An integrated fuzzy-based multi-criteria decision-making approach for the selection of an effective manufacturing system

A case study of Indian manufacturing company

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Abstract

Purpose – The research paper presents analysis and prioritization of barriers influencing the improvement in the effectiveness of manufacturing system. The purpose of this paper is to develop an integrated fuzzy-based multi-criteria decision-making (F-MCDM) framework to assist management of the case company in the selection of most effective manufacturing system. The framework helps in prioritizing the manufacturing systems on the basis of their effectiveness affected by the barriers.

Design/methodology/approach – In this paper, on the basis of experts' opinion, five barriers have been identified in a brain-storming session. The problem of prioritization of manufacturing system is a multi-criteria decision-making (MCDM) problem and hence is solved by using the F-MCDM approach using dominance matrix.

Findings – Manufacturing systems' effectiveness for Indian industries is influenced by barriers. The prioritization of manufacturing systems depends on qualitative factor decision-making criteria. Among the manufacturing systems, leagile manufacturing system is given the highest priority followed by lean manufacturing system, agile manufacturing system, flexible manufacturing system and cellular manufacturing system.

Research limitations/implications – The selection of an appropriate manufacturing system plays a vital role for sustainable growth of the manufacturing company. In the present work, barriers which influence the effectiveness of manufacturing system have been identified. On the basis of degree of influence of barriers on the effectiveness of the manufacturing system, five alternative manufacturing systems are prioritized. The framework will help the management of the case company to take reasonable decision for the adoption of the appropriate manufacturing system.

Practical implications – The results of the research work are very useful for the manufacturing companies interested in analyzing the alternative manufacturing systems on the basis of their effectiveness and their sensitivity toward various barriers. The management of Indian manufacturing company will take decision to adopt a manufacturing system whose effectiveness is least sensitive toward barriers. Effectiveness of such manufacturing system will improve with time without having retardation due to barriers. With improved effectiveness of the manufacturing system, the manufacturing company would be able to survive with global competition. The result of the present work is based on the inputs from the case company and may vary for the other manufacturing company. In the present work, only five alternative manufacturing systems and five barriers have been considered. To obtain the better result, MCDM approach with more number of alternative manufacturing systems and barriers might be considered.

Originality/value – The research work is based on the fuzzy analytic hierarchy process framework and on the case study conducted by the authors. The work carried out is original in nature and based on the real-life case study.

Keywords Manufacturing, Agile, Effectiveness, Flexible, Fuzzy-based multi-criteria decision-making framework

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1. Introduction

Most of the researchers and industrialists agree that the pressure of global competition will continue to grow in the twenty-first century (World Bank, 2012; Goyal and Grover, 2013). The survival of the company will depend on the effectiveness of its manufacturing system.

There is need to improve the effectiveness of the manufacturing system. Improvement in effectiveness of any manufacturing system is a continuous process and gets affected by various barriers. In the present research work, five manufacturing systems namely flexible manufacturing system (FMS), leagile manufacturing system (LaMS), cellular manufacturing system (CMS), lean manufacturing system (LMS) and agile manufacturing system (AMS) are considered by the management of the case company which is a leading Indian manufacturing auto company. The management is interested to analyze effectiveness of which manufacturing system is least affected by the barriers under consideration. These manufacturing systems are prioritized on the basis of their effectiveness influenced by different barriers. Lack of management commitment, lack of cross-functional workforce, lack of integrated condition monitoring system, lack of training of manpower and resistance of worker against change are the barriers.

Decision making for the selection of an effective manufacturing system is most important scientific, environmental and economic effort for the sustainable growth of the case company. In a real-life scenario, the prioritization of manufacturing systems is a complex problem and depends on multiple criteria. A fuzzy logic-based multiple alternatives, multi-criterion and a multi-person decision-making heuristic model has been developed for solving the problem. In past research work, many analytical and heuristic methods were developed for solving the optimization problem in manufacturing and service sector industries. In the present paper, an attempt is made to prioritize the manufacturing systems on the basis of their effectiveness least influenced by the barriers.

2. Literature review

FMSs are characterized by their ability to integrate various entities and for their flexibility. An information system is the means to interface and integrate the entities of manufacturing systems, the mode of synchronizing the various entities and the method of coordinating them in order to achieve the objectives (Weber and Moodie, 1989). The procedure for evaluating alternative FMSs is based on a combined multiple attribute decision-making method using TOPSIS and analytic hierarchy process (AHP) methods together for a given industrial application (Rao, 2008). Goyal and Grover (2013) discussed the measuring of effectiveness in a manufacturing system using the combined approach of analytical network process with graph theoretic and matrix approach leading to single numerical index. A "flexible manufacturing system suitability index" is proposed that evaluates and ranks FMSs for the given industrial application. Solimanpur and Foroughi (2011) developed an integrated approach based on Levenshtein's (1996) algorithm and mathematical programming for the cell formation problem (CFP) considering the issues. Raj *et al.* (2008) discussed and analyzed the effectiveness of various enablers which help in the implementation of FMS in any industry. In his research, an ISM-based model has been developed to analyze the interactions among different FMS enablers – top management commitment, clear vision, effective long-term planning, team spirit and motivation, availability of resources, availability of good vendors, drive out fear, work culture in the organization, effective methodologies like MRP, MAP,TOP, etc., funds for FMS operational and control techniques, availability of trained personnel, automated production with robots, willingness of human resources to adopt FMS, automated production with AGVs, effective use of IT standards, availability of adequate space and availability of support from government. Madhavi *et al.* (2013) developed a new mathematical model to simultaneously tackle CFP and cell layout problem (CLP) considering forward and backtracking movement and new assumptions for distance between cells employing the sequence data production volume.

Cellular manufacturing, an innovative manufacturing strategy derived from group technology concept, is an approach that can be used to improve both flexibility and efficiency in today's modern competitive manufacturing environments, such as FMS and just-in-time production.

According to Prince and Kay (2003), the term "agile manufacturing" means the ability to respond to sudden changes and meet widely varied customer requirements in terms of price, specification, quality, quantity and delivery. Mohammadi and Forghani (2014) presented an integrated method to design a CMS and its intra- and inter-CLP considering several factors. Coping with cell formation with a simultaneous workers assignment problem to cells has attracted many researcher's attention (e.g. Suer and Bera, 1998; Mahdavi *et al.*, 2010; Rafiei and Ghodsi, 2013; Sakhaii *et al.*, 2015; Azadeh *et al.*, 2015; Agarwal *et al.*, 2006) considering the skill and working ability of operators in a manufacturing system is very sufficient, especially when they are being assigned to the manufacturing cell; this consideration results in a more reliable work place design improving the productivity index of the system (Azadeh *et al.*, 2015; Agarwal and Shankar, 2002a, b).

Most of the published research works since that of Bellman and Zadeh (1970) assume such a fuzzy preferences scheme and consists of finding the best alternative among the available alternatives under the given different criteria in fuzzy environment. This search for best alternative has generally been carried out by one of two different approaches: the Bellman and Zadeh implied conjunction approaches and the weighted average rating method. Bass and Kwakarnaak (1977) proposed an algorithm to rate and ranking multiple alternatives in decision-making problems that are uncertain or imprecise in nature. They assume that all the alternatives can be centralized by a set of attribute associated with weight that is the measure of its importance and that each alternative can also be rated with respect to each attribute. Javadi *et al.* (2013) proposed comprehensive mixed-integer linear programming model to concurrently tackle the CFP, inter-cell and layout with regard to the main operational specification.

Paydar *et al.* (2014) extended a mixed-integer linear mathematical model to integrate preparation, production planning in a supply chain and configuration of cells while considering some critical parameters.

The AHP is a structured technique based on multi-criteria decision making (MCDM) for converting the subjective assessments of relative importance into a set of weights (Saaty, 1977, 1982, 1987).

Wu *et al.* (2013) discussed and proposed prioritization method for intuitionistic fuzzy preference and interval-valued intuitionistic fuzzy AHP method for multi-criteria decision-making problem. Liang and Wang (1991) explored the group preference aggregation procedure in AHP and violation social choice axiom conduct the rank of site selection rating on the basis of fuzzy and decision-making criteria.

3. Methodology

Case study: the case study was conducted in a manufacturing company located in National Capital Region of India. The case company is involved in manufacturing of automotive components for a multinational company. The case company is using conventional manufacturing systems for manufacturing of the components. The management of the case company is interested in selecting the most effective manufacturing system to sustain in the competitive market. The manufacturing system should be flexible and responsive to the needs of the customer. Alternative manufacturing systems are FMS, LMS, AMS, CMS and LaMS. The current study will be useful for the management of the case company to select the most effective manufacturing systems according to their needs. The findings of the research are communicated to the management of the case company. The management will implement the finding of the research only after analyzing its financial implications.

In this work, five barriers have been identified in a brain-storming session. In the brain-storming session, experts having experience of ten years have participated. The problem of prioritization of manufacturing systems on the basis of effect of barriers on the effectiveness of the manufacturing system is a multi-criteria decision-making problem. The problem is solved by using fuzzy-based multi-criteria decision-making (F-MCDM) approach using dominance matrix (DM) as follows.

3.1 F-MCDM approach

In order to prioritize manufacturing systems on the basis of their effectiveness influenced by barriers, an MCDM framework is developed.

The main objectives of the approach are:

- to identify the set of barriers and different decision makers, every decision maker/expert having their own set of viewpoints for set of manufacturing systems;
- to develop the viewpoints in a matrix form for the different barriers across a different manufacturing systems;
- to develop the mean aggregate matrix, the geometric mean aggregate matrix, the pessimistic aggregate matrix and the modified aggregation matrix;
- to aggregate the membership values using modified pessimistic aggregation;
- to identify an effective manufacturing system using the DM approach by introducing tolerance limit and weightages for each criteria; and
- to conduct the sensitivity analysis of effective manufacturing system.

For selecting the best from a set of available alternatives, F-MCDM approach is used. Fuzzy values are used to represent rating and weights and are aggregated by a utility function. F-MCDM approach (Saaty, 1987; Prakash *et al.*, 2017) embeds the fuzzy techniques to MCDM.

For implementing the research methodology, following steps are adopted:

- Step 1: problem identification.

  The management of the case company wants to select an effective manufacturing system for sustainable growth. They are looking for a manufacturing system whose effectiveness is least affected by the barriers. The data are collected for the MCDM framework and are utilized to solve the problem. The influence of barriers on the effectiveness of the manufacturing systems is compared using Saaty's scale.

- Step 2: selection of evaluation criteria.

  The evaluation criteria are in terms of qualitative factors. The criteria are identified based on applicability and computational complexity. The defined evaluation criteria will be used as the attributes of MCDM formulation and are the input data of decision matrix for selection method.

- Step 3: initial short listing.

  In the initial shot listing, the infeasible alternatives and criteria are eliminated. Alternatives represent the different choices of action available with the decision makers. Usually, the set of alternatives is assumed to be finite, ranging from various to hundreds. They are supposed to be short list, ranked and eventually prioritized. The alternatives which possess unacceptable and infeasible attribute values are eliminated in the short-listing process. The conjunctive method is employed to remove the unacceptable alternatives. Any alternative which has an attribute value worse than the cut-off values will be eliminated. The cut-off values given by the decision makers play a key role in eliminating the alternatives.

- Step 4: assigning the weights on evaluation criteria.

  Criteria represent the different dimensions from which the alternatives can be viewed. If the numbers of criteria are large in some cases, they may be arranged in a hierarchical manner. Some criteria may be major criteria and each major criterion may be associated with several sub-criteria. Similarly, each sub-criterion may be associated with various sub-criteria and so on.

After the initial short listing, the decision maker's preference information on the evaluation criteria is defined. This will reflect which criterion is more important to the experts. Relative weights are assigned to each evaluation criterion to describe the experts' preference information, the weights must be carefully considered based on the experts' preferences and experiences and subjective scale between 0.0 and 1.0 is used with calibration that 0.0 stands for extremely unimportant while 1.0 represents extremely important.

The normalized matrix a_{ij} is represented as in the following equation:

$$a_{ij} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \ldots & a_{1N} \\ a_{21} & a_{22} & a_{23} & \ldots & a_{2N} \\ . & & & & \\ . & & & & \\ a_{M1} & a_{M2} & a_{M3} & \ldots & a_{MN} \end{bmatrix} \tag{1}$$

where N is the number of alternatives and M is the number of criteria, and a_{ij} is the membership value of ith alternative ($i=1-N$) in terms of the jth criterion ($j=1-M$).

Each membership value is raised to the power equivalent to the relative weight (w_j) of the corresponding criterion. In general, for realistic comparison, the exponential values of weights are considered. Here, each weight value is exponential to given membership values. The total weighted membership values are to be placed in the position matrix for evaluation.

Therefore, the weighted position matrix "x" for a_{ij} is represented as in Equation (2): $X=[a_{ij}\ w_j]$ where "x" indicates weighted position matrix; "a_{ij}" indicates normalized matrix; and "w_j" indicates weight assigned.

Thus, the weighted position matrix is shown in Equation (3):

$$X = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \ldots & a_{1N} \\ a_{21} & a_{22} & a_{23} & \ldots & a_{2N} \\ . & & & & \\ . & & & & \\ a_{M1} & a_{M2} & a_{M3} & \ldots & a_{MN} \end{bmatrix} * \begin{bmatrix} w_1 & w_1 & w_1 & \ldots & w_N \\ w_2 & w_2 & w_2 & \ldots & w_N \\ . & & & & \\ . & & & & \\ w_N & w_N & w_N & \ldots & w_N \end{bmatrix} \tag{2}$$

where * represents exponential form of weights. Therefore, weighted position matrix is as follows:

$$X = \begin{bmatrix} a_{11}w_1 & a_{12w_1} & a_{13}w_1 & \ldots & a_{1N}w_N \\ a_{21}w_2 & a_{22}w_2 & a_{23}w_2 & \ldots & a_{2N}w_N \\ . & & & & \\ . & & & & \\ a_{M1}w_N & a_{M2}w_N & a_{M3}w_N & \ldots & a_{MN}w_N \end{bmatrix} \tag{3}$$

- Step 5: selection of alternatives using F-MCDM approach.

  The DM is chosen to select the most suitable alternative considering its simplicity. Basically, the DM provides dominance of each alternative to others.

Dominance method for decision making is characterized by a set of alternatives, set of criteria and numerous decision makers, each with their own set of viewpoints. This process can be represented in a matrix form and is known as the evaluation matrix. In judging the finite set of manufacturing systems ($A_1, A_2, \ldots, A_N$) across a set of barriers ($B_1, B_2, \ldots, B_M$), one can assign a value for each barriers and for each manufacturing system. Since one evaluation matrix would not adequately define the evaluation of all decision makers, a series of matrices is developed over a range of positions. Since the evaluation is based on subjective interpretations, there is no choice but to tolerate some level of imprecision and ambiguity.

An inherent property of DMs is that they are additive. Therefore, if the features in an aggregate matrix are subdivided into k sets and a DM is calculated for each set, then the complete DM for the entire aggregate matrix is simply the matrix sum of the k DMs. The difference between the column sums and the row sums of the DM gives the dominance relation between the alternatives. This dominance relation is normalized with respect to the most inferior alternative as the datum for ease of reference and expressed as a dominance vector of dimension N.

The opinion of the expert can be easily expressed in matrix format. A decision matrix A is an ($M \times N$) matrix in which element a_{ij} indicates the performance of alternative A_i when it is evaluated in terms of decision criterion C_j, (for $i = 1, 2, 3, \ldots, M$, and $j = 1, 2, 3, \ldots, N$). In order to display the dominance structure between all possible pairs of lean manufacturing tools, an $N \times N$ matrix, called the DM is constructed. The element d_{ij} is the number of factors for which the membership value of lean tool "*J*" is greater than that of manufacturing system "*i*."

The dimensionality N is equal to the number of manufacturing system under consideration. It is also assumed that the decision maker has determined the weights of relative performance of the decision criteria (denoted as W_j, for $j = 1, 2, 3, \ldots, N$).

The weighted matrix is as shown in Table I:

- Step 6: evaluation of the alternatives.

  The concept of membership plays a vital role in this application. Membership is defined over a range from 0 (low) to 1 (high) against some qualitative scale. By convention, low represents the least desirable end of the scale and high represents the most desirable end of the scale.

The membership value of 1.0 is treated as complete satisfaction of needs associated with a qualitative feature and the membership value of 0.0 as complete dissatisfaction.

Alt. ↓	Barriers → B_1	B_2	B_3	B_4	…..	B_N	Weights ↓
A_1	a_{11}	a_{12}	a_{13}	a_{14}	…	a_{1N}	w_1
A_2	a_{21}	a_{22}	a_{23}	a_{24}	…	a_{2N}	w_2
A_3	a_{31}	a_{32}	a_{33}	a_{34}	…	a_{3N}	w_3
.	.	.	.	.		.	
.	.	.	.	.		.	
A_M	a_{M1}	a_{M2}	a_{N3}	a_{N4}	…	a_{MN}	w_N

Table I. Weighted matrix

Intermediate values can be assigned depending on the degree of satisfaction. In order to define a basis on which an alternative can be considered superior to another, the concept of dominance is invoked. A manufacturing system is said to dominate another manufacturing system for a given feature if and only if its aggregate membership value is greater than that of the other manufacturing system. A manufacturing system is said to be superior to a second manufacturing system if it dominates the second manufacturing system in more features than the number of features in which the second dominates the first. If the *j*th column is summed, the total number of dominances of manufacturing system *j* over all other manufacturing system is obtained. Similarly, if the *i*th row is summed, the number of times that the *i*th manufacturing system is dominated by all other manufacturing system is obtained. The sums of columns and rows can be compared and from this one can see that most favorable outcomes have higher column sums and lower row sums. The method with the highest column sum and lowest row sum is recommended as the most appropriate alternative under consideration:

- Step 7: sensitivity analysis.

  Sensitivity analysis is performed on the MCDM method selection algorithm in order to analyze its robustness with respect to parameter variations, such as the variation of DM's preference information and the input data (Triantaphyllou and Sanchez, 1997). Assessment of dominance is quite sensitive to errors in the data of the position matrix. They are potentially changed by the addition or removal of even a single option to or from the set under consideration. To avoid such sensitive errors, sensitivity analysis is carried out for the effective use and implementation of qualitative factors. A tolerance limit of (± 0.03) is considered in the decision-making process of DM. For example, if membership value assigned to one alternative is 0.65 and the membership value of another alternative is 0.67 so, according to dominance criteria concerned, domination of 0.67 over 0.65 cannot be considered because the difference between these two membership values is 0.02 which is falling under the limit of tolerance ± 0.03.

The objective of a typical sensitivity analysis of an MCDM problem is to find out when the input data (i.e. the a_{ij} and w_j values) are changed into new values, the ranking of the alternatives will change. Above-said statement can be explained in detail by taking min-max criteria. By applying min-max criteria, the entire rankings may change for example from Table VI, modified aggregated matrix max. membership value 0.73 of barrier B1 corresponding to alternative A1 is maximum and membership value of 0.50 corresponding to alternative A4 is minimum, so as per min-max criteria, rankings of alternatives will be as A4 stands in the first position and A1 stands in the last position, whereas per assigning weightages to criteria, the positions are entirely different. To avoid such ambiguity and lacunas, sensitivity analysis is to be carried out to select the best alternative among available alternatives.

The available manufacturing systems are:

- FMS – A1;
- LaMS – A2;
- CMS – A3;
- LMS – A4; and
- AMS – A5.

The collected data are in the form of qualitative factors.

4. Ranking of alternatives

The manufacturing systems are to be ranked based on the qualitative criteria. A questionnaire has been prepared to evaluate the effective manufacturing system against these alternatives.

The questionnaire was circulated to different manufacturing sector experts to have their opinions in terms of membership values examined by experts that are shown in Table II.

The questionnaire deals with qualitative barriers influencing the effectiveness of the manufacturing system that are:

- lack of management commitment – B1;
- lack of cross-functional workforce – B2;
- lack of integrated condition monitoring system – B3;
- lack of training of manpower – B4; and
- resistance of worker against change – B5.

An interview with the different manufacturing strategies experts was also conducted to collect data for evaluating the "qualitative criteria" affecting the barriers in manufacturing system selection. A correspondence between the qualitative barriers and the different manufacturing system was made explicit, and a numerical scale between 0.0 and 1.0 was established. A value of 0.5 indicates a neutral effect while a value of 1.0 is defined as complete satisfaction.

To assess the impact of qualitative and quantitative factors, the various lean manufacturing implementing firms are approached and their membership values are placed in different matrices.

In response to the questionnaire, each expert is given his/her degree of belief about the effective manufacturing tools in terms of 0-1 with respect to the criteria. The transformed results of the questionnaire are tabulated in position matrices for each expert and are as follows.

For example, the membership value of "A21" in mean aggregated (Table III) is obtained as follows. Here "21" indicates the second row of the first column of above matrix which is formed by using the following equation:

$$\mu_{ij} = \frac{1}{k}\sum_{i=1}^{k} \mu_{ij}^{1} \tag{4}$$

where μ_{ij} is the mean aggregated membership value; k the number of position matrices; i the row; and j the column, and the procedure for obtaining the above value is as follows:

$$X_{21} = [x_{21}^{1} + x_{21}^{2} + \cdots + x_{21}^{12}]/12.$$

Where X_{21} is the mean aggregated membership value ($=0.69$); and $x_{21}^{1}, x_{21}^{2}, \ldots, x_{21}^{12}$ are the membership values of factor against each alternative assigned by experts and shown as the position matrices in Table II.

Now X_{21} is calculated as shown above.

$X_{21} = 0.69$ and is tabulated in the mean aggregated matrix (Table III) at the second row of the first column. Remaining membership values are also calculated in the same manner and are positioned in Table III of mean aggregated matrix as shown above.

After identifying the mean aggregated values, the pessimistic aggregated matrix should be formed to minimize the risk of taking the values of memberships given by all the experts from the different companies for each factor against each alternative. To form pessimistic aggregated matrix, minimum membership value of each factor against each alternative from all the position matrices is taken and formed in a matrix shape as shown in Table IV. For example, membership value of "X_{34}" of pessimistic aggregated matrix is obtained as follows. Here "34" indicates the third row of the fourth column of pessimistic aggregated

		A1	A2	A3	A4	A5
Expert 1	B1	0.75	0.60	0.45	0.60	0.55
	B2	0.52	0.80	0.50	0.55	0.65
	B3	0.65	0.45	0.60	0.55	0.75
	B4	0.50	0.60	0.35	0.40	0.55
	B5	0.75	0.70	0.60	0.65	0.80
Expert 2	B1	0.85	0.75	0.70	0.55	0.50
	B2	0.75	0.70	0.55	0.70	0.75
	B3	0.80	0.65	0.65	0.75	0.80
	B4	0.65	0.70	0.60	0.45	0.65
	B5	0.75	0.60	0.75	0.50	0.60
Expert 3	B1	0.75	0.65	0.70	0.75	0.70
	B2	0.75	0.60	0.65	0.70	0.65
	B3	0.65	0.60	0.55	0.70	0.70
	B4	0.70	0.55	0.80	0.65	0.60
	B5	0.60	0.40	0.70	0.60	0.55
Expert 4	B1	0.70	0.65	0.70	0.80	0.75
	B2	0.75	0.70	0.75	0.75	0.65
	B3	0.80	0.80	0.60	0.75	0.55
	B4	0.60	0.75	0.65	0.70	0.60
	B5	0.55	0.65	0.60	0.75	0.65
Expert 5	B1	0.75	0.65	0.70	0.60	0.55
	B2	0.65	0.70	0.55	0.60	0.75
	B3	0.75	0.70	0.60	0.65	0.70
	B4	0.55	0.50	0.60	0.65	0.65
	B5	0.70	0.65	0.80	0.75	0.60
Expert 6	B1	0.75	0.80	0.70	0.75	0.60
	B2	0.80	0.75	0.70	0.60	0.55
	B3	0.70	0.60	0.55	0.55	0.65
	B4	0.85	0.65	0.75	0.70	0.80
	B5	0.65	0.70	0.70	0.65	0.55
Expert 7	B1	0.80	0.75	0.65	0.55	0.60
	B2	0.70	0.65	0.50	0.60	0.75
	B3	0.65	0.60	0.75	0.70	0.70
	B4	0.55	0.75	0.60	0.40	0.65
	B5	0.65	0.60	0.70	0.55	0.75
Expert 8	B1	0.80	0.75	0.70	0.65	0.60
	B2	0.70	0.65	0.60	0.75	0.55
	B3	0.55	0.60	0.80	0.65	0.60
	B4	0.50	0.60	0.75	0.70	0.65
	B5	0.45	0.70	0.55	0.65	0.60
Expert 9	B1	0.70	0.75	0.55	0.60	0.65
	B2	0.75	0.70	0.80	0.65	0.60
	B3	0.65	0.60	0.70	0.55	0.60
	B4	0.80	0.75	0.75	0.65	0.60
	B5	0.60	0.80	0.75	0.65	0.55
Expert 10	B1	0.80	0.75	0.70	0.85	0.75
	B2	0.70	0.65	0.55	0.60	0.65
	B3	0.55	0.40	0.65	0.50	0.45
	B4	0.75	0.70	0.70	0.65	0.50
	B5	0.65	0.60	0.55	0.70	0.75
Expert 11	B1	0.75	0.70	0.80	0.65	0.60
	B2	0.65	0.60	0.55	0.70	0.75
	B3	0.60	0.80	0.75	0.65	0.55
	B4	0.70	0.65	0.55	0.40	0.45
	B5	0.75	0.65	0.60	0.70	0.55
Expert 12	B1	0.65	0.55	0.70	0.55	0.50
	B2	0.60	0.65	0.70	0.75	0.55
	B3	0.70	0.60	0.65	0.75	0.55
	B4	0.65	0.60	0.60	0.45	0.55
	B5	0.75	0.60	0.70	0.50	0.55

Table II.
Experts' opinion

matrix which can be calculated by using the following equation:

$$\begin{aligned}\mu_{ij} &= \mu_{ij}^1 + \mu_{ij}^2 + \cdots + \mu_{ij}^k \\ &= \min\left(\mu_{ij}^1, \mu_{ij}^2, \ldots, \mu_{ij}^k\right)\end{aligned} \tag{5}$$

where μ_{ij} is the membership value:

$$\mu_{ij}^1, \mu_{ij}^2, \ldots, \mu_{ij}^k$$

where i and j are row and column, respectively, and $1, 2, \ldots, k$ indicates the number of matrices formed.

Minimum value among all the values of each criterion is taken and formed as single matrix as shown in Table IV, and $X_{34} = 0.50$ is calculated as shown below.

$X_{34} = \text{min. of } \left[x_{34}^1, x_{34}^2, \ldots, x_{34}^{12}\right]$ is the minimum membership values of criteria against alternatives.

So, minimum value is "0.50" among all the membership values and is positioned in the matrix, in the fifth row of the forth column of the matrix, and remaining minimum membership values for all the criteria against alternatives are tabulated as pessimistic aggregated matrix as shown in Table IV.

After identifying the pessimistic aggregated values, the geometric mean aggregated matrix should be formed to minimize the risk of taking the values of memberships given by all the experts from the different companies for each factor against each alternative. To form geometric mean aggregated by taking the geometric mean of the corresponding elements as shown in Table V.

	A1	A2	A3	A4	A5
B1	0.75	0.70	0.67	0.66	0.61
B2	0.69	0.68	0.62	0.66	0.65
B3	0.67	0.62	0.65	0.65	0.63
B4	0.65	0.65	0.64	0.56	0.61
B5	0.65	0.64	0.67	0.64	0.63

Table III. Mean aggregation of responses

	A1	A2	A3	A4	A5
B1	0.65	0.60	0.45	0.55	0.50
B2	0.52	0.60	0.50	0.55	0.55
B3	0.55	0.45	0.55	0.50	0.50
B4	0.50	0.50	0.35	0.40	0.45
B5	0.45	0.40	0.55	0.50	0.55

Table IV. Pessimistic aggregation of responses

	A1	A2	A3	A4	A5
B1	0.75	0.69	0.66	0.65	0.61
B2	0.69	0.68	0.61	0.66	0.65
B3	0.67	0.61	0.65	0.64	0.62
B4	0.64	0.65	0.63	0.54	0.61
B5	0.65	0.63	0.66	0.63	0.62

Table V. Geometric mean aggregation of responses

These membership values of the experts are combined in a single matrix using modified pessimistic aggregation for each criterion against the alternatives since pessimistic aggregation attempts to minimize the risk, while the modified pessimistic aggregation may prove to be useful to have a spectrum of polarized opinions of the experts.

The final aggregated membership values are from modified pessimistic aggregation, which is an average of arithmetic mean, pessimistic aggregation and geometric aggregation. Table VI is the modified pessimistic aggregation table for the position matrices of various experts. These values are obtained by taking different membership values for the factors affecting manufacturing system selection by experts.

For example, membership value of "X_{34}" of modified pessimistic aggregation is obtained by using the following equation:

$$X_{ij}(\text{Modified}) = 1/3\{x_{ij}(\text{mean aggregate}) + x_{ij}(\text{pessimistic aggregate}) + x_{ij}(\text{geometric aggregate})\}\ldots \quad (6)$$

And the procedure for obtaining the above membership value is as follows.

X_{34} = one-third of every membership value of criteria against alternative of mean aggregated matrix, pessimistic aggregated matrix and geometric mean aggregate matrix.

So, $X_{34} = \{[x_{34}^{\text{ma}} + x_{34}^{\text{pa}} + x_{34}^{\text{gma}}\}/3]$, here x_{34}^{ma}, x_{34}^{pa}, and x_{34}^{ma}, are membership values of criteria against alternative of the third row of the fourth column of mean aggregated matrix, pessimistic aggregated matrix and geometric mean aggregate matrix, respectively.

Here ma is the mean aggregation; pa the pessimistic aggregation; and gma the geometric mean aggregation.

So, $X_{34} = \{(0.65 + 0.50 + 0.64]/3\}$.

$X_{34} = 0.60$ and is tabulated in the modified pessimistic aggregated matrix (Table VI), remaining aggregated membership values are also calculated in the same manner and are positioned in the table.

5. Comparison of alternatives

The basis on which alternatives are ranked is based on DM. An alternative is said to dominate another alternative for any given feature if its aggregate membership values are greater than that of the other alternative. An alternative is defined to be superior to a second alternative if it dominates the second alternative in more features than the number of features in which the second dominates the first.

In many cases, there may be alternatives which are very close to each other on the basis of the DM. In these situations, the magnitude of the dominances which is the difference in the membership values in the aggregate matrix can be examined. Because of the uncertainty or fuzziness of the information contained in the aggregate matrix entries, it is useful to establish a tolerance limit. That is, if the membership value of a second alternative is outside the specified limit, then dominance exists, while if it is within the limit, the alternatives can

Table VI. Modified aggregation of responses

	A1	A2	A3	A4	A5
B1	0.73	0.66	0.59	0.62	0.57
B2	0.63	0.65	0.58	0.62	0.62
B3	0.63	0.56	0.62	0.60	0.58
B4	0.60	0.60	0.54	0.50	0.56
B5	0.58	0.56	0.63	0.59	0.60

be considered equivalent with respect to that feature. This range is set arbitrarily (± 0.04). A higher value of this may result in losing too much information thereby causing imprecise decision leading to distortion in the criteria for the decision making.

6. DM structure

In order to display the dominance structure between all possible pairs of lean manufacturing tools, an N by N matrix, called the DM is constructed. The element d_{ij} is the number of features for which the membership value of manufacturing system j is greater than that of manufacturing system i.

For example, in modified pessimistic aggregation as shown in Table VI, the element a_{12} indicates that how many times criteria of alternative 2 dominates criteria of alternative 1 and is tabulated in DM at a_{12}.

The dimensionality N is equal to the number of lean manufacturing tools under consideration. If the jth column is summed, the total i number of dominances of manufacturing system jth over all, other manufacturing system is obtained. Similarly, if the ith row is summed number of times jth manufacturing system is dominated by all, other manufacturing system is obtained. The sum of columns and rows can be compared and it can be seen that most favorable outcomes have higher column sums and lower row sums. An inherent properly of DMs is that they are additive.

Therefore, if the features in an aggregate matrix are subdivided into "k" sets and a DM is calculated for each set, then the complete DM for the entire aggregate matrix is simply the matrix sum of the k DMs. The difference between the column sums and the row sums of the DM gives the dominance relation between the alternatives.

This dominance relation is normalized with respect to the most inferior alternative as the datum for ease of reference is expressed as a dominance vector of dimension N. The dominance of alternatives for the modified pessimistic aggregation is given in Table VII.

On the basis of the above DM, the effective alternative is identified as follows:

- sum up all the column and row values;
- choose the column with highest value and lowest row totals to select the effective manufacturing system;
- if two alternative column sums are same, choose the alternative with minimum row sum;
- if sums of columns and rows are the same, choose an alternative arbitrarily; and
- to choose the next best, delete the values of the best lean tool and repeat the procedure.

The alternatives are ranked with above methodology and are shown in Table VIII.

As per Table VIII, the ranking of manufacturing system is as follows:

(1) A2 (17, 3) LaMS;

(2) A5 (9, 5) AMS;

(3) A4 (6, 4) LMS;

	A1	A2	A3	A4	A5
A1	–	5	1	3	3
A2	0	–	1	2	0
A3	4	4	–	3	4
A4	2	3	2	–	2
A5	1	5	1	3	–

Table VII. Dominance matrix of the modified pessimistic aggregation

(4) A1 (4, 1) FMS; and

(5) A3 (1, 0) CMS.

In Table VIII, highest column sum is 17 and lowest row sum is 3 for the alternative A2. Therefore, using DM, the alternative A2 is the best alternative corresponding to LaMS. To choose the next best, the values of these alternatives values are removed and the procedure is repeated for the remaining manufacturing system.

In the process following are the limitations:

- all qualitative factors are given equal importance;
- some important factors might have been overlooked; and
- in few cases, inferior factors are ranked equally with other factors.

To overcome such limitations, concept of weightage (0.0-1.0) given by experts has been introduced.

7. Assigning the weights on evaluation criteria

The membership values given for quantitative factors are of equal importance. To overcome certain drawbacks given by different experts, before evaluating the alternatives, weightages for each factor have been introduced to get accuracy in selecting effective alternative among available alternatives. Satty's multi-criteria decision algorithms are assigned for weightages and are tabulated in Table IX.

After identifying the weightages to be assigned to the membership values of features of available alternatives from the experts, these weightages are assigned exponentially to all the factors in Table VI that are placed in Table X.

The alternatives are ranked according to previous methodology, given in Table XI.

Ranking of factor with weighted values is as follows:

(1) A2 (9, 1) LaMS;

(2) A4 (8, 6) LMS;

(3) A5 (3, 0) AMS;

(4) A1 (2, 0) FMS; and

(5) A3 (0, 0) CMS.

Table VIII. Analysis of dominance matrix

	A1	A2	A3	A4	A5	Row sum			
A1	–	5	1	3	3	12	7	4	1
A2	0	–	1	2	0	3	1	0	0
A3	4	4	–	3	4	15	11	7	4
A4	2	3	2	–	2	9	6	4	2
A5	1	5	1	3	–	10	5	2	1
Column sum	7	17	5	11	9				
	7	14	4	9	9				
	6	10	3	6	7				
	4	5	1	3	4				

Table IX. Weightages of factors

Factor	B1	B2	B3	B4	B5
Weights	0.474	0.144	0.13	0.202	0.05

8. Results and discussion

Due to diverse needs of industries, various manufacturing systems are available for implementation with the barriers such as lack of management commitment, lack of cross-functional workforce, lack of integrated condition monitoring system, lack of training of manpower and resistance of worker against change. The selection of appropriate manufacturing system plays a vital role for effective system. Based on the barriers and different manufacturing systems, the important barriers are identified and effective manufacturing system is selected. The factors applied are numerous, subjective and difficult to quantify. The expert's subjective knowledge is converted into numerical measure and is used to select the alternatives. Since the membership values are very close to many features, alternatives are affected for comparison. Because of uncertainty of fuzziness of information contained in aggregate matrix, entire tolerance limit was established. That is, if a membership value of a second alternative is outside the specific limit then dominance exists while if it is within the limit the alternative can be considered equivalent with respect to that feature within the range of ± 0.04.

Since some inferior factors rank equally with other factors to avoid these lacunas, concept of weightage between 0.0 and 1.0 was introduced and the alternatives are ranked based on weightages. The alternatives are selected without weightages and with weightages in the selection process using DM. The ranking of manufacturing systems is shown in Table XII.

	A1	A2	A3	A4	A5	Weight
B1	0.59	0.66	0.59	0.59	0.59	0.474
B2	0.82	0.84	0.79	0.87	0.83	0.144
B3	0.84	0.88	0.83	0.92	0.86	0.13
B4	0.79	0.82	0.85	0.73	0.79	0.202
B5	0.94	0.96	0.92	0.96	0.94	0.05

Table X. Weighted aggregated table

	A1	A2	A3	A4	A5	Row sum			
A1	–	2	1	2	0	5	3	0	0
A2	0	–	0	1	0	1	0	0	0
A3	0	4	–	3	1	8	4	0	0
A4	2	2	2	–	2	8	6	2	0
A5	0	1	0	3	–	4	1	0	0
Column sum	2	9	3	9	3				
	2	8	3	8	3				
	2	6	3	6	3				
	2	4	2	2	2				

Table XI. Weighted dominance matrix analyses

Sl. No.	Manufacturing systems	Ranking Without weight	With weight
1	LaMS	1	1
2	AMS	2	3
3	LMS	3	2
4	FMS	4	4
5	CMS	5	5

Table XII. Ranking of manufacturing systems

Here ranking of manufacturing systems are LaMS (A2), AMS (A5), LMS (A4), FMS (A1) and CMS (A3), respectively, that are without weights and A2 corresponds to LaMS, A5 corresponds to AMS, A4 corresponds to Lean manufacturing system, A1 corresponds to FMS and A3 corresponds to CMS.

After introducing the weightages, the position of alternative LMS (A4) and AMS (A5) has been changed as LaMS (A2), LMS (A4), AMS (A5), FMS (A1) and CMS (A3), respectively. This indicates the importance of weightages that is reflected in the selection and ranking of alternatives.

The results obtained are communicated to the management of the case company. These results will be discussed at top-level management. Decision for implementation in the case company will be based on analysis of its financial implications.

9. Conclusion

Manufacturing systems' effectiveness of any manufacturing company is affected by barriers. The management of the case company wants to select a manufacturing system whose effectiveness is least affected by the barriers. The five manufacturing systems are available to the management. The management desires to analyze and prioritize five manufacturing systems on the basis of their sensitiveness toward barriers. The prioritization of manufacturing systems depends on qualitative factor decision-making criteria and hence becomes a complex MCDM problem. The problem is solved by using F-MCDM framework using DM.

The major findings of the research work are listed as below:

- The alternate manufacturing systems are ranked according to their support values. For example, LaMS is ranked first and has supporting values as 17 and 3. AMS, LMS, FMS and CMS are ranked accordingly with supporting values (9,5), (6,4), (4,1), (1,0), respectively.
- The ranking of the manufacturing systems depends on the degree of influence of barriers on the effectiveness of the manufacturing system.
- There is minor change in the ranking of manufacturing systems due to consideration of weight of barriers.

The results of the research work are useful for the case company. The case company is interested in analyzing the alternative manufacturing systems on the basis of their effectiveness and their sensitivity toward various barriers. The management of Indian manufacturing company will take decision to adopt a manufacturing system whose effectiveness is least sensitive toward barriers. Effectiveness of the manufacturing system will improve with time without having retardation due to barriers. With improved effectiveness of the manufacturing system, the manufacturing company would be able to survive with global competition. The result of the present work is based on the inputs from the case company and may vary for the other manufacturing company. In the present work, only five alternative manufacturing systems and five barriers have been considered. To obtain the better result, the MCDM approach with more number of alternative manufacturing systems and barriers might be considered.

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