Selecting environmentally conscious manufacturing program using combinatorial mathematics approach

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Abstract

Selecting the best environmentally conscious manufacturing (ECM) program alternative is an important problem in the manufacturing environment. This paper presents a combinatorial mathematics approach that considers the values of the attributes and their relative importance together to provide a better accurate evaluation of the alternatives. Also, the approach allows the decision maker to systematically assign the values of relative importance to the attributes and fuzzy logic is used for conversion of qualitative attributes into quantitative attributes. An example is included to illustrate the approach.

Keywords: Environmentally conscious manufacturing, Multiple attribute decision making, Combinatorial mathematics approach.

Introduction

Environmentally Conscious Manufacturing (ECM) deals with green principles that are concerned with developing approaches for manufacturing products from conceptual design to final delivery to consumers, and ultimately to the end-of-life (EOL) disposal, that satisfy environmental standards and requirements. Environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers, forcing them to produce and dispose of products in an environmentally responsible manner. These have created a need to develop algorithms, models, heuristics, and software for addressing designing, recycling, and other issues (such as the economic viability, logistics, disassembly, recycling, and remanufacturing) for an ever increasing number of products produced and discarded (Ilgin and Gupta, 2009; Bufardi *et al.,* 2003).

In recent years, environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers to produce, and dispose of products in an environmentally responsible manner. Almost every function within organizations has been influenced by external and internal pressures to become environmentally sound. Issues such as green consumerism and green product development have impacted marketing. One of the functions that has been profoundly influenced by environmental pressures is the organizational operations and manufacturing function.

The objective of an ECM program selection procedure is to identify the ECM program selection attributes, and obtain the most appropriate combination of the attributes in conjunction with the real requirements of the industrial application. Many precision-based approaches for ECM program selection have been developed. Sarkis (1995) linked supply chain management aspects with environmentally conscious design and manufacturing. Sarkis (1998) categorized environmentally conscious business practices into five major components: design for the environment, life cycle analysis, total quality environmental management, green supply chain and ISO 14000 environmental management system requirements.

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Cordeiro and Sarkis (1997) presented the aspects of environmental proactivism and firm performance as evidenced from industry analyst forecasts. Sarkis and Weinrach (2001) evaluated environmentally conscious waste treatment technologies using the DEA approach. Khan *et al.* (2002) proposed a holistic and integrated approachology, Green Pro-I, for process/product design. The approachology was simple and applicable at the early design stage, and was more robust against uncertainty in the data. Madu *et al.* (2002) presented a hierarchic metric approach for integration of green issues in manufacturing. Rao (2004) used digraph and matrix approaches for the evaluation of ECM programs.

Kuo *et al.* (2006) presented an innovative approach, namely, green fuzzy design analysis (GFDA), which involves simple and efficient procedures to evaluate product design alternatives based on environmental consideration using fuzzy logic. The hierarchical structure of environmentally conscious design indices was constructed using the analytical hierarchy process (AHP), which included five aspects: (1) energy, (2) recycling, (3) toxicity, (4) cost, and (5) material. Bovea and Wang (2007) proposed a design for environment (DFE) approachology which integrates quality function deployment (QFD), life cycle analysis (LCA) and life cycle costing (LCC) and contingent valuation techniques for the evaluation of the customer, environmental, cost criteria and customer willingness-to-pay, respectively. Li *et al.* (2008) employed a fuzzy connected graph to represent the product structure while AHP is used to convert life cycle environmental objectives along with other functional and manufacturing concerns into fuzzy relationship values. Qian and Zhang (2009) developed a approachology for environmentally conscious modularity assessment of electromechanical products by using fuzzy AHP. Ilgin and Gupta (2009) have described about the environmentally conscious product design. Rao (2009) had applied VIKOR approach for ECM program selection. Yun *et al.* (2010) had applied the extension evaluation approach for the selection of eco-friendly brake friction material.

Environmentally conscious manufacturing (ECM) is concerned with developing approaches for designing and manufacturing of new products from conceptual design to final delivery, and ultimately to the end-of-life disposal such that all the environmental standards and requirements are satisfied. In recent years, environmental awareness and recycling regulations have been putting pressure on many manufacturers and consumers to produce, and dispose of products in an environmentally responsible manner. Almost every function within organizations has been influenced by external and internal pressures to become environmentally sound. Issues such as green consumerism and green product development have impacted marketing. Finance, information systems and technology, human resources and training, engineering and research, and development are all organizational functions that have been influenced by these environmental pressures.

ECM programs include proactive measures such as life-cycle analysis of products, design for the environment, design for disassembly, total quality environmental management, remanufacturing, ISO14000 certification, and green supply chains. Each of these programs crosses inter- and intra-organizational boundaries. These programs work hand in hand with other environmental alternatives such as development of environmental management systems, and green purchasing (Sarkis, 1999).

Even though there are many MADM approaches available to solve the selection problems but they have their own merits and demerits. Hence, a combinatorial mathematics approach (CMA) is considered in this paper for the systematically evaluation of ECM programs.

Combinatorial mathematics approach (CMA)

The stepwise procedure of the proposed approach is given below.

Step 1: Decision matrix

Decision matrix is the collection of attribute data for each alternative. The attributes may be objective or subjective. The subjective attributes are represented in linguistic terms and these are required to be converted into corresponding crisp scores. A seven point fuzzy scale is used for the conversion of qualitative value of an attribute (Figure 1) into corresponding crisp scores as explained in Table 1.

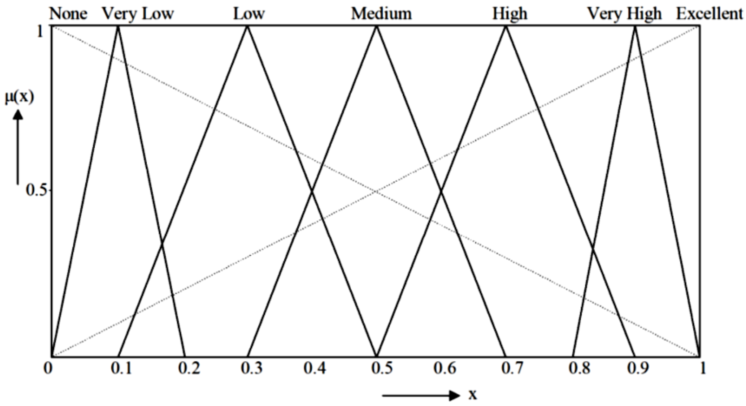

Figure 1. Linguistic terms to fuzzy numbers conversion

Table 1. Conversion of linguistic terms into crisp scores (seven point scale)

Linguistic term	Fuzzy number	Membership function μ(x)	μ_R (M$_i$)	μ_L (M$_i$)	μ_T (M$_i$)
None	M1 (0, 0, 0)	$\mu_{M_1}(x)=1,\ \ x=0$	0	1	0
Very low/very poor	M2 (0, 0.1, 0.2)	$\mu_{M_2}(x)=\begin{cases}(x-0)/(0.1), & 0\le x\le 0.1\\(0.2-x)/(0.1), & 0.1\le x\le 0.2\end{cases}$	0.1818	0.9091	0.1364
Low/poor	M3 (0.1, 0.3, 0.5)	$\mu_{M_3}(x)=\begin{cases}(x-0.1)/(0.2), & 0.1\le x\le 0.3\\(0.5-x)/(0.2), & 0.3\le x\le 0.5\end{cases}$	0.4167	0.75	0.3333
Medium	M4 (0.3, 0.5, 0.7)	$\mu_{M_4}(x)=\begin{cases}(x-0.3)/(0.2), & 0.3\le x\le 0.5\\(0.7-x)/(0.2), & 0.5\le x\le 0.7\end{cases}$	0.5833	0.5833	0.5
High/good	M5 (0.5, 0.7, 0.9)	$\mu_{M_5}(x)=\begin{cases}(x-0.5)/(0.2), & 0.5\le x\le 0.7\\(0.9-x)/(0.2), & 0.7\le x\le 0.9\end{cases}$	0.75	0.4167	0.6667
Very high/very good	M6 (0.8, 0.9, 1)	$\mu_{M_6}(x)=\begin{cases}(x-0.8)/(0.1), & 0.8\le x\le 0.9\\(1-x)/(0.1), & 0.9\le x\le 1\end{cases}$	0.9091	0.1818	0.8636
Excellent	M7 (1, 1, 1)	$\mu_{M_7}(x)=1,\ \ x=1$	1	0	1

μR (Mi): Right score; μL (Mi): Left score; μT (Mi): Total score

Step 2: Normalization / Normalized decision matrix

Normalization is the procedure to set the attribute data on same scale so that comparisons can be made easier. Following normalization procedure is adopted in the proposed approach. Let x_{ij} is the normalized value of y_{ij} for attribute *j* of alternative *i*, then

$$x_{ij}=\frac{y_{ij}}{\max_j(y_{ij})} \quad \text{; if } j^{th} \text{ attribute is beneficial} \qquad (1)$$

$$x_{ij}=\frac{\min_j(y_{ij})}{y_{ij}} \quad \text{; if } j^{th} \text{ attribute is non-beneficial} \qquad (2)$$

Step 3: Relative importance of attributes

The relative importance of attributes is the judgment made by the decision maker(s) after analyzing the attributes with respect to the goal or objective. A pair-wise comparison matrix is constructed using a scale of relative importance suggested by Saaty (1980, 2000). The judgments are entered using the fundamental scale of the AHP. The consistency check is carried out similar to the AHP process as explained below.

- The scale for pair wise comparison is given in Table 2. Assuming '*n*' attributes, the pair wise comparison of attribute *i* with attribute *j* yields a square matrix $B_{n\times n}$ where b_{ij} denotes the comparative importance of attribute *i* with respect to attribute *j*. In the matrix, $b_{ij} = 1$ when $i = j$ and $b_{ji} = 1/b_{ij}$.

$$B_{n\times n} = B_1 = \begin{bmatrix} 1 & b_{12} & b_{13} & \dots & \dots & b_{1n} \\ b_{21} & 1 & b_{23} & \dots & \dots & b_{2n} \\ b_{31} & b_{32} & 1 & \dots & \dots & b_{3n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & b_{n3} & \dots & \dots & 1 \end{bmatrix} \quad (3)$$

Table 2. Scale for pair wise comparison

Degree of importance	Definition
1	Equal (no preference)
2	Intermediate between 1 and 3
3	Moderately preferable
4	Intermediate between 3 and 5
5	Strongly preferable
6	Intermediate between 5 and 7
7	Very strongly preferable
8	Intermediate between 7 and 9
9	Extremely strongly preferable
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Reciprocals of 2, 3, 4, 5, 6, 7, 8 and 9

- Find the relative normalized weight (w_j) of each attribute by (i) calculating the geometric mean of the i^{th} row of relative importance matrix B_1, and (ii) normalizing the geometric means of rows in the comparison matrix. This can be represented as:

$$GM_i = \left[\prod_{j=1}^{n} b_{ij}\right]^{1/n} \quad (4)$$

$$w_j = GM_i / \sum_{i=1}^{n} GM_i \quad (5)$$

The geometric mean approach of AHP is commonly used to determine the relative normalized weights of the attributes, because of its simplicity, ease of determination of the maximum Eigen value and reduction in inconsistency of judgments.

- Calculate matrices B_3 and B_4 such that $B_3 = B_1 \times B_2$ and $B_4 = B_3/B_2$, where $B_2 = [w_1, w_2, .., w_j]^T$.
- Determine the maximum Eigen value λ_{max} that is the average of matrix B_4.
- Calculate the consistency index CI = $(\lambda_{max} - n) / (n - 1)$. The smaller the value of CI, the smaller is the deviation from the consistency.
- Obtain the random index (RI) for the number of attributes used in decision making.
- Calculate the consistency ratio CR = CI / RI.

Each RI is an average random consistency index (CI) derived from a sample of size 500 of randomly generated reciprocal matrices with entries from the set {1/9, 1/8, 1/7, 1/6, 1/5, 1/4, 1/3, 1/2, 1, 2, 3, 4, 5, 6, 7, 8, 9} to see if its CI is 0.10 or less. It is required that the CR value of the relative importance of attributes should not be more than 0.10. If the previous approach yields a CR greater than 0.10 then a re-examination of the pairwise judgments is recommended until a CR less than or equal to 0.10 is achieved (Triantaphyllou and Mann, 1990; Triantaphyllou *et al.,* 1990).

Step 4: Formation of alternative selection attribute matrix for each alternative

The alternative selection attribute matrix is formed by keeping the normalized values for attributes data for the respective alternative as the diagonal elements. This matrix is represented by '*C*'.

$$C = \begin{bmatrix} A_1 & b_{12} & b_{13} & \dots & \dots & b_{1n} \\ b_{21} & A_2 & b_{23} & \dots & \dots & b_{2n} \\ b_{31} & b_{32} & A_3 & \dots & \dots & b_{3n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & b_{n3} & \dots & \dots & A_n \end{bmatrix} \qquad (6)$$

Where, $[A_1, A_2, A_3, \dots \dots, A_n]$ are the normalized values of attributes for the considered alternative.

Step 5: Get the permanent function value of the alternative selection attribute matrix for each alternative

The permanent function value of the alternative selection attribute matrix '*C*' for each alternative is calculated as given in Rao (2007). It is represented by *per(C)* and is also called as *index score* for the respective alternative.

For example, the permanent function of a 6×6 matrix is written as equation (7). The permanent function (*C*) contains terms arranged in (6 + 1) groupings and these groupings represent the measures of attributes and the relative importance loops. The first grouping represents the measures of the attributes. The second grouping is absent, as there is no self-loop. The third grouping contains 2-attribute relative importance loops and measures of four attributes. Each term of the fourth grouping represents a set of a 3-attribute relative importance loop, or its pair, and measures of three attributes. The fifth grouping contains two sub-groupings. Each term of the first sub-grouping is a set of two 2-attribute relative importance loops and the measures of two attributes. Each term of the second sub-grouping is a set of a 4-attribute relative importance loop, or its pair, and the measures of two attributes. The sixth grouping contains two sub-groupings. Each term of the first sub-grouping is a set of a 3-attribute relative importance loop, or its pair, and a 2-attribute relative importance loop and the measure of one attribute. Each term of the second sub-grouping is a set of 5-attribute relative importance loop, or its pair, and the measure of one attribute. The seventh grouping contains four sub-groupings. Each term of the first sub-grouping is a set of a 4-attribute relative importance loop, or its pair, and a 2-attribute relative importance loop. Each term of the second sub-grouping is a set of a 3-attribute relative importance loop, or its pair, and another 3-attribute relative importance loop, or its pair. Each term of the third sub-grouping is a set of three 2-attribute relative importance loops. Each term of the fourth sub-grouping is a set of a 6-attribute relative importance loop, or its pair. After identifying these combinatorial terms, and by associating a proper physical meaning with these, a new mathematical meaning of the multinomial is obtained.

$$
\begin{aligned}
per(C) = {} & \prod_{i=1}^{6} A_i + \sum_{i=1}^{5}\sum_{j=i+1}^{6}\sum_{k=1}^{3}\sum_{l=k+1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{ji})A_k A_l A_m A_n \\
& + \sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{jk}b_{ki} + b_{ik}b_{kj}b_{ji})A_l A_m A_n \\
& + \left(\sum_{i=1}^{3}\sum_{j=i+1}^{6}\sum_{k=i+1}^{5}\sum_{l=i+2}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{ji})(b_{kl}b_{lk})A_m A_n \right. \\
& \left. + \sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{jk}b_{kl}b_{li} + b_{il}b_{lk}b_{kj}b_{ji})A_m A_n \right) \\
& + \left(\sum_{i=1}^{4}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{5}\sum_{m=l+1}^{6}\sum_{n=1}^{6}(b_{ij}b_{jk}b_{ki} + b_{ik}b_{kj}b_{ji})(b_{lm}b_{ml})A_n \right. \\
& \left. + \sum_{i=1}^{2}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=j+1}^{6}\sum_{n=1}^{6}(b_{ij}b_{jk}b_{kl}b_{lm}b_{mi} + b_{im}b_{ml}b_{lk}b_{kj}b_{ji})A_n \right) \\
& + \left(\sum_{i=1}^{3}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=j+1}^{6}\sum_{m=1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{jk}b_{kl}b_{li} + b_{il}b_{lk}b_{kj}b_{ji})(b_{mn}b_{nm}) \right. \\
& + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=j+1}^{6}\sum_{l=1}^{4}\sum_{m=l+1}^{5}\sum_{n=m+1}^{6}(b_{ij}b_{jk}b_{ki} + b_{ik}b_{kj}b_{ji})(b_{lm}b_{mn}b_{nl} + b_{ln}b_{nm}b_{ml}) \\
& + \sum_{i=1}^{1}\sum_{j=i+1}^{6}\sum_{k=i+1}^{3}\sum_{l=i+2}^{6}\sum_{m=k+1}^{5}\sum_{n=k+2}^{6}(b_{ij}b_{ji})(b_{kl}b_{lk})(b_{mn}b_{nm}) \\
& \left. + \sum_{i=1}^{1}\sum_{j=i+1}^{5}\sum_{k=i+1}^{6}\sum_{l=i+1}^{6}\sum_{m=i+1}^{6}\sum_{n=j+1}^{6}(b_{ij}b_{jk}b_{kl}b_{lm}b_{mn}b_{ni} + b_{in}b_{nm}b_{ml}b_{lk}b_{kj}b_{ji}) \right)
\end{aligned} \tag{7}
$$

Step 6: Rank of alternatives

The rank of alternatives are based on the permanent function value of the alternative selection attributes matrix i.e. *per(C)*, also called as *index score*. The alternative for which the value of index score is highest is the best choice for the considered decision making problem.

Example

An ECM program selection problem is considered to demonstrate and validate the CMA approach. Sarkis (1999) presented an illustrative problem for evaluating ECM programs for an industrial application. Sarkis (1999) assumed that the management had determined its missions, priorities, and objectives in place. It was also assumed that a set of fifteen alternatives had been determined, and that all could be evaluated on each of the six attributes identified for the given industrial application. The attributes that will be used to evaluate these alternatives will include cost, quality, recyclability, process waste reduction, packaging waste reduction and regulatory compliance. The first two attributes selected, cost and quality, are standard performance measures that may be used to evaluate any program or project within an organization. The remaining measures are those that focus primarily on the environmental characteristics of operations and manufacturing. These environmentally based factors cover a spectrum from reactive environmental measures (e.g. regulatory compliance) to proactive measures (e.g. process waste reduction). Now, the various steps of CMA approach for ECM program selection are given as follow.

Step 1 Decision Matrix:

The decision matrix of the problem is given in Table 3 having 15 alternative ECM programs and six selection attributes.

Table 3. Data of the ECM programs selection example (Sarkis, 1999)

ECM programs	Attributes					
	C	Q	R	PRWR	PAWR	RC
1	706967	2	29	17	0	51
2	181278	3	5	14	7	45
3	543399	4	5	3	7	71
4	932027	7	15	10	17	57
5	651411	4	19	7	0	21
6	714917	5	15	6	19	5
7	409744	1	8	17	1	35
8	310013	6	23	15	18	32
9	846595	2	28	16	19	24
10	625402	3	21	16	7	34
11	285869	2	1	13	12	54
12	730637	3	3	4	1	12
13	794656	5	27	14	14	65
14	528001	1	6	5	9	41
15	804090	2	26	6	5	70

C: Cost (US$), Q: Quality (% defects), R: Recyclability (% recyclable material), PRWR: Process waste reduction (% reduction), PAWR: Packaging waste reduction (%reduction) and RC: Regularity compliance (% reduction in violations)

Step 2: Normalization / Normalized decision matrix

The attributes are of two types: beneficial and non-beneficial. The attributes R, PRWR, PAWR and RC are beneficial and the attributes C and Q are non-beneficial. The normalized values of data x_{ij} for these attributes are determined using equations (1) and (2) for beneficial and non-beneficial attributes respectively. The normalized decision matrix is given in Table 4.

Table 4. Normalized data of the ECM program selection example

ECM programs	Attributes					
	C	Q	R	PRWR	PAWR	RC
1	0.2564	0.50	1	1	0	0.7183
2	1	0.3333	0.1724	0.8235	0.3684	0.6338
3	0.3336	0.25	0.1724	0.1765	0.3684	1
4	0.1945	0.1429	0.5172	0.5882	0.8947	0.8028
5	0.2783	0.25	0.6552	0.4118	0	0.2958
6	0.2536	0.20	0.5172	0.3529	1	0.0704
7	0.4424	1	0.2759	1	0.0526	0.4930
8	0.5847	0.1667	0.7931	0.8824	0.9474	0.4507
9	0.2141	0.50	0.9655	0.9412	1	0.3380
10	0.2899	0.3333	0.7241	0.9412	0.3684	0.4789
11	0.6341	0.50	0.0345	0.7647	0.6316	0.7606
12	0.2481	0.3333	0.1034	0.2353	0.0526	0.1690
13	0.2281	0.20	0.9310	0.8235	0.7368	0.9155
14	0.3433	1	0.2069	0.2941	0.4737	0.5775
15	0.2254	0.50	0.8966	0.3529	0.2632	0.9859

Step 3: Relative importance of attributes

The relative importance of the attributes may be assigned using analytic hierarchy process (AHP) approach. Sarkis (1999) had used a more general form of the AHP known as analytical network process (ANP) for assigning the relative importance of attributes. The same values of relative importance of attributes are considered here which are given below.

Attributes	C	Q	R	PRWR	PAWR	RC
C	1	3	2	1	2	3
Q	1/3	1	1/3	1/4	1/3	1
R	1/2	3	1	1/2	1/2	2
PRWR	1	4	2	1	2	4
PAWR	1/2	3	2	1/2	1	2
RC	1/3	1	1/2	1/4	1/2	1

Cost (C) is considered as moderately preferable than the quality (Q) in ECM program selection. Hence relative importance value of 3 is assigned to C over Q and a relative importance value of 1/3 is assigned to Q over C. Similarly the relative importance among other attributes can be explained. However, in actual practice, these values of relative importance of attributes can be judiciously decided by the decision maker.

The weights of attributes obtained using the procedure described in section 2 are: w_C = 0.2613, w_Q = 0.0659, w_R = 0.1371, w_{PRWR} = 0.2876, w_{PAWR} = 0.1727 and w_{RC} = 0.0754. The value CR = 0.0174 which is much less than the allowed CR value of 0.1. Thus, there is good consistency in the judgments made.

Step 4: Formation of alternative selection attribute matrix for each alternative

The "alternative selection attribute matrix" is formed by keeping the normalized values for attributes data for the respective alternative as the diagonal elements. The "alternative selection attribute matrix" for alternative 1 is given below and similarly the other alternative selection attribute matrices are obtained.

$$C_1 = \begin{bmatrix} 0.2564 & 3 & 2 & 1 & 2 & 3 \\ 1/3 & 0.50 & 1/3 & 1/4 & 1/3 & 1 \\ 1/2 & 3 & 1 & 1/2 & 1/2 & 2 \\ 1 & 4 & 2 & 1 & 2 & 4 \\ 1/2 & 3 & 2 & 1/2 & 0 & 2 \\ 1/3 & 1 & 1/2 & 1/4 & 1/2 & 0.7183 \end{bmatrix}$$

Step 5: Get the permanent function value of the alternative selection attribute matrix for each alternative

The permanent function value (or index score) of the alternative selection attribute matrix '*C*' for each alternative is calculated using the equation (7). The index score values for the alternatives obtained are: ECM1= 541.0829, ECM2= 532.9109, ECM3= 449.6507, ECM4= 512.6410, ECM5= 420.6097, ECM6= 449.9200, ECM7= 525.2307, ECM8= 571.3380, ECM9= 580.2651, ECM10= 514.6767, ECM11= 532.6148, ECM12= 374.1169, ECM13= 573.0647, ECM14= 493.0809, ECM15= 519.2702. Therefore, the rank order of alternative ECM programs obtained using the CMA approach is: 9 – 13 – 8 – 1 – 2 – 11 – 7 – 15 – 10 – 4 – 14 – 6 – 3 – 5 – 12.

The rank order of alternative ECM programs given by Sarkis (1999) using RCCR DEA and RCCR/AR DEA models were: 8 – 2 – 11 – 9 – 7 – 14 – 1 – 15 – 13 – 10 – 3 – 6 – 5 – 4 – 12 and 11 – 8 – 9 – 7 – 2 – 1 – 15 – 10 – 14 – 13 – 6 – 3 – 4 – 5 – 12 respectively. CCR DEA model is the data envelopment analysis ratio model developed by Charnes, Cooper and Rhodes (Charnes *et al.,* 1978). RCCR DEA is the reduced CCR DEA model and RCCR/AR DEA is the assurance region RCCR DEA model.

The best alternative ECM program obtained using the CMA is 'alternative 9', whereas Sarkis (1999) suggested 'alternative 8' and 'alternative 11' using RCCR DEA and RCCR/AR DEA models respectively. On comparing the 'alternative 9' and 'alternative 8', it is found that ‘alternative 9’ is better with respect to attributes four attributes ‘Q’, ‘R’, ‘PRWR’, and ‘PAWR’ with combined weight as 66% and ‘alternative 8’ is better with respect to only two attributes ‘C’ and ‘RC’, so ‘alternative 9’ should be preferred over ‘alternative 8’. Again, on comparing the ‘alternative 9’ and ‘alternative 11’, it is found that ‘alternative 9’ is better with respect to attributes three attributes ‘R’, ‘PRWR’, and ‘PAWR’ with combined weight as 60% and ‘alternative 11’ is better with respect to two attributes ‘C’ and ‘RC’ with combined weight as 34%, so ‘alternative 9’ should be preferred over ‘alternative 11’, which is same as obtained by using the CMA approach. Furthermore, the worst alternative found by using CMA is same as given by Sarkis (1999) using RCCR DEA and RCCR/AR DEA models. The DEA approach proposed by Sarkis (1999) did not make any provision for consideration of qualitative attributes and the CMA overcomes this drawback. This shows the validity and applicability of the CMA to the decision making situations of the environmentally conscious manufacturing. Though the considered problem is not having any qualitative attribute, the combinatorial matrix approach is capable to deal with both the types of attributes, i.e. qualitative and quantitative, if such attributes are present in the problem. The approach systematically converts the qualitative attributes into the corresponding crisp values.

The proposed ECM program selection procedure CMA is relatively a new approach and can be used for any type of decision-making situation and has an edge over the multiple attribute decision making (MADM) methods. The computation used is comparatively simple compared to the other MADM methods. The measures of the attributes and their relative importance are used together to rank the alternatives and hence it provides a better evaluation of the alternatives. The use of permanent concept characterizes the considered selection problem as it contains all possible structural components of the attributes and their relative importance. The method can deal with the ECM program selection problems considering both qualitative and quantitative attributes. The ranked value judgment on a fuzzy conversion scale for the qualitative attributes introduced by the proposed method will be more useful to the designers. However, the proposed method does not claim that it is the ‘best’ method for ECM program selection. The method may be considered as an effective decision making aid. The decision maker may try few valid MADM methods for a considered ECM program selection problem. Application of different MADM methods may give different ECM program rankings for the considered weights of attributes. However, it does not matter so long as the first choice ECM program is consistent. If the first choice is different for different MADM methods, then the final selection may be made on the basis of an aggregation of the results of those MADM methods that have a very significant positive Spearman’s rank correlation coefficient. When the average rankings have a tie, the alternatives with the same average ranking can be examined in greater detail by considering their performance with respect to additional attributes or by using other methods to help distinguish their differences.

A final decision can be taken keeping in view of the practical considerations. All possible constraints likely to be experienced by the user have to be considered. These include constraints such as ECM program availability constraints, ECM program processing constraints, economic constraints, management constraints, social constraints, and political constraints. If the first choice ECM program as decided by the results of those MADM methods that have a very significant positive Spearman’s rank correlation coefficient can’t be considered due to certain constraints, then the user may opt for the second choice ECM program. If the second choice ECM program also can’t be considered due to certain constraints, then the user may opt for the third choice ECM program, and so on.

Conclusions

A combinatorial mathematics approach (CMA) is proposed in this paper to deal with the ECM program selection problem of the manufacturing environment considering both qualitative and quantitative attributes. The approach allows the decision-maker to systematically assign the values of relative importance to the attributes using AHP. The approach represents the qualitative attribute on a conversion scale using fuzzy logic and helps the users in assigning the values. The uniqueness of the decision making approach presented in this paper is that it offers a general procedure that can be applicable to diverse selection problems encountered in the manufacturing environment that incorporate vagueness and a number of selection attributes. The approach is logical, simple and convenient to implement. This approach can be extended to any other decision making situations of the manufacturing environment.

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