Development of fuzzy PROMETHEE algorithm for the evaluation of Indian world-class manufacturing organisations

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Abstract: Establishing a performance-oriented evaluation in manufacturing sectors is the key to successful administrations and further improvement. However, because of lacking relative comparable measuring standards, it is difficult to measure the relative performance of one organisation while comparing to other organisations with regard to the multiple criteria decision making (MCDM) of performance evaluation. This paper aims to focus on the evaluation of world class manufacturing (WCM) practices in Indian manufacturing sectors. The algorithm in this paper is based on the concept of fuzzy set theory and the PROMETHEE. This algorithm is then applied to three heavy engineering sector organisations in India. These organisations are ranked according to their WCM practices.

Keywords: fuzzy PROMETHEE; heavy engineering sector; world class manufacturing; WCM; India.

Reference to this paper should be made as follows: Digalwar, A.K. and Date, P.A. (2016) 'Development of fuzzy PROMETHEE algorithm for the evaluation of Indian world-class manufacturing organisations', *Int. J. Services and Operations Management*, Vol. 24, No. 3, pp.308–330.

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1 Introduction

In the competitive and dynamic world of today, organisations are compelled to adapt a manufacturing strategy that would excel their customers' requirements as well as ensure company's growth in the market. A manufacturing strategy is a plan for moving from where it is to where it wants to be. World-class manufacturing (WCM) is one such strategy which helps organisations to attain their desired goals because it is not just confined to a particular area but focuses on the organisation as a whole.

The term 'WCM' was coined by Hayes and Wheelwright (1984) to describe organisations that achieved a global competitive advantage through the use of their manufacturing capabilities as a strategic weapon. It is a subset of 'best practices' paradigm of operations strategy (Voss, 1995). It refers to being the best organisation in one's particular sector of industry (Todd, 1995). Oliver et al. (1994) explained that to qualify as world class, a plant had to demonstrate outstanding performance on measures of both productivity and quality. WCM requires an overall willingness to establish closer connections with everyone from customers and suppliers to workers; an unwavering commitment to self-analysis and improvement; and an aggressive approach to technologies that can help turn visionary strategies into gold-medal realities. It has often been characterised by three core strategies of customer focus; quality; and agility; and six supporting competencies viz. employee involvement; supply management; technology, product development; environmental responsibility and employee safety; and corporate citizenship (Kinni, 1996).

During the past few decades, research on WCM attracted attention from both academia and industry. There are many reviews (Gunasekaran et al., 1998; Khurrum et al., 2013; Digalwar et al., 2013; Singh and Ahuja, 2014; Muthukumar et al., 2014; Sugumaran et al., 2014; Ojha et al., 2014) available in the literature addressing issues surrounding the definition, classification, nature and need of different dimensions of WCM like *total quality management, total productive maintenance, supply chain management, JIT/Lean manufacturing, etc.* Over the last few years, it has been observed that the organisations that have incorporated WCM as a manufacturing strategy have fared well, resulting in improvements in all areas. Adopting WCM practices has resulted in improvement in an aviation joint venture in China (DeFilippo, 1997). Implementation of WCM practices in a Swedish cemented carbide tools manufacturer was recognised as an economic success for the company and also resulted in improvement in the production and control systems (Lind, 2001). Companies following WCM practices in Saudi have shown a better coordination in their supply chains (Falah et al., 2003). It has been observed that the world class logistics firms have outperformed their non-world-class counterparts globally (Closs and Xu, 2000). WCM practices are not only suitable for make-to-stock (cellular layout) companies but also for make-to-order (job shop) companies, as is evident from the study of an agricultural equipment manufacturer by Hendry (1998). Brown et al. (2007) have shown that world-class plants incorporate both strategic operations content and strategic operations processes, whilst low-performing plants do not, through their study of manufacturing/assembly plants in the computer industry. Thus, it is evident that organisations all around the world have started incorporating world-class practices and have shown considerable amount of improvements in the organisation as a whole.

The theory on WCM suggests the strategy that an organisation must adopt. The tools and techniques used to implement this strategy have been left to the organisation to choose for themselves. This system works because there cannot be a unified set of practices for all the different types of organisations. Since the organisations implementing WCM largely differ from each other in terms of the sector of industry in which they operate. Therefore, the question arises as to how one evaluates the world class manufacturing practices of an organisation in a particular sector? How are organisations operating in a particular sector compared with each other with respect to their world-class practices?

Many researchers (Kasul and Motwani, 1995; Gunasekaran, 2000; Motwani, 2001; Kodali et al., 2004; Flynn et al., 1994; Digalwar and Sangwan, 2007; Tuzkaya et al., 2009; Digalwar et al., 2014) focused on development and validation of factors for implementation of WCM practices, however they have paid much less attention in development of methodology/algorithms for evaluation of WCM systems. This paper addresses these questions. A methodology has been proposed in this paper to evaluate Indian WCM firms based on performance indicators of WCM and eventually rank them according to their WCM practices. Present work makes use of the expertise of the decision makers to evaluate the organisations. Fuzzy PROMETHEE algorithm has been developed to rank the case organisations. This study will help organisations to benchmark with respect to the WCM pioneers in their sectors.

2 Fuzzy PROMETHEE algorithm

The Preference Ranking Order Method for Enrichment Evaluation (PROMETHEE) is a multi-criteria decision making (MCDM) algorithm given by Vincke and Brans (1985). It ranks a set of alternatives based on their performance over a set of criteria. In this case, the alternatives are the case organisations which are to be evaluated on their WCM practices and the criteria are the performance indicators used for WCM. Fuzzy set theory has been incorporated into the PROMETHEE method to deal with qualitative linguistic variables. The PROMETHEE and fuzzy PROMETHEE algorithms have been widely used in the literature in numerous fields of study due to following advantages.

- it is a user friendly outranking method
- it has been successfully applied to real life problems

- ease of application, efficiency and its interactivity – it has a transparent influence of each criterion and weight on the solution
- it is based on the importance of a performance difference between two solutions which is best describing whether a solution should be preferred to another one
- it is a ranking method quite simple in conception and application compared to other methods for MCDM
- it is well adapted to problems where a finite number of alternative actions can be ranked
- qualitative data and linguistic variables can be dealt with easily.

Most of the 'Fuzzy PROMETHEE' algorithms use the Fuzzy AHP technique to assign weights to the performance indicators or to the criteria. However, in this paper, the fuzzy set theory is used to assign weights to the performance indicators and to analyse qualitative data. Table 1 shows the various fields of study where PROMETHEE and fuzzy PROMETHEE algorithms have been applied.

Table 1 Application of PROMETHEE model in different study

S. no.	*Author(s)*	*Area of application*
1	Avikal et al. (2014)	Disassembly line balancing
2	Tavakoli et al. (2013)	Supplier selection
3	Gupta et al. (2012)	Selection of logistic service provider
4	Makan et al. (2012)	Selection of landfill site
5	Mouzakitis et al. (2011)	Assessment of companies as investment opportunities
6	Yilmaz and Dagdeviren, (2011)	Equipment selection
7	Mehrabad and Anvari (2010)	Evaluation of flexible manufacturing systems
8	Rao and Patel (2010)	Production research
9	Athawale and Chakraborty (2010)	Facility location selection
10	Juan et al. (2010)	Urban renewal projects
11	Tuzkaya et al. (2010)	Selection of material handling equipment
12	Halouani et al. (2009)	Project selection
13	Zhang et al. (2009)	Environmental management
14	Anand and Kodali (2008)	Selection of manufacturing systems
15	Dagdeviren (2008)	Equipment selection
16	Lin (2008)	Hazard monitoring and assessment
17	Chou et al. (2007)	Ecological engineering
18	Marinoni (2005)	Geographical information systems (GIS)
19	Geldermann and Rentz (2001)	Identification of best available techniques (BAT)
20	Geldermann et al. (2000)	Environmental assessment
21	Goumas and Lygerou (2000)	Alternative energy exploitation

3 Background of case organisations

For emerging country like India, the manufacturing sector is an important engine of growth. India's gross domestic product (GDP) in the fiscal year 2012–2013 as reported by Government of India is US$933 billion. The contribution of Industry to India's GDP is US$252 billions that are 27.03% and that of manufacturing sector is US$143 billion that is 15.24%. The growth of Industry as compared to the fiscal year 2011–2012 is 3.12% and that of manufacturing sector is 1.89%. The net growth is 4.96%. Thus, it can be seen very clearly that the manufacturing sector have a significant contribution in India's GDP. For India to keep progressing, it is of utmost importance that these sectors show phenomenal growth (Data Portal India, 2013).

The Indian engineering industry has witnessed an unprecedented growth in the past few years resulting from an increased investment in infrastructure development and industrial production. Today the engineering sector plays a significant role in the development of other industrial sectors in the economy. Last year the engineering sector alone contributed around 8% to the country's GDP.

The heavy engineering companies in India are some of the vanguard corporation in the country's economy. The heavy engineering goods and services in the country account a major share in the production and the distribution of engineering goods. The whole concept of heavy engineering includes the production of construction and industrial machinery, like turbines, transformers and even non-electrical heavy machinery, boilers, ships, aerospace equipment, nuclear equipment, etc. A recent engineering audit concluded that the heavy engineering sector in India makes use of the latest technology and services and are on power with the other striving to meet the international standards. These companies are also preferred for investment.

For the purpose of this study, three pioneer companies in the heavy engineering sector of India have been considered. For the sake of confidentiality, their names have not been revealed. The three companies will be henceforth referred to as company A, company B and company C in the paper. In order to understand the context in which the method was applied, we briefly present the motivation of the case study organisations to be a part of this research. Company A and company C had incurred heavy losses in the years 2006–2007 and 2005–2006 respectively. That is when their top management decided to incorporate WCM practices as a strategic measure to recover from the losses and to improve product quality and service. Company A and company C has been practicing WCM since 2008 and 2007 respectively. Company B has been practicing WCM over last ten years. It gradually shifted to WCM practices with the aim to become a market leader in its industry. All the three organisations have been practicing WCM for five years or more and wanted to see where they stand in terms of their WCM practices. They wanted their WCM practices to be analysed and compared to other WCM practitioners so that they can improve upon their WCM practices. The present study proposes to evaluate the world-class companies in the Indian heavy engineering sector by using the Fuzzy PROMETHEE algorithm.

4 Methodology

The aim of this study is to evaluate the WCM practices of Indian manufacturing organisations and rank them according to their practices. For this purpose, three case companies in the heavy engineering sector of India were studied. First of all, a questionnaire was developed and sent to the three case companies. The questionnaire consisted of questions about WCM practices being followed in the organisation. The respondents had to rate their practices on a five-point scale (i.e., 'very low', 'low', 'medium', 'high' and 'very high'). For example, in response to a question about reduction in manufacturing lead time that was achieved through WCM implementation, one of the respondents responded 'very high' implying that WCM practices followed by the organisation helped in reducing manufacturing lead time to a 'very high' extent.

Their responses of the three case companies (i.e., company A, company B and company C) were recorded and analysed using the Fuzzy PROMETHEE algorithm. The fuzzy PROMETHEE algorithm was preferred over other algorithms owing to its many advantages as listed in Section 2. Also, the algorithm ranks the alternatives based on their performance over all the criteria. Hence, it was best suited for this study as we had to rank the three organisations (alternatives) based on their performance on WCM performance measures (criteria).

The following sub-sections explain the application of fuzzy PROMETHEE algorithm to the problem in hand (i.e., ranking WCM organisations based on their WCM practices) in detail.

4.1 Generation of criteria and alternatives

The criteria used in this paper are the performance measures for WCM adopted from Sangwan and Digalwar (2008). They have given a set of 12 critical factors and 73 performance measures for WCM practices in Indian scenario. The 12 critical factors are top management commitment; knowledge management; employee training and empowerment; innovation and technology; vendor management; production planning and control; quality; flexibility; cost; environment, health and safety; customer service and satisfaction; and company growth. These are listed in Table 2.

The alternatives used in this study are the three case organisations referred to as company A, company B and company C. The company identities are not revealed for the sake of confidentiality. These companies are to be ranked according to their WCM practices based on their performance over the criteria using fuzzy PROMETHEE algorithm.

Table 2 Critical factors and performance measures (criteria) for evaluation of WCM

Critical factor	*Performance measures or criteria*	*Code*
Top management commitment	Resource allocation	TM1
	Planning for change	TM2
	Monitoring the progress	TM3
	Involvement in strategic quality management	TM4

Source: Sangwan and Digalwar (2008)

Table 2 Critical factors and performance measures (criteria) for evaluation of WCM (continued)

Critical factor	*Performance measures or criteria*	*Code*
Knowledge management	Availability of resources for KM	KM1
	Suitability of organisation culture for KM	KM2
	Willingness of employees to share knowledge	KM3
	Information, communication and technology (ICT) used for KM	KM4
	Number of times the knowledge has helped to solve problems	KM5
	KM helps to reduce response/lead time, reduction in rejection process cycle time	KM6
	Decrease in new product development cycle time by KM	KM7
	Presentations, meetings, discussion, etc., help to create new knowledge	KM8
Employee training and empowerment	Frequency of training and retraining	ETE1
	Training inside the company by in-house trainer (excluding on-the-job training)	ETE2
	Training inside the company by outside trainer	ETE3
	Total expenditure for training	ETE4
	Identification of training needs	ETE5
	Satisfaction of employees with overall training	ETE6
	Workers authorised to inspect their own work	ETE7
	Workers encouraged to solve problems	ETE8
	Extent of cross-functional team usage	ETE9
Innovation and technology	Development in manufacturing processes	IT1
	Reduction in manufacturing lead time	IT2
	Development of innovative products	IT3
	Development of environmentally friendly products and packaging	IT4
Environment, health and safety	Investment in safety (safety training budget)	EHS1
	Levels of communication about health and safety issues	EHS2
	Clarity in health and safety policies	EHS3
	Organising for safety (control, communication, cooperation and competence)	EHS4
	Health and safety auditing	EHS5
	Percentage of staff attending safety committee meetings	EHS6
	Top management and workforce involvement in health and safety	EHS7
	Testing of employees' knowledge of health and safety policies	EHS8
Vendor management	Suppliers selection based on quality rather than price or schedule	VM1
	Thoroughness of supplier rating system	VM2
	Extension of long term contracts to suppliers	VM3
	Clarity of specifications provided to suppliers	VM4
	Suppliers' responsiveness to requests for change	VM5
	Relationship with supplier	VM6

Source: Sangwan and Digalwar (2008)

Table 2 Critical factors and performance measures (criteria) for evaluation of WCM (continued)

Critical factor	*Performance measures or criteria*	*Code*
Production planning and control	Extent of preventive/productive maintenance work	PPC1
	Stability of production scheduled	PPC2
	Degree of automation of the process	PPC3
	Number of Kaizens performed	PPC4
Quality	Development of quality policies and system	QC1
	Product reliability, durability, functionality relative to competitors	QC2
	Percentage of surveyed customers satisfied	QC3
	Consistency in quality	QC4
	System effectiveness in identifying non-conformance of product	QC5
Flexibility	Extent to which quality is affected by product mix/volume changes	FX1
	Extent to which cost is affected by product mix/volume	FX2
	Extent to which delivery performance is affected by product mix/volume	FX3
	Use of e-procurement	FX4
	Extent of IT tools usage	FX5
	Extent of multipurpose tools usage	FX6
Cost	Product cost and process redesign cost	CST1
	Cost related to material handling, distribution and storage	CST2
	After sales service cost (warranty)	CST3
	Percentage reduction in data maintenance cost	CST4
	Plant maintenance cost	CST5
Customer services and satisfaction	Interaction with customers/potential customers	CSS1
	Feedback on quality, delivery and price performance	CSS2
	Responsiveness to customer needs	CSS3
	Customer satisfaction by product (features, quality, cost, durability, reliability)	CSS4
	Sales by customer recommendation	CSS5
	Quality and process of customer service	CSS6
	Customer service representative knowledge, skill and attitude	CSS7
	Time taken in transferring the problem to the person who could solve it in the best way	CSS8
	ICT usage for customer service	CSS9
	Technical support provided to the customer	CSS10
Company growth	Profitability	CG1
	Increase in market share	CG2
	Reputation of organisation in market	CG3
	Increase in number of customers	CG4

Source: Sangwan and Digalwar (2008)

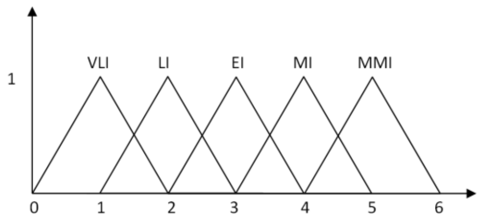
4.2 Assigning weights to criteria

The first step is to assign weights to the criteria so that a measure of relative importance of a criterion over all the other criteria is established. This is done by using a linguistic variable called 'degree of importance'. It has five linguistic values as shown in Table 3; the associated fuzzy numbers are shown in Figure 1.

Table 3 Linguistic values and fuzzy numbers for the linguistic variable 'degree of importance'

Linguistic values	*Fuzzy no.*
Much more important	(4, 5, 6)
More important	(3, 4, 5)
Equally important	(2, 3, 4)
Less important	(1, 2, 3)
Very less important	(0, 1, 2)

Figure 1 Fuzzy numbers for linguistic variable 'degree of importance'



Using this linguistic variable, pairwise comparison of the criteria is done to obtain a *Pairwise Comparison Matrix*. Each entry in the pairwise comparison matrix is a fuzzy number. A series of steps is then followed to obtain the *Fuzzy Weights* of the criteria. Thereafter, *Degree of Possibility* is calculated which gives the *Normalised Crisp Weights* for each criterion. The above mentioned series of steps are performed using the following equations:

$$\text{Row sum, } S_{ri} = \sum_{j=1}^{j=n} b_{ij} = \left(\sum_{j=1}^{j=n} e_{ij}, \sum_{j=1}^{j=n} f_{ij}, \sum_{j=1}^{j=n} g_{ij}\right); \quad (1)$$

$$\text{Total sum, } S_t = \sum_{i=1}^{j=n} S_{ri}; \quad (2)$$

$$\text{Fuzzy weight} = S_{ri} \otimes [S_t]^{-1} \quad (3)$$

where

b_{ij} is the fuzzy number in i^{th} row, j^{th} column of pairwise comparison matrix

(e_{ij}, f_{ij}, g_{ij}) is the triangular fuzzy number represented by b_{ij}

N is the number of criteria used (n = 73 in this study).

Thus, these equations show the computations for obtaining fuzzy weights for each criterion. Next step is to calculate the degree of possibility for each pair of criteria. The degree of possibility establishes the superiority of a criterion over another criterion in terms of its importance to the decision maker. The degree of possibility, for each pair of criteria, is defined as follows.

$$\text{Degree of possibility, } V\left(S_i \geq S_j\right) = \begin{cases} 1, & \text{if } f_i \geq f_j \\ \dfrac{g_i - e_j}{\left(g_i - f_i\right) + \left(f_i - e_j\right)}, & \text{if } e_j \leq g_i \, ; \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

$i, j = 1,2,3\ldots,n \quad \text{and} \quad i \neq j;$

After obtaining the degree of possibility, the next step in the algorithm is to obtain the crisp weights for each criterion. This is done by selecting the minimum degree of possibility for each criterion to get the weight vector W'. Normalising the weight vector W' gives us the normalised weight vector W, which is nothing but the weights of all the criteria.

Minimum degree of possibility for i^{th} criteria,

$$D'\left(A_i\right) = \min\left\{V\left(S_i \geq S_j\right)\right\} \tag{5}$$

For j = 1, 2, 3 …, n; the weight vector,

$$W' = \left\{D'\left(A_1\right), D'\left(A_2\right), \ldots, D'\left(A_n\right)\right\}^T \tag{6}$$

Normalising the weight vector, $W = \{D(A_1), D(A_2), \ldots, D(A_n)\}^T$

In this study all the 73 criteria are said to be equally important with respect to each other. For instance, the first criterion 'Resource allocation' is equally important to the second criterion 'Planning for change' in Table 1. Thus, this pair is assigned the linguistic value 'equally important' and corresponding fuzzy number (2, 3, 4). Similarly, each pair of criteria have been assigned the linguistic value 'equally important' and corresponding fuzzy number (2, 3, 4).

To further simplify the calculations, each criterion has been assigned a weight of crisp value 1. This can be done because in this study, all the criteria are said to be equally important with respect to each other. If this were not the case then we could not have assigned a constant weight to all the criteria.

4.3 Evaluation of alternatives for each criterion

Thus far, we have the responses of the three case organisations and the weighted criteria. In this study, we have treated all criteria to be equally important and assigned the crisp weight with value equal to one to each criterion. The next step in the Fuzzy PROMETHEE algorithm is to evaluate the alternative that is the three case organisations with respect to each criterion. First of all, each company is evaluated for each criterion. This is done for all the three companies for all the 73 criteria using the linguistic variable 'Degree of Comparison'. It has five linguistic values namely 'very high', 'high', 'medium', 'low' and 'very low'. This linguistic variable is the same as the one which was used in the survey. Table 4 shows the linguistic values and corresponding fuzzy numbers for 'Degree of comparison'.

Table 4 Linguistic values and fuzzy numbers for the linguistic variable 'degree of comparison'

Linguistic values	*Fuzzy no.*
Very high	(4, 5, 6)
High	(3, 4, 5)
Medium	(2, 3, 4)
Low	(1, 2, 3)
Very low	(0, 1, 2)

For instance, the survey responses suggest that the resource allocation (TM1) for Company A is 'very high'. So, it has been assigned the linguistic value 'very high' and the corresponding fuzzy number (4, 5, 6). In this way, the criteria-alternative (CA) matrix is formed. This is shown in Table 5.

Table 5 CA matrix

Linguistic values of CA matrix				*Fuzzy values of CA matrix*			
Criteria	*Company A*	*Company B*	*Company C*	*Criteria*	*Company A*	*Company B*	*Company C*
TM1	Very high	Very high	High	TM1	(4, 5, 6)	(4, 5, 6)	(3, 4, 5)
TM2	High	Very high	Very high	TM2	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
TM3	High	Very high	Very high	TM3	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
TM4	Very high	Very high	High	TM4	(4, 5, 6)	(4, 5, 6)	(3, 4, 5)
KM1	High	Very high	Medium	KM1	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)
KM2	High	Very high	Low	KM2	(3, 4, 5)	(4, 5, 6)	(1, 2, 3)
KM3	High	Very high	High	KM3	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
KM4	High	Very high	Medium	KM4	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)
KM5	High	Very high	Low	KM5	(3, 4, 5)	(4, 5, 6)	(1, 2, 3)
KM6	High	Very high	Very high	KM6	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
KM7	High	Very high	Very high	KM7	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
KM8	High	High	High	KM8	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)
ETE1	Medium	Very high	Very high	ETE1	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
ETE2	Medium	Medium	Medium	ETE2	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
ETE3	High	Very high	Medium	ETE3	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)
ETE4	Low	High	Medium	ETE4	(1, 2, 3)	(3, 4, 5)	(2, 3, 4)
ETE5	High	Very high	High	ETE5	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
ETE6	Medium	High	Medium	ETE6	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
ETE7	High	Very high	Very high	ETE7	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
ETE8	High	Very high	High	ETE8	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
ETE9	High	High	Low	ETE9	(3, 4, 5)	(3, 4, 5)	(1, 2, 3)
IT1	Medium	High	Very low	IT1	(2, 3, 4)	(3, 4, 5)	(0, 1, 2)
IT2	Medium	Very high	Low	IT2	(2, 3, 4)	(4, 5, 6)	(1, 2, 3)
IT3	Medium	Very high	Low	IT3	(2,3,4)	(4, 5, 6)	(1, 2, 3)
IT4	Medium	Very high	High	IT4	(2, 3, 4)	(4, 5, 6)	(3, 4, 5)

Table 5 CA matrix (continued)

Linguistic values of CA matrix				*Fuzzy values of CA matrix*			
Criteria	*Company A*	*Company B*	*Company C*	*Criteria*	*Company A*	*Company B*	*Company C*
EHS1	High	High	High	EHS1	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)
EHS2	High	High	Very high	EHS2	(3, 4, 5)	(3, 4, 5)	(4, 5, 6)
EHS3	Very high	High	Very high	EHS3	(4, 5, 6)	(3, 4, 5)	(4, 5, 6)
EHS4	Very high	High	High	EHS4	(4, 5, 6)	(3, 4, 5)	(3, 4, 5)
EHS5	Very high	High	Medium	EHS5	(4, 5, 6)	(3, 4, 5)	(2, 3, 4)
EHS6	High	High	Very high	EHS6	(3, 4, 5)	(3, 4, 5)	(4, 5, 6)
EHS7	Very high	High	Very high	EHS7	(4, 5, 6)	(3, 4, 5)	(4, 5, 6)
EHS8	Very high	High	Medium	EHS8	(4,5,6)	(3, 4, 5)	(2, 3, 4)
VM1	High	High	High	VM1	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)
VM2	Medium	Very high	Very high	VM2	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
VM3	Medium	Very high	Very high	VM3	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
VM4	Low	Very high	Very high	VM4	(1, 2, 3)	(4, 5, 6)	(4, 5, 6)
VM5	High	Very high	High	VM5	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
VM6	High	Very high	Very high	VM6	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
PPC1	High	High	Medium	PPC1	(3, 4, 5)	(3, 4, 5)	(2, 3, 4)
PPC2	High	High	High	PPC2	(3, 4, 5)	(3, 4, 5)	(3, 4, 5)
PPC3	Medium	Medium	Medium	PPC3	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
PPC4	Medium	Medium	Medium	PPC4	(2, 3, 4)	(2, 3, 4)	(2, 3, 4)
QC1	High	Very high	High	QC1	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
QC2	High	Very high	High	QC2	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
QC3	High	Very high	Medium	QC3	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)
QC4	Very high	Very high	High	QC4	(4, 5, 6)	(4, 5, 6)	(3, 4, 5)
QC5	Very high	Very high	Medium	QC5	(4, 5, 6)	(4, 5, 6)	(2, 3, 4)
FX1	High	Very high	Very high	FX1	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
FX2	High	Very high	High	FX2	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
FX3	High	Very high	Very high	FX3	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
FX4	Medium	High	Medium	FX4	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
FX5	Medium	High	High	FX5	(2, 3, 4)	(3, 4, 5)	(3, 4, 5)
FX6	Medium	High	Medium	FX6	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
CST1	Medium	Very high	Very high	CST1	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
CST2	Medium	Very high	Very high	CST2	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
CST3	Medium	Very high	Very high	CST3	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
CST4	Medium	Very high	Medium	CST4	(2, 3, 4)	(4, 5, 6)	(2, 3, 4)
CST5	Medium	High	Very high	CST5	(2, 3, 4)	(3, 4, 5)	(4, 5, 6)
CSS1	High	Very high	Very high	CSS1	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
CSS2	High	Very high	High	CSS2	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
CSS3	High	Very high	High	CSS3	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
CSS4	High	Very high	High	CSS4	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)
CSS5	High	Very high	High	CSS5	(3, 4, 5)	(4, 5, 6)	(3, 4, 5)

Table 5 CA matrix (continued)

Linguistic values of CA matrix				*Fuzzy values of CA matrix*			
Criteria	*Company A*	*Company B*	*Company C*	*Criteria*	*Company A*	*Company B*	*Company C*
CSS6	Very high	Very high	High	CSS6	(4, 5, 6)	(4, 5, 6)	(3, 4, 5)
CSS7	Very high	Very high	Very high	CSS7	(4, 5, 6)	(4, 5, 6)	(4, 5, 6)
CSS8	High	Very high	Medium	CSS8	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)
CSS9	High	Very high	Very high	CSS9	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
CSS10	High	Very high	Very high	CSS10	(3, 4, 5)	(4, 5, 6)	(4, 5, 6)
CG1	Medium	Very high	Very high	CG1	(2, 3, 4)	(4, 5, 6)	(4, 5, 6)
CG2	Medium	High	Medium	CG2	(2, 3, 4)	(3, 4, 5)	(2, 3, 4)
CG3	Very high	Very high	Very high	CG3	(4, 5, 6)	(4, 5, 6)	(4, 5, 6)
CG4	High	Very high	Medium	CG4	(3, 4, 5)	(4, 5, 6)	(2, 3, 4)

4.3.1 Difference matrix

Once the fuzzy numbers are assigned to each alternative for each criterion, the difference matrix is then constructed by pairwise comparison of all the alternatives over all the criteria. The difference of the fuzzy numbers is calculated for each pair of alternatives for each criterion. Standard fuzzy operations are used for the same.

$$\text{Fuzzy difference, } d_k\left(b_i, b_j\right) = (e, f, g) = b_i - bj = \left(e_i, f_i, g_i\right) - \left(e_j, f_j, g_j\right) = \left(e_i - g_j, f_i - f_j, g_i - e_j\right)$$

For instance, consider the first criterion, i.e., resource allocation (TM1). For this criterion, we do a pairwise comparison of each pair of alternatives. Consider the pair company A-company B. The fuzzy value for company A corresponding to TM1 is (4, 5, 6). The fuzzy value for company B corresponding to TM1 is also (4, 5, 6). We take the difference of these two fuzzy numbers and plug it into the difference matrix.

$$(4, 5, 6) - (4, 5, 6) = (4 - 6, 5 - 5, 6 - 4) = (-2, 0, 2)$$

In this way each pair of alternatives is evaluated for each criterion to get an entry in the difference matrix shown in Table 6.

Table 6 Difference matrix

Difference matrix						
Criteria	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
TM1	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–3, –1, 1)	(–3, –1, 1)
TM2	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
TM3	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
TM4	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–3, –1, 1)	(–3, –1, 1)
KM1	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)
KM2	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)	(1, 3, 5)	(–4, –2, 0)	(–5, –3, –1)
KM3	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)

Table 6 Difference matrix (continued)

	Difference matrix					
Criteria	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
KM4	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)
KM5	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)	(1, 3, 5)	(–4, –2, 0)	(–5, –3, –1)
KM6	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
KM7	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
KM8	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
ETE1	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
ETE2	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
ETE3	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)
ETE4	(–4, –2, 0)	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)	(–1, 1, 3)	(–3, –1, 1)
ETE5	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
ETE6	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
ETE7	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
ETE8	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
ETE9	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–4, –2, 0)	(–4, –2, 0)
IT1	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)	(1, 3, 5)	(–4, –2, 0)	(–5, –3, –1)
IT2	(–4, –2, 0)	(–1, 1, 3)	(0, 2, 4)	(1, 3, 5)	(–3, –1, 1)	(–5, –3, –1)
IT3	(–4, –2, 0)	(–1, 1, 3)	(0, 2, 4)	(1, 3, 5)	(–3, –1, 1)	(–5, –3, –1)
IT4	(–4, –2, 0)	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)	(–1, 1, 3)	(–3, –1, 1)
EHS1	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
EHS2	(–2, 0, 2)	(–3, –1, 1)	(–2, 0, 2)	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)
EHS3	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)
EHS4	(–1, 1, 3)	(–1, 1, 3)	(–3, –1, 1)	(–2, 0, 2)	(–3, –1, 1)	(–2, 0, 2)
EHS5	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–1, 1, 3)	(–4, –2, 0)	(–3, –1, 1)
EHS6	(–2, 0, 2)	(–3, –1, 1)	(–2, 0, 2)	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)
EHS7	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)
EHS8	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–1, 1, 3)	(–4, –2, 0)	(–3, –1, 1)
VM1	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
VM2	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
VM3	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
VM4	(–5, –3, –1)	(–5, –3, –1)	(1, 3, 5)	(–2, 0, 2)	(1, 3, 5)	(–2, 0, 2)
VM5	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3,– 1, 1)
VM6	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
PPC1	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–3, –1, 1)	(–3, –1, 1)
PPC2	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
PPC3	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
PPC4	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)

Table 6 Difference matrix (continued)

	Difference matrix					
Criteria	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
QC1	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
QC2	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
QC3	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)
QC4	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–3, –1, 1)	(–3, –1, 1)
QC5	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–4, –2, 0)	(–4, –2, 0)
FX1	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
FX2	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
FX3	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
FX4	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
FX5	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
FX6	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CST1	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
CST2	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
CST3	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
CST4	(–4, –2, 0)	(–2, 0, 2)	(0, 2, 4)	(0, 2, 4)	(–2, 0, 2)	(–4, –2, 0)
CST5	(–3, –1, 1)	(–4, –2, 0)	(–1, 1, 3)	(–3, –1, 1)	(0, 2, 4)	(–1, 1, 3)
CSS1	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
CSS2	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CSS3	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CSS4	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CSS5	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CSS6	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–3, –1, 1)	(–3, –1, 1)
CSS7	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
CSS8	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)
CSS9	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
CSS10	(–3, –1, 1)	(–3, –1, 1)	(–1, 1, 3)	(–2, 0, 2)	(–1, 1, 3)	(–2, 0, 2)
CG1	(–4, –2, 0)	(–4, –2, 0)	(0, 2, 4)	(–2, 0, 2)	(0, 2, 4)	(–2, 0, 2)
CG2	(–3, –1, 1)	(–2, 0, 2)	(–1, 1, 3)	(–1, 1, 3)	(–2, 0, 2)	(–3, –1, 1)
CG3	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)	(–2, 0, 2)
CG4	(–3, –1, 1)	(–1, 1, 3)	(–1, 1, 3)	(0, 2, 4)	(–3, –1, 1)	(–4, –2, 0)

4.3.2 Preference function

The preference of alternative ‘b_i’ over alternative ‘b_j’ with respect to a criterion ‘k’ is measured with the help of a preference function $P_k(b_i, b_j)$. It is applied to each element $d_k(b_i, b_j)$ in the difference matrix. In order to define the preference function, the following thresholds have to be fixed:

The indifference threshold ‘q’ is the lowest value of $d_k(b_i, b_j)$ below which there is indifference between selecting ‘b_i’ or ‘b_j’. In this study, q = (–2, 0, 2).

The preference threshold ‘p’ is the lowest value of $d_k(b_i, b_j)$ above which there is strict preference of ‘b_i’ over ‘b_j’. In this study, p = (0, 2, 4)

In this study, the preference function is the same for all the criteria and is defined as follows.

$$P_k(b_i, b_j) = \begin{cases} 1, & \text{if } dk(b_i, b_j) \geq p \\ \dfrac{g_i - e_j}{(g_i - e_j) - (f_i - f_j) + 20}, & \text{if } q < dk(b_i, b_j) < p \\ 0, & \text{if } d_j(a, b) = q \end{cases}$$

Comparison of two fuzzy numbers is done according to degree of possibility.

4.3.3 Preference matrix and global preference index

The preference matrix is obtained when the preference function is applied on the difference matrix. Table 7 shows the preference matrix. The global preference index is computed by taking the column sum of each column. The global preference index is a crisp measure of how strongly an alternative is preferred over another alternative for all the criteria.

Table 7 Preference matrix

Criteria	*Weights*	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
TM1	1	0	0.75	0	0.75	0	0
TM2	1	0	0	0.75	0	0.75	0
TM3	1	0	0	0.75	0	0.75	0
TM4	1	0	0.75	0	0.75	0	0
KM1	1	0	0.75	0.75	1	0	0
KM2	1	0	1	0.75	1	0	0
KM3	1	0	0	0.75	0.75	0	0
KM4	1	0	0.75	0.75	1	0	0
KM5	1	0	1	0.75	1	0	0
KM6	1	0	0	0.75	0	0.75	0
KM7	1	0	0	0.75	0	0.75	0
KM8	1	0	0	0	0	0	0
ETE1	1	0	0	1	0	1	0
ETE2	1	0	0	0	0	0	0
ETE3	1	0	0.75	0.75	1	0	0
ETE4	1	0	0	1	0.75	0.75	0
ETE5	1	0	0	0.75	0.75	0	0
ETE6	1	0	0	0.75	0.75	0	0
ETE7	1	0	0	0.75	0	0.75	0
ETE8	1	0	0	0.75	0.75	0	0
ETE9	1	0	1	0	1	0	0

Table 7 Preference matrix (continued)

Criteria	*Weights*	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
IT1	1	0	1	0.75	1	0	0
IT2	1	0	0.75	1	1	0	0
IT3	1	0	0.75	1	1	0	0
IT4	1	0	0	1	0.75	0.75	0
EHS1	1	0	0	0	0	0	0
EHS2	1	0	0	0	0	0.75	0.75
EHS3	1	0.75	0	0	0	0	0.75
EHS4	1	0.75	0.75	0	0	0	0
EHS5	1	0.75	1	0	0.75	0	0
EHS6	1	0	0	0	0	0.75	0.75
EHS7	1	0.75	0	0	0	0	0.75
EHS8	1	0.75	1	0	0.75	0	0
VM1	1	0	0	0	0	0	0
VM2	1	0	0	1	0	1	0
VM3	1	0	0	1	0	1	0
VM4	1	0	0	1	0	1	0
VM5	1	0	0	0.75	0.75	0	0
VM6	1	0	0	0.75	0	0.75	0
PPC1	1	0	0.75	0	0.75	0	0
PPC2	1	0	0	0	0	0	0
PPC3	1	0	0	0	0	0	0
PPC4	1	0	0	0	0	0	0
QC1	1	0	0	0.75	0.75	0	0
QC2	1	0	0	0.75	0.75	0	0
QC3	1	0	0.75	0.75	1	0	0
QC4	1	0	0.75	0	0.75	0	0
QC5	1	0	1	0	1	0	0
FX1	1	0	0	0.75	0	0.75	0
FX2	1	0	0	0.75	0.75	0	0
FX3	1	0	0	0.75	0	0.75	0
FX4	1	0	0	0.75	0.75	0	0
FX5	1	0	0	0.75	0	0.75	0
FX6	1	0	0	0.75	0.75	0	0
CST1	1	0	0	1	0	1	0
CST2	1	0	0	1	0	1	0
CST3	1	0	0	1	0	1	0
CST4	1	0	0	1	1	0	0
CST5	1	0	0	0.75	0	1	0.75

Table 7 Preference matrix (continued)

Criteria	*Weights*	*A-B*	*A-C*	*B-A*	*B-C*	*C-A*	*C-B*
CSS1	1	0	0	0.75	0	0.75	0
CSS2	1	0	0	0.75	0.75	0	0
CSS3	1	0	0	0.75	0.75	0	0
CSS4	1	0	0	0.75	0.75	0	0
CSS5	1	0	0	0.75	0.75	0	0
CSS6	1	0	0.75	0	0.75	0	0
CSS7	1	0	0	0	0	0	0
CSS8	1	0	0.75	0.75	1	0	0
CSS9	1	0	0	0.75	0	0.75	0
CSS10	1	0	0	0.75	0	0.75	0
CG1	1	0	0	1	0	1	0
CG2	1	0	0	0.75	0.75	0	0
CG3	1	0	0	0	0	0	0
CG4	1	0	0.75	0.75	1	0	0
Global preference index		*3.75*	*17.5*	*40.75*	*32*	*21*	*3.75*

For instance, when preference function is applied to the element in the first row and first column of the difference matrix, i.e., (–2, 0, 2), we get the value 0 because (–2, 0, 2) is equal to the indifference threshold, q = (–2, 0, 2). This simply means that we are indifferent in choosing between company A and company B with respect to the criteria TM1. In this way, each entry of the preference matrix is calculated. The global preference of pair A-B is 3.75 which means that company A is preferred over company B with an index of 3.75 over all the criteria. Similarly, company B is preferred over company A with an index of 40.75.

4.4 *Outranking flows*

Positive outranking flow gives a measure of the strength of the alternative as compared to other alternatives over all the criteria. Negative outranking flow gives a measure of weakness of the alternative as compared to other alternatives over all the criteria. The net outranking flow is used to obtain complete ranking of the alternatives. Table 8 shows the outranking flows:

Positive outranking flow of alternative 'a', $\Phi^{+}(a) = \frac{1}{k-1}\sum\left[\Pi(a,b)\right]$

Negative outranking flow of alternative 'a', $\Phi^{-}(a) = \frac{1}{k-1}\sum\left[\Pi(b,a)\right]$

Net outranking flow of alternative 'a', $\Phi(a) = \Phi^{+}(a) - \Phi^{-}(a)$

where $\Pi(a, b)$ is the global preference index of the pair of alternatives (a, b).

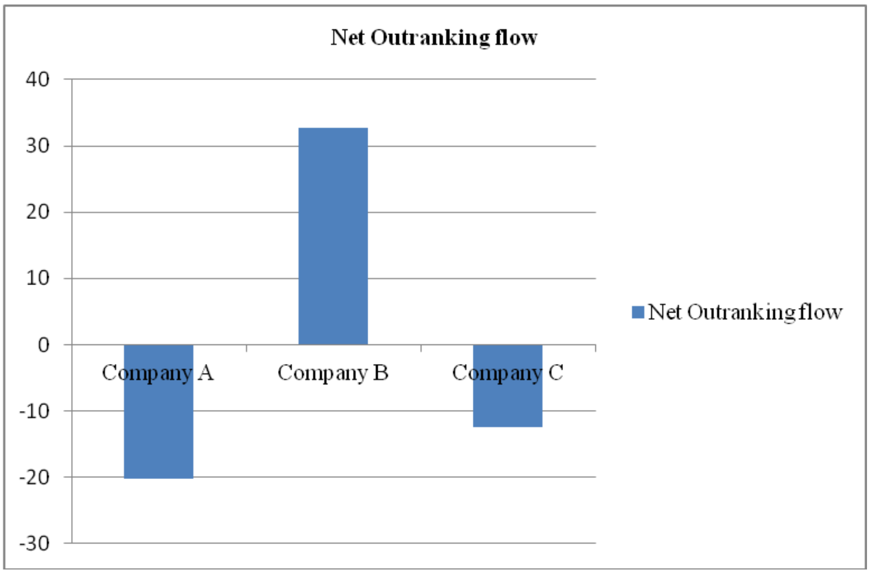
Table 8 Outranking flows

Alternatives	*Positive outranking flows*	*Negative outranking flows*	*Net outranking flows*	*Ranking*
A	10.625	30.875	–20.25	3
B	36.375	3.75	32.625	1
C	12.375	24.75	–12.375	2

5 Results and discussions

Fuzzy PROMETHEE algorithm has been developed then it has been applied for testing the WCM practices of three heavy engineering sector companies. These companies are ranked according to their WCM practices. Table 8 and Figure 2 shows outranking flows, net outranking flow of company B is 32. 625 compare to –20.25 of company A and –12.375 of company C. The results clearly show that in the given scenario, company B fares well. Company B has been practicing WCM for the last ten years. The results do not imply the fact that company B is better than any of the other two in terms of each and every criterion. There may be certain criteria where either company A or company C or both of them may be better than company B. However, WCM practices of company B have been proved to be much better than those of the others holistically.

Figure 2 Net outranking flows of the company (see online version for colours)



6 Conclusions

The objective of this paper was to rank a set of case organisations based on their WCM practices. For this purpose, the criteria for WCM were selected through literature. Secondly, the MCDM algorithm fuzzy PROMETHEE was decided upon owing to its many advantages. To test this framework, the heavy engineering sector in India was targeted as engineering industry has witnessed an unprecedented growth in the past few years resulting from an increased investment in infrastructure development and industrial production. Three pioneer companies in the heavy engineering sector were studied. A survey was made and the responses of the companies were recorded and evaluated by the decision makers. A detailed step-by-step fuzzy PROMETHEE algorithm was presented and from the extensive analysis, it can be concluded that company B is the best in WCM practices over company A and C. It is believed that this paper will provide an opportunity for the managers to understand the concept of fuzzy PROMETHEE and apply the same in real-life situation to supplement their decision making efforts.

Acknowledgements

The authors wish to express their gratitude to experts who were interviewed for their valuable information, support and time. The authors would like to thank the anonymous reviewers for their valuable suggestions and comments to improve the manuscript.

References

Anand, G. and Kodali, R. (2008) 'Selection of lean manufacturing systems using the PROMETHEE', *Journal of Modelling in Management*, Vol. 3, No. 1, pp.40–70.

Athawale, V.M. and Chakraborty, S. (2010) 'Facility location selection using PROMETHEE II method', *Proceedings of the 2010 International Conference on Industrial Engineering and Operations Management*, Dhaka, Bangladesh, 9–10 January, pp.59–64.

Avikal, S., Mishra, P.K. and Jain, R. (2014) 'A fuzzy AHP and PROMETHEE method-based heuristic for disassembly line balancing problems', *International Journal of Production Research*, Vol. 52, No. 5, pp.1306–1317.

Brown, S., Squire, B. and Blackmon, K. (2007) 'The contribution of manufacturing strategy involvement and alignment to world-class manufacturing performance', *International Journal of Operations & Production Management*, Vol. 27, No. 3, pp.282–302.

Chou, W., Lin, W. and Lin, C. (2007) 'Application of fuzzy theory and PROMETHEE technique to evaluate suitable ecotechnology method: a case study in Shihmen Reservoir Watershed, Taiwan', *Ecological Engineering*, Vol. 31, No. 4, pp.269–280.

Closs, D.J. and Xu, K. (2000) 'Logistics information technology practice in manufacturing and merchandising firms: an international benchmarking study versus world class logistics firms', *International Journal of Physical Distribution and Logistics*, Vol. 30, No. 10, pp.869–886.

Dagdeviren, M. (2008) 'Decision making in equipment selection: an integrated approach with AHP and PROMETHEE', *Journal of Intelligent Manufacturing*, Vol. 19, pp.397–406.

Data Portal India (2013) *GDP of India and Major Sectors of Economy, Share of Each Sector to GDP and Growth Rate of GDP and Other Sectors of Economy 1951–52 Onward* [online] http://data.gov.in/dataset/gdp-india-and-major-sectors-economy-share-each-sector-gdp-and-growth-rate-gdp-and-other-sect (accessed 17 October 2013).

DeFilippo, J.S. (1997) 'World-class manufacturing in Chengdu: a case study on China's first aviation joint venture', *International Journal of Technology Management*, Vol. 13, No. 5, pp.681–694.

Digalwar, A.K. and Sangwan, K.S. (2007) 'Development and validation of performance measures for world class manufacturing practices in India', *Journal of Advanced Manufacturing Systems*, Vol. 6, No. 1, pp.21–38.

Digalwar, A.K., Haridas, P. and Joseph, I.N. (2014) 'Development and validation of quality management constructs for software industries: an empirical investigation from India', *International Journal of Services and Operations Management*, Vol. 17, No. 4, pp.458–478.

Digalwar, A.K., Tagalpallewar, A.R. and Sunnapwar, V.K. (2013) 'Green manufacturing performance measures: an empirical investigation from Indian manufacturing industries', *Measuring Business Excellence*, Vol. 17, No. 4, pp.59–75.

Falah, K.A., Zairi, M. and Ahmed, A.M. (2003) 'The role of supply chain management in world-class manufacturing', *International Journal of Physical Distribution and Logistics Management*, Vol. 33, No. 5, pp.396–407.

Flynn, B.B., Schoeder, R.G. and Sakakibara, S. (1994) 'A frame work for quality management research and an associated measurement instrument', *Journal of Operations Management*, Vol. 11, No. 4, pp.339–366.

Geldermann, J. and Rentz, O. (2001) 'Integrated technique assessment with imprecise information as a support for the identification of best available techniques (BAT)', *OR Spectrum*, Vol. 23, No. 1, pp.137–157.

Geldermann, J., Spengler, T. and Rentz, O. (2000) 'Fuzzy outranking for environmental assessment: case study: iron and steel making industry', *Fuzzy Sets and Systems*, Vol. 115, No. 1, pp.45–65.

Goumas, M. and Lygerou, V. (2000) 'An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects', *European Journal of Operational Research*, Vol. 123, No. 3, pp.606–613.

Gunasekaran, A. (2000) 'World class manufacturing in small and medium enterprises', *International Journal of Manufacturing Technology and Management*, Vol. 2, Nos. 1–7, pp.777–789.

Gunasekaran, A., Goyal, S.K., Martikainen, T. and Yli-Olli, P. (1998) 'Total quality management a new perspective for improving quality and productivity', *International Journal of Quality and Reliability Management*, Vol. 15, Nos. 8/9, pp.947–968.

Gupta, R., Sachdeva, A. and Bhardwaj, A. (2012) 'Selection of logistic service provider using fuzzy PROMETHEE for a cement industry', *Journal of Manufacturing Technology Management*, Vol. 23, No. 7, pp.899–921.

Halouani, N., Chabchoub, H. and Martel, J.M. (2009) 'PROMETHEE-MD-2T method for project selection', *European Journal of Operations Research*, Vol. 195, No. 3, pp.841–849.

Hayes, R.H. and Wheelwright, S.C. (1984) *Restoring Our Competitive Edge: Competing Through Manufacturing*, Wiley, New York.

Hendry, L.C. (1998) 'Applying world class manufacturing to make-to-order companies: problems and solutions', *International Journal of Operations and Production Management*, Vol. 18, No. 11, pp.1086–1100.

Juan, Y., Roper, K.O., Castro-Lacouture, D. and Kim, J.H. (2010) 'Optimal decision making on urban renewal projects', *Management Decision*, Vol. 48, No. 2, pp.207–234.

Kasul, R.A. and Motwani, J.G. (1995) 'Performance measurements in world-class operations: a strategic model', *Benchmarking for Quality Management and Technology*, Vol. 2, No. 2, pp.20–36.

Khurrum, M., Bhutta, S., Rosado-Feger, A.L., Huq, F. and Muzaffar, A. (2013) 'Exploratory study of adoption of lean management practices in Pakistani textile mills', *International Journal of Services and Operations Management*, Vol. 15, No. 3, pp.338–357.

Kinni, T. (1996) *America's Best: Industry Week's Guide to World-Class Manufacturing Plants*, Wiley, New York.

Kodali, R.B., Sangwan, K.S. and Sunnapwar, V.K. (2004) 'Performance value analysis for the justification of world-class manufacturing systems', *Journal of Advanced Manufacturing Systems*, Vol. 3, No. 1, pp.85–102.

Lin, W. (2008) 'Earthquake-induced landslide hazard monitoring and assessment using SOM and PROMETHEE techniques: a case study at the Chiufenershan area in Central Taiwan', *International Journal of Geographical Information Science*, Vol. 22, No. 9, pp.995–1012.

Lind, J. (2001) 'Control in world class manufacturing – a longitudinal case study', *Management Accounting Research*, Vol. 12, No. 1, pp.41–74.

Makan, A., Malamis, D., Assobhei, O., Loizidou, M. and Mountadar, M. (2012) 'Multi-criteria decision analysis for the selection of the most suitable landfill site: case of Azemmour, Morocco', *International Journal of Management Science and Engineering Management*, Vol. 7, No. 2, pp.96–109.

Marinoni, O. (2005) 'A stochastic spatial decision support system based on PROMETHEE', *International Journal of Geographical Information Science*, Vol. 19, No. 1, pp.51–68.

Mehrabad, M.S. and Anvari, M. (2010) 'Provident decision making by considering dynamic and fuzzy environment for FMS evaluation', *International Journal of Production Research*, Vol. 48, No. 15, pp.4555–4584.

Motwani, J. (2001) 'Critical factors and performance measures of TQM', *The TQM Magazine*, Vol. 13, No. 4, pp.292–300.

Mouzakitis, S., Karamolegkos, G., Ntanos, E. and Psarras, J. (2011) 'A fuzzy multi-criteria outranking approach in support of business angel's decision analysis process for the assessment of companies as investment opportunities', *Journal of Optimization Theory and Applications*, Vol. 150, No. 3, pp.156–165.

Muthukumar, N., Tamizhiyothi, K., Resmi, A.T. and Nachiappan, R.M. (2014) 'Study on imperative factors of continuous improvement tool-total productive lean manufacturing for improvement of organisational culture towards world class performance', *International Journal of Enterprise Network Management*, Vol. 6, No. 1, pp.42–66.

Ojha, R., Vij, A.K. and Vrat, P. (2014) 'Manufacturing excellence and its critical factors: an interpretive structural methodology application', *Journal of Advances in Management Research*, Vol. 11, No. 3, pp.312–332.

Oliver, N., Delbridge, R., Jones, D. and Lowe, J. (1994) 'World class manufacturing: further evidence in the lean production debate', *British Journal of Management*, Special Issue, Vol. 5, Supplement S1, pp.S53–S63.

Rao, R.V. and Patel, B.K. (2010) 'Decision making in the manufacturing environment using an improved PROMETHEE method', *International Journal of Production Research*, Vol. 48, No. 16, pp.4665–4682.

Sangwan, K.S. and Digalwar, A.K. (2008) 'Evaluation of world-class manufacturing systems: a case of Indian automotive industries', *International Journal of Services and Operations Management*, Vol. 4, No. 6, pp.687–708.

Singh, I. and Ahuja, I.S. (2014) 'An evaluation of just in time (JIT) implementation on manufacturing performance in Indian industry', *Journal of Asia Business Studies*, Vol. 8, No. 3, pp.278–294.

Sugumaran, C., Muthu, S., Devdasan, S.R., Srinivasan, K., Sivaran, N.M. and Rupavathi, N. (2014) 'Integration of QFD and AHP with TPM: an implementation study in automotive accessories manufacturing company', *International Journal of Productivity and Quality Management*, Vol. 14, No. 3, pp.263–295.

Tavakoli, M., Tabriz, A.A., Farahani, R. and Rezapour, E. (2013) 'Application of fuzzy goal programming and F-PROMETHEE approaches in evaluating and selecting the best suppliers is supply chain', *Journal of Basic and Applied Scientific Research*, Vol. 3, No. 2, pp.1115–1127.

Todd, J. (1995) *World Class Manufacturing*, McGraw International, UK.

Tuzkaya, G., Gulsun, B., Kahraman, C. and Ozgen, D. (2010) 'An integrated fuzzy multi-criteria decision making methodology for material handling equipment selection problem and an application', *Expert Systems with Applications*, Vol. 37, No. 4, pp.2853–2863.

Tuzkaya, G., Ozgen, A., Ozgen, D. and Tuzkaya, U.R. (2009) 'Environmental performance evaluation of suppliers: A multi-criteria decision approach', *International Journal of Environmental Science and Technology*, Vol. 6, No. 3, pp.477–490.

Vincke, J.P. and Brans, P. (1985) 'A preference ranking organization method (the PROMETHEE method for MCDM)', *Management Science*, Vol. 31, No. 4, pp.641–656.

Voss, C.A. (1995) 'Alternative paradigms for manufacturing strategy', *International Journal of Operations and Production Management*, Vol. 15, No. 4, pp.5–16.

Yilmaz, B. and Dagdeviren, M. (2011) 'A combined approach for equipment selection: F-PROMETHEE method and zero-one goal programming', *Expert Systems with Applications*, Vol. 38, No. 9, pp.11641–11650.

Zhang, K., Kluck, C. and Achari, G. (2009), 'A comparative approach for ranking contaminated sites based on the risk assessment paradigm using fuzzy PROMETHEE', *Environmental Management*, Vol. 44, No. 5, pp.952–967.