Relative Closeness Coefficient
A	0.547
B	0.394
C	0.592
D	0.434

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