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Abstract

Purpose – The recent global market trend is seemed enforcing existing manufacturing organizations (as well as service sectors) to improve existing supply chain systems or to take up/adapt advanced manufacturing strategies for being competitive. The concept of the agile supply chain (ASC) has become increasingly important as a means of achieving a competitive edge in highly turbulent business environments. An ASC is a dynamic alliance of member enterprises, the formation of which is likely to introduce velocity, responsiveness, and flexibility into the manufacturing system. In ASC management, supplier/partner selection is a key strategic concern. Apart from traditional supplier/partner selection criteria; different agility-related criteria/attributes need to be taken under consideration while selecting an appropriate supplier in an ASC. The paper aims to discuss these issues.

Design/methodology/approach – Therefore, evaluation and selection of potential supplier in an ASC have become an important multi-criteria decision making problem. Most of the evaluation criteria being subjective in nature; traditional decision-making approaches (mostly dealing with objective data) fail to solve this problem. However, fuzzy set theory appears an important mean to tackle with vague and imprecise data given by the experts. In this work, application potential of the fuzzy multi-level multi-criteria decision making (FMLMCDM) approach proposed by Chu and Velásquez (2009) and Chu and Varma (2012) has been examined and compared to that of Fuzzy-techniques for order preference by similarity to ideal solution (TOPSIS) and Fuzzy-MOORA in the context of supplier selection in ASC.

Findings – It has been observed that similar ranking order appears in FMLMCDM as well as Fuzzy-TOPSIS. In Fuzzy-MOORA, the best alternative appears same as in case of FMLMCDM as well as Fuzzy-TOPSIS; but for other alternatives ranking order differs. A comparative analysis has also been made in view of working principles of FMLMCDM, Fuzzy-TOPSIS as well as Fuzzy-MOORA.

Originality/value – Application feasibility of FMLMCDM approach has been verified in comparison with Fuzzy-TOPSIS and Fuzzy-MOORA in the context of agile supplier selection.

Keywords Decision support systems, Agility, Agile supply chain (ASC), Supplier/partner selection, Fuzzy multi-level multi-criteria decision making (FMLMCDM), Fuzzy-TOPSIS, Fuzzy-MOORA

Paper type Research paper

1. Introduction

During supplier selection in agile supply chain (ASC), subjectivity of evaluation information (human judgment) often creates conflict and bears some kind of uncertainty mainly due to the multidimensionality and the vagueness associated with the concept of

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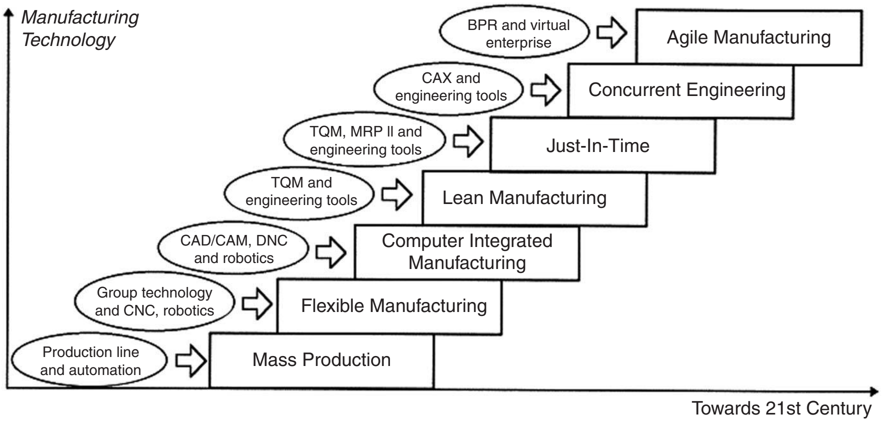
agility-related supplier evaluation criteria. Due to the ill-defined and vague evaluation indices which exist within agile suppliers' assessment, most of the indices are described subjectively by linguistic terminologies which are characterized by ambiguity and multi-possibility, and the conventional assessment approaches cannot fruitfully handle such measurement. However, fuzzy set theory (FST) provides a useful tool for dealing with decisions in which the phenomena are imprecise and vague in nature. Literature depicts application of FST to some extent in formulating decision support tools toward evaluation and selection of potential suppliers in supply chain management (SCM). However, limited work has been documented so far in addressing aspects of supplier evaluation in an ASC. The formation and subsequent exploration of an integrated criteria hierarchy, combining both general as well as agility-related supplier selection criteria, is definitely a challenging task. Therefore, it is believed that application potential of fuzzy-based decision support modules need to be attempted and examined. Therefore, the unified objective of the present work is to examine application feasibility of fuzzy multi-level multi-criteria decision making (FMLMCDM) approach (Chu and Velásquez, 2009; Chu and Varma, 2012) in comparison with Fuzzy-techniques for order preference by similarity to ideal solution (TOPSIS) as well as Fuzzy-MOORA to facilitate suppliers' evaluation and selection in an ASC.

The FMLMCDM approach seems relatively new and somewhat different in comparison to existing decision-making approaches available in literature resources. The specialty of this technique is that it can consider an integrated criteria hierarchy (in which each main criterion is divided into a number of sub-criterions; each sub-criterion is further divided into various sub-criterions and so on) in order to evaluate various alternatives. The methodology explores fuzzy mathematics in the initial stage but layer-wise computations are based on defuzzified values of the fuzzy numbers which are representative of criteria ratings as well as their priority weights. Such approximation may invite errors in the final ranking order of candidate alternatives. It is, therefore, indeed essential to verify and compare the results obtained from FMLMCDM to that of existing fuzzy-based decision support modules which explores nil or minimal use of defuzzification operation. In view of this, the present work compares the alternative suppliers ranking order obtained from FMLMCDM to that of Fuzzy-TOPSIS and Fuzzy-MOORA.

2. State of art

Manufacturing strategies/practices has undergone many evolutionary stages and paradigm shifts in the past (Figure 1). The paradigm shift has been observed from a craft industry to mass production then to computer integrated manufacturing toward lean manufacturing; and nowadays, it is the agile manufacturing. Agile manufacturing is basically the introduction of velocity, flexibility, and responsiveness into the manufacturing system. The concept of agility has now-a-days been extended and merged to the supply chain (SC) philosophy. The SC that is conceptualized and constructed based on agile strategies is called an ASC.

SC agility is basically an operational strategy focussed on promoting adaptability, flexibility, and has the ability to respond and react quickly and effectively to market changes. A SC is the process of moving goods from the customer order through the raw materials stage, supply, production, and distribution of products to the customer. All organizations have SCs of varying levels, depending upon the size of the organization and the type of product manufactured. These networks obtain supplies and components, change these materials into finished products and then



Source: Cheng *et al*. (1998)

Figure 1.
Development in manufacturing technology

distribute them to the customer. Included in this SC process are customer orders, order processing, inventory, scheduling, transportation, storage, and customer service. A necessity in coordinating all these activities is the information service network. The difference between SCM and SC agility is the extent of capability that the organization possesses. Key to the success of an ASC is the speed and flexibility with which these activities can be accomplished and the realization that customer needs and customer satisfaction are the very reasons for the network. Customer satisfaction is paramount. Achieving this capability requires all physical and logical events within the SC to be performed quickly, accurately, and effectively. The faster parts, information, and decisions flow through an organization, the faster it can respond to customer needs (Shari and Zhang, 1999; Mason-Jones and Towill, 1999; Christopher, 2000; Sanchez and Nagi, 2001; Gunasekaran and Yusuf, 2002; Arteta and Giachetti, 2004).

The definition of "agility" as expressed by Goldman *et al.* (1995) "Agility is dynamic, context specific, focused on aggressive changes and growth oriented. It is not about improving efficiency, cutting costs, or avoidance of competitiveness. It's about succeeding and about winning profits, market share and customers in the very center of competitive storms that many companies now fear."

The term agile manufacturing first came into popular usage with the publication of the report by Lacocca Institute (USA) in 1991, entitled "21st Century Manufacturing Enterprise Strategy" (Nagel and Dove, 1991). The manufacturing agility they defined is the ability to thrive in a competitive environment with continuous and unanticipated change, to respond quickly to rapidly changing, fragmenting, and globalizing markets which are driven by demands for high-quality, high-performance, low-cost customer-oriented products and services. More recent publications on SC agility could be found in Lin *et al.* (2006a, b), Sherehiy *et al.* (2007), Jain *et al.* (2008), Wang (2009), Braunscheidel and Suresh (2009), Ganguly *et al.* (2009), Inman *et al.* (2011), Tseng and Lin (2011).

Competitive advantages associated with SCM philosophy can be achieved by strategic collaboration with suppliers and service providers. The success of a SC is highly dependent on selection of good suppliers (Ng, 2008). Recently, SCM and the supplier (vendor) selection process have received considerable attention in the business management literature.

Supplier selection is a complex decision-making processes in SCM. Due to increased market uncertainty in recent times, the concept of ASC has paid more attention on selection of agile partner/suppliers. The overall performance of the company/enterprise is highly influenced by their supplier's network integration as well as cooperation. During supplier/partner selection, various quantitative and qualitative, operational and strategic criteria must be considered simultaneously.

During the 1990s, many manufacturers seek to collaborate with their suppliers in order to upgrade their management performance and competitiveness (Shin *et al.*, 2000; Chen *et al.*, 2006). Simply looking for vendors offering the lowest prices is not "efficient sourcing" any more. Multiple criteria need to be taken into account when selecting suppliers to meet various and unified business needs (Ng, 2008). This process is essentially considered as a multi-criteria decision making (MCDM) problem which is affected by different tangible and intangible criteria including price, quality, performance, technical capability, delivery, reliability, etc. (Önüt *et al.*, 2009). For any manufacturing or service business, selecting the right upstream suppliers is a key success factor that will significantly reduce purchasing cost, increase downstream customer satisfaction, and improve competitive ability (Liao and Kao, 2010).

A number of alternative approaches have been proposed and well documented in past literature to solve such suppliers' selection problems: mathematical programming models, multiple attribute decision aid methods, cost-based methods, statistical and probabilistic methods, combined methodologies and many others (Önüt *et al.*, 2009).

Pi and Low (2005) developed an evaluation and selection system of suppliers using Taguchi loss functions based on four attributes: quality, on-time delivery, price, and service. These four attributes were transferred into the quality loss and combined into one decision variable for effective decision making. In another reporting, Pi and Low (2006) provided a method for quantifying the supplier's attributes to quality-loss using a Taguchi loss function, and these quality losses were also transferred into a variable for decision making by an analytical hierarchy process (AHP). Chen *et al.* (2006) presented a fuzzy decision-making approach to deal with such supplier selection problems in SC system. A hierarchy MCDM model based on fuzzy sets theory was proposed. According to the concept of the TOPSIS, a closeness coefficient was defined to determine appropriate ranking order of all suppliers by calculating the distances to the both fuzzy positive-ideal solution (FPIS) and fuzzy negative-ideal solution (FNIS), simultaneously. Bevilacqua *et al.* (2006) suggested a method that transferred the house of quality (HOQ) approach typical of quality function deployment (QFD) problems to the supplier selection process.

Li *et al.* (2008) proposed a gray-based rough set approach to deal with supplier selection problem in SCM. The proposed approach took advantage of mathematical analysis power of gray system theory while at the same time utilizing data mining and knowledge discovery power of rough set theory. The said method was found suitable to the decision making under more uncertain environments. Demirtas and Ustun (2008) proposed an integrated approach of analytic network process (ANP) and multi-objective mixed integer linear programming (MOMILP) to consider both tangible and intangible factors in choosing the best suppliers and thereby, defining the optimum quantities among selected suppliers in order to maximize the total value of purchasing as well as to minimize the budget and defect rate. Ng (2008) proposed a weighted linear program for the multi-criteria supplier selection problem. Chou and Chang (2008) presented a strategy-aligned fuzzy simple multi-attribute rating technique (SMART) for solving the supplier/vendor selection problem from the perspective of strategic management of the SC.

Amid *et al.* (2009) developed a weighted additive fuzzy multi-objective model for the supplier selection problem under price breaks in a SC. Wu (2009a) presented a hybrid model using data envelopment analysis (DEA), decision trees (DT) and neural networks (NNs) to assess supplier performance. Wu (2009a, b) presented an integrated multi-objective decision-making process by using ANP and mixed integer programming (MIP) to optimize the selection of supplier. Lee (2009) proposed an analytical approach to select suppliers under a fuzzy environment. A fuzzy analytic hierarchy process (FAHP) model, which incorporated the benefits, opportunities, costs and risks (BOCR) concept was constructed to evaluate various aspects of suppliers. Önüt *et al.* (2009) developed a supplier evaluation approach based on the ANP and TOPSIS methods to help a telecommunication company in the GSM sector in Turkey under the fuzzy environment. Zhang *et al.* (2009) proposed an approach based on vague sets group decision to deal with the supplier selection problem in SC systems. Wu (2009b) used gray-related analysis and Dempster-Shafer theory to deal with supplier selection-fuzzy group decision-making problem. Guneri *et al.* (2009) presented an integrated fuzzy and linear programming approach to the supplier selection problem.

Shen and Yu (2009) considered the strategic and operational factors simultaneously to secure the efficacy of supplier selection (VS) on initial stage of new product development (NPD). The authors suggested strategic factors come from the supplier's management system itself (i.e. customer, long-term, and process oriented criteria) while the related performances indices of supplier constitute operational factors (i.e. producer, short-term and outcome oriented criteria). The work adopted supplier's process capability indices (PCIs) and process yields as operational factors to estimate their quality capabilities. The business process-oriented criteria related with the performance of business process improvement (BPI) were employed as the strategic criteria for supplier assessment visit. A fuzzy approach with supply risk consideration was employed then to aggregate the total scores of individual suppliers objectively. Wang and Yang (2009) introduced AHP and fuzzy compromise programming to obtain a more reasonable compromise solution for allocating order quantities among suppliers with their quantity discount rate offered. Boran *et al.* (2009) proposed application of TOPSIS method combined with intuitionistic fuzzy set to select appropriate supplier in group decision-making environment. Ebrahim *et al.* (2009) proposed the scatter search algorithm for supplier selection and order lot sizing under multiple price discount environment.

Sanayei *et al.* (2010) reported a research on group decision-making process for supplier selection with VIKOR under fuzzy environment. Chamodrakas *et al.* (2010) suggested an approach for decision support system enabling effective supplier selection processes in electronic marketplaces. The authors introduced an evaluation method with two stages: initial screening of the suppliers through the enforcement of hard constraints on the selection criteria and final supplier evaluation through the application of a modified variant of the fuzzy preference programming (FPP) method. Keskin *et al.* (2010) applied fuzzy adaptive resonance theory (ART)'s classification ability to the supplier evaluation and selection area. Liao and Kao (2010) integrated the Taguchi loss function, AHP and multi-choice goal programming (MCGP) model for solving the supplier selection problem. Awasthi *et al.* (2010) presented a fuzzy multi-criteria approach for evaluating environmental performance of suppliers. Büyüközkan and Çifçi (2011) examined the problem of identifying an effective model based on sustainability principles for supplier selection operations in SCs. The paper developed an approach based on fuzzy ANP within multi-person decision-making scheme under incomplete preference relations. Yucel and Guneri (2011) investigated on supplier section problem by using a weighted additive fuzzy programming approach. First, linguistic values expressed as trapezoidal fuzzy numbers were used to assess the weights of the factors. By applying the distances of each factor between fuzzy positive ideal rating and fuzzy negative ideal rating, weights were obtained. Then applying suppliers' constraints, goals, and weights of the factors, a fuzzy multi-objective linear model was developed to overcome the selection problem and assign optimum order quantities to each supplier. Dalalah *et al.* (2011) presented a hybrid fuzzy model for group multi-criteria decision making (GMCDM) in relation to supplier selection. A modified fuzzy DEMATEL model was presented to deal with the influential relationship between the evaluations criteria. Liao and Kao (2011) proposed integrated Fuzzy-TOPSIS and MCGP approach to solve the supplier selection problem. Ertay *et al.* (2011) proposed a methodology, which was capable of evaluating and monitoring suppliers' performance, was constructed, using FAHP to weight the established decision criteria and ELECTRE III to evaluate, rank and classify performance of suppliers regarding relative criteria. The proposed methodology was applied to a real-life supplier-selection and classification problem of a pharmaceutical company.

Zouggari and Benyoucef (2012) presented an efficient decision-making approach for group multi-criteria supplier selection problem, which clubbed supplier selection process with order allocation for dynamic SCs to cope market variations. Fuzzy-AHP method was used first for supplier selection through four classes (Class I: performance strategy, Class II: quality of service, Class III: innovation and Class IV: risk), which were qualitatively meaningful. Thereafter, using simulation-based Fuzzy-TOPSIS technique, the criteria application was quantitatively evaluated for order allocation among the selected suppliers. Büyüközkan (2012) proposed a decision model for supplier performance evaluation by considering various environmental performance criteria. An integrated, fuzzy group decision-making approach was adopted to evaluate green supplier alternatives. More precisely, a FAHP was applied to determine the relative weights of the evaluation criteria and an axiomatic design (AD)-based fuzzy group decision-making approach was applied to rank the green suppliers. Pitchipoo *et al.* (2012) developed an appropriate hybrid model by integrating the AHP and grey relational analysis (GRA) for supplier evaluation and selection, which comprises three stages. In Stage I, the most influential criteria were selected by mutual-information-based feature selection. Stage II focussed on the determination of the weights of the attributes using AHP, while Stage III was used for the determination of the best supplier using GRA.

Parthiban and Zubar (2013) selected the best performing supplier among the group according to the prioritization of performance criterion through the application of techniques like modified interpretive structural modeling (MISM), impact matrix cross-reference multiplication applied to a classification (MICMAC), and AHP. Pitchipoo *et al.* (2013) proposed a structured, integrated decision model for evaluating suppliers by combining the fuzzy analytical hierarchy process (FAHP) and GRA. Ghorbani *et al.* (2013) proposed a three-phase approach for supplier selection based on the Kano model and fuzzy multi-criteria decision making. Initially, the importance weight of the criteria was calculated using a fuzzy Kano questionnaire and FAHP. In the second phase, the Fuzzy-TOPSIS technique was used to screen out in capable suppliers. Finally, in the third phase, the filtered suppliers which were qualified, once again would be evaluated by the same approach for the final ranking. Huang and Hu (2013) proposed to develop a systematic process for automotive industry supplier selection: a two-stage solution approach for supplier selection using fuzzy analytic network process-goal programming (FANP-GP) and de novo programming (DNP). The first stage was the

FANP method integrated with the GP model to select the best supplier and to decide the optimal order quantity. In the second stage, the selected suppliers were evaluated based on the DNP method by adjusting their resource constraints and increase their capacity to achieve the minimum total procurement budget. Haldar *et al.* (2014) developed a quantitative approach for strategic supplier selection under a fuzzy environment in a disaster scenario (unwanted disturbances).

Recently, the concept of the ASC has become increasingly important as means of achieving a competitive edge in rapidly changing business environments (Lin *et al.*, 2006a, b). An ASC is a dynamic alliance of member companies, the formation of which is likely to need to change frequently in response to fast-changing markets (Christopher and Towill, 2000). In this context, it has been realized that today's more dynamic business environment increases the need for greater agility in SCs, which increases both the importance and frequency of partner/supplier selection decision making (Wu and Barnes, 2010). In ASCs, companies must align with their supply partners to streamline their operations, as well as working together to achieve the necessary levels of agility throughout the entire SC and not just within an individual company (Christopher and Towill, 2000; Lin *et al.*, 2006a, b; Wu and Barnes, 2011; Wu *et al.*, 1999; Luo *et al.*, 2009). Relevant literatures on suppliers/partners selection in ASC have been furnished in Table I.

Supplier/partner selection is, therefore, considered as a fundamental issue in SCM as it contributes significantly to overall SC performance. However, such decision making is problematic due to the need of considering tangible and intangible factors both, which cause vagueness, ambiguity, and complexity (Yucel and Guneri, 2011; Wu and Barnes, 2011, 2014). At the same time, the vagueness of the information in this type of problem makes decision making more complicated (Amid *et al.*, 2006; Yang, 2010). Consequently, many researchers have realized the application potential of FST as offering an efficient means of handling this uncertainty effectively and of converting human judgments into meaningful results (Wu and Barnes, 2014; Yang, 2010; Yucel and Guneri, 2011; Zadeh, 1965; Amid *et al.*, 2006). As an example, Wu and Barnes (2014) proposed a fuzzy intelligent approach for partner selection in ASCs by using FST in combination with radial basis function artificial NN. The paper included a worked empirical application of the model with data from 84 representative companies within the Chinese electrical components and equipment industry, to demonstrate its suitability for helping organizational decision makers (DMs) in partner selection.

Literature depicts that application of FST has been immensely popularized in analyzing different aspects of SCM followed by supplier/partner selection. However, most of the approaches have the following limitations (literature gap):

(1) These approaches are based on either subjective or objective data set. A combination of both subjective as well as objective data have hardly been considered in a particular decision-making tool.

(2) Most of the decision-making approaches utilize only a set of evaluation criteria (single level). In practice, main evaluation criteria may be divided into a number of sub-criteria; each sub-criterion can further be divided into sub-sub criteria and so on. Hence, selection of a decision-making module capable of exploring an integrated criteria hierarchy is of utmost important.

Chu and Velásquez (2009) and Chu and Varma (2012) suggested a multiple levels multiple criteria decision making (MLMCDM) model under fuzzy environment to

Sl. No.	Citation	Contribution	Methodology/approach
1	Ren *et al.* (2005)	Proposed a decision-making methodology and a hierarchical model for the selection of agile partners	A set of agile decision domains and attributes is identified. Based on a questionnaire survey, the weights of agile dimensions, decision domains and attributes are determined. The reliability analysis reveals that all agile attributes show a high level of internal consistency, thus they provide a validated base for the research
2	Sarkis *et al.* (2007)	Provided a practical model usable by organizations to help form agile virtual enterprises. The model helped to integrate a variety of factors, tangible and intangible, strategic and operational, for decision-making purposes	Analytical network process (ANP) is applied
3	Anuziene and Bargelis (2007)	Presented the decision support system (DSS) framework for agile manufacturing of mechanical products which allowed the selection of proper decision applying technologies, facilities and processes located in partner network in relation to the Lithuanian industry	DSS framework interface was modelled and programmed using WEB-based technologies. The framework computed manufacturing costs of different product machining options that were compared and the most cost efficient choice was selected
4	Zhou *et al.* (2008)	Developed a method for the partner evaluation of the agile supply chain of Shenyang Machine Tool Co. Ltd	The method combined analytic hierarchy process (AHP) and fuzzy comprehensive evaluation (FCE)
5	Luo *et al.* (2009)	Developed a model that helped to overcome the information-processing difficulties inherent in screening a large number of potential suppliers in the early stages of the selection process	Based on radial basis function artificial neural network (RBF-ANN), the model enabled potential suppliers to be assessed against multiple criteria using both quantitative and qualitative measures. Its efficacy was illustrated using empirical data from the Chinese electrical appliance and equipment manufacturing industries
6	Kahraman and Kaya (2010)	Designed and implemented a procedure for judging the suitability of suppliers for an organization competing on agile manufacturing characteristics	A fuzzy analytic hierarchy process was used for the selection of the best supplier for agile manufacturing
7	Aishwarya and Balaji	Validated a tool, Agile Supply Chain Transformation Matrix (ASCTM), and the implementation methodology for a systematic approach to achieve agility in the supplier-buyer supply chain	The ASCTM tool was constructed using the quality function deployment (QFD) and analytic hierarchy process (AHP) technique. This tool could help companies create and improve their agility by relating the business changes with the appropriate approaches for supplier-buyer supply chain configuration and supplier-buyer relationship establishment and determine the business processes and

(*continued*)

Table I.
Literatures on suppliers/partners selection in agile supply chain

Sl. No.	Citation	Contribution	Methodology/approach
			the infrastructures needed to support the creation of agile capability
8	Wu and Barnes (2009)	A supplier evaluation guide line was discussed in agile supply chain	Neural network-based supplier evaluation model is established. BP dynamic neural network is applied in constructing model and the amelioration weight reset arithmetic is imported in supplier evaluation and selection model. Finally, service-oriented software development method is used to develop neural network-based supplier selection expert system
9	Wu and Barnes (2010)	Formulated partner selection criteria for agile supply chains	A Dempster-Shafer belief acceptability optimization approach is explored
10	Wu and Barnes (2012)	Presented a four-phase dynamic feedback model for supply partner selection in agile supply chains (ASCs)	The model draws on both quantitative and qualitative techniques, including the Dempster-Shafer and optimization theories, radial basis function artificial neural networks (RBF-ANN), analytic network process-mixed integer multi-objective programming (ANP-MIMOP), Kraljic's supplier classification matrix and principles of continuous improvement

Table I.

evaluate and select suppliers, where a general hierarchical structure was developed to depict the relationship among parent criteria and their sub-criteria and sub-sub-criteria and so on. However, the reliability of the FMLMCDM method in various applications of MCDM problems is missing in the current literature. So this paper tries to explore the reliability aspect of the method using a real case from an automotive industry (located at Tamil Nadu, India) by comparing it with already existing methods such as Fuzzy-TOPSIS and Fuzzy-MOORA.

Evaluating suppliers, many criteria including quantitative, such as cost/price, as well as qualitative, such as relationship closeness, must be considered (Choi and Hartley, 1996; Chou and Chang, 2008; Dowlatshahi, 2000; Verma and Pullman, 1998; Weber *et al.*, 1998; Shyur and Shih, 2006). In addition, criteria may have different importance. Referring specifically to a multi-criterion analysis, the value of a certain alternative concerning a given attribute often cannot be precisely defined, the DM is unable (or unwilling) to express his/her preferences precisely, the evaluations or opinions are expressed in linguistic terms (Bevilacqua *et al.*, 2006). Besides, the relative importance of criteria is usually expressed by means of linguistics judgments (Bottani and Rizzi, 2008). Therefore, a MCDM approach for the selection and evaluation of suppliers under fuzzy environment is indeed necessary. A review of fuzzy MCDM methods could be found in Carlsson and Fuller (1996), Chu and Lin (2009), Ribeiro (1996) and some recent applications could be seen in Al-Najjar and Alsyouf (2003), Chou *et al.* (2006), Chou (2007), Önüt *et al.* (2009). Moreover, many of the criteria used in the supplier's evaluation process may have sub-criteria and these sub-criteria may in turn have sub-sub-criteria, etc., which was addressed in the work by Chu and Varma (2012).

In this context, present work explores application potential of the FMLMCDM module toward appropriate supplier selection in the arena ASC. Results obtained thereof, have been compared to that of two MCDM approaches, i.e., Fuzzy-TOPSIS and Fuzzy-MOORA. A case industrial example has also been reported here.

3. Methodology

3.1 Research design

This paper explores first the FMLMCDM methodology as proposed by Chu and Velásquez (2009) and Chu and Varma (2012) toward evaluating agile suppliers under fuzzy environment. The general hierarchy criteria (GHC) may consist of qualitative (QL) and/or quantitative (QT) criterions. A hierarchical structure that was mathematically developed by Chu and Velásquez (2009) and Chu and Varma (2012) to depict the multiple levels multiple criteria and formulas has been adapted here. Quantitative criteria (QL) are further classified to benefit (B) and cost (C) ones. Benefit criterion has the characteristics: the higher-the-better (HB); and cost criterion has the characteristics: the lower-the-better (LB). Ratings of suppliers vs qualitative criteria and the importance weights of all the criteria are assessed in linguistic values represented by triangular fuzzy numbers. However, when there is more than one level in the criteria hierarchy, the multiplication of more than three fuzzy numbers will be encountered. Since no standard solution is available in fuzzy mathematics to produce the membership function for the multiplication of more than three fuzzy numbers. The best way to resolve the above limitation may be to defuzzify all the fuzzy numbers before applying them to the suggested model. Thus, the concept of Center of Area (COA) defuzzification (Tong, 1978) has been adapted here. The entire fuzzy-based decision-making module needs in-depth knowledge and understanding of fuzzy sets, fuzzy numbers, linguistic values, and defuzzification of fuzzy numbers by COA method that could be found in Zadeh (1975), Dubois and Prade (1978), VanLaarhoven and Pedrycz (1983), Kaufmann and Gupta (1991).

In this paper a two-level of hierarchical framework for agile supplier selection has been adopted from the knowledge acquired from past literature. The definitions of various main criteria as well as sub-criteria have been presented in the Appendix. The framework consists of the various main criteria as well as sub-criterions in which some criteria have been qualitative and some have been assumed quantitative in nature. A group of experts (DMs) has been assigned to provide initially the importance weights of all the criteria and performance extent (ratings) of alternatives against all qualitative and quantitative criteria using linguistic variables. Linguistic information data has then been converted into equivalent triangular fuzzy numbers. For ranking of suppliers additive weighted methodology has been utilized along with the "COA" deffuzification approach before weighted aggregation of performance ratings. Finally, the most appropriate supplier has been selected and some managerial implication has been drawn to improve performance of the ASC in view of effective agile supplier/partner selection.

In the second phase, Fuzzy-TOPSIS as well as Fuzzy-MOORA has been applied. In Fuzzy-TOPSIS, criteria rating as well as weights are represented by fuzzy numbers; however, defuzzification of fuzzy numbers is not required. Based on fuzzy operational rules, a closeness coefficient is determined. Alternatives are then ranked based on their closeness coefficient value. Since the present problem deals with both qualitative as well as quantitative data set; quantitative evaluation data need to be fuzzified first to apply the standard Fuzzy-TOPSIS methodology.

In Fuzzy-MOORA, a ratio system is developed, where each performance of an alternative on an attribute is to be compared with the representative for all the alternatives. Next, the overall performance of each alternative is calculated as the difference between sums of its normalized performances for beneficial attributes and non-beneficial attributes. The overall performance indices are arranged in the descending order and ranked best to worst, i.e., the alternative with the highest overall performance index is the best choice.

Similar to Fuzzy-TOPSIS, in Fuzzy-MOORA also, based on fuzzy operational rules, an overall performance index is determined. Alternatives are then ranked based on their overall performance value. Since the present problem deals with both qualitative as well as quantitative data set; here also quantitative evaluation data need to be fuzzified first to apply the standard Fuzzy-MOORA technique.

The same two-level of hierarchical framework has been reutilized in this phase and the evaluation data have been analyzed through Fuzzy-TOPSIS as well as Fuzzy-MOORA, respectively. As Fuzzy-TOPSIS and Fuzzy-MOORA work under a set of criteria (single level); based on backward computation procedure, appropriateness rating as well as priority weight of various sub-criterions (Level II) have been utilized (fuzzy weighted average) to compute appropriateness rating of various main-criterions (Level I).

The fuzzy index has been calculated at Level II and then extended to the Level I. The evaluation index platform (at Level II) encompasses several sub-criterions.

The fuzzy index of each main-criterion (at Level I) has been calculated as follows:

$$U_i = \frac{\sum_{j=1}^{n} \left(w_{i,j} \otimes U_{i,j} \right)}{\sum_{j=1}^{n} w_{i,j}} \tag{1}$$

Here $U_{i,j}$ represents aggregated fuzzy performance measure (rating) and $w_{i,j}$ represents aggregated fuzzy weight for priority importance corresponding to jth sub-criteria $C_{i,j}$ (at Level II) which is under ith main criterion (at Level I).

In doing so, a multi-level hierarchy criterion has been converted into a single set of criteria thus facilitating to use Fuzzy-TOPSIS as well as Fuzzy-MOORA for final decision making. Finally, the results obtained from FMLMCDM, has been compared to that of Fuzzy-TOPSIS and Fuzzy-MOORA in relation to agile supplier selection data. The details of FMLMCDM have been presented below. The basics of Fuzzy-TOPSIS could be found in Ding (2011), Liao and Kao (2011), Haldar *et al.* (2014) and Fuzzy-MOORA in Brauers (2004), Mandal and Sarkar (2012), Chatterjee and Bose (2012), Kalibatas and Turskis (2008), Gadakh *et al.* (2013), Brauers *et al.* (2008), Brauers and Zavadskas (2009).

3.1.1 FMLMCDM approach. Some important mathematical notations used in the proposed model are defined as follows (Chu and Varma, 2012): D_v denotes decision maker $v, v=1, \ldots, q$; A_i denotes fuzzy numbers used to evaluate the importance of the importance of the criteria, $i=1, \ldots, n$; B_i denotes fuzzy numbers used to evaluate the suitability of alternatives vs qualitative criteria, $i=1, \ldots, n$; $e(A_i)$ denotes the defuzzified value of A_i through COA; $e(B_i)$ denotes the defuzzified value of B_i through COA; $f_{x_1 x_2 \ldots x_i \ldots x_n}$ denotes the n level (general) hierarchy structure to depict the relationship among criteria; $m_{x_1 x_2 \ldots x_{(i-1)}}$ denotes number of sub-criteria for criterion $f_{x_1 x_2 \ldots x_i}$; $w_{x_1 x_2 \ldots x_i v}$ denotes the weight given by the vth decision maker to the $x_1 x_2 \ldots x_i$th criterion, $1 \leqslant v \leqslant q$; W denotes vector; M denotes matrix; $r_{x_1 x_2 \ldots x_i t v}$ denotes the suitability given by the vth DM to the $x_1x_2 \ldots x_i$th criterion for alternative t; $R_{m_{x_1x_2 \ldots x_{(i-1)}} \times p}$ Denotes $m_{x_1x_2 \ldots x_{(i-1)}} \times p$ matrix of the $m_{x_1x_2 \ldots x_{(i-1)}}$ suitability values of sub-criteria of the criterion $f_{x_1x_2 \ldots x_{(i-1)}}$ from p alternatives.

In this section, the proposed COA defuzzification method is applied to establish a MLMCDM model under fuzzy environment (Chu and Varma, 2012). Suppose the importance weights of different criteria and the ratings of various alternatives under qualitative criteria in the model are assessed in linguistic terms (Zadeh, 1975) represented by triangular fuzzy numbers. Further suppose a set of linguistic terms represented by positive triangular fuzzy numbers A_i, $i = 1, \ldots, n$, are applied by DM D_v, $v = 1, \ldots, q$, to evaluate the importance of the criteria. Also a set of linguistic terms represented by positive triangular fuzzy numbers B_i, $i = 1, \ldots, n$, are applied by DM to evaluate the suitability of alternatives vs qualitative criteria. By applying defuzzification rules (Chu and Varma, 2012), we obtain the values of COA of these fuzzy numbers as $e(A_i)$ and $e(B_i)$, respectively (Figures A1-A3, Equations (A1)-(A3), in Appendix). The proposed model is developed by the following procedure:

Step 1: establish a multiple levels hierarchy structure for criteria.

A general hierarchical structure to depict criteria is presented as follows (Table II):

$$F_{x_i} = \left\{ f_{x_1x_2 \ldots x_i \ldots x_n} \right\} \quad (2)$$

For example, f_{x_1} represents the first level criteria of evaluated alternatives, $f_{x_1x_2}$ represents second level criteria of f_{x_1}, and the number of the second level criteria is m_{x_1}. Herein, the criteria in the hierarchical structure are assumed to be independent.

Step 2: decide the weights.

When DM assign weights to criteria, they must understand the meanings of the linguistic weights and their corresponding fuzzy numbers; in other words, we assume that DM' understanding of the concept of "importance" is in full compliance with the way that weights are used in the model.

The average weights associated with n level hierarchical structure are developed the following equation:

$$w_{x_1x_2 \ldots x_i} = \frac{1}{q}\left\{ w_{x_1x_2 \ldots x_i1} + w_{x_1x_2 \ldots x_i2} + \ldots + w_{x_1x_2 \ldots x_iv} + \ldots + w_{x_1x_2 \ldots x_iq} \right\} \quad (3)$$

Here $w_{x_1x_2 \ldots x_iv}$ is a defuzzified triangular fuzzy number from $e(A_i)$. Also $w_{x_1x_2 \ldots x_i}$ represents the weight of criterion $f_{x_1x_2 \ldots x_i}$.

Step 3: average alternative suitability vs qualitative criteria.

The average suitability of alternative t, $t = 1, \ldots, p$, vs each subjective criterion associated with n level hierarchy structure is presented as follows:

$$r_{x_1x_2 \ldots x_it} = \frac{1}{q}\left\{ r_{x_1x_2 \ldots x_it1} + r_{x_1x_2 \ldots x_it2} + \ldots + r_{x_1x_2 \ldots x_itv} + \ldots + r_{x_1x_2 \ldots x_itq} \right\} \quad (4)$$

Here $r_{x_1x_2 \ldots x_itv}$ is a defuzzified triangular fuzzy number from $e(B_i)$ and $r_{x_1x_2 \ldots x_it}$ represents the average suitability of alternative t vs criterion $f_{x_1x_2 \ldots x_i}$.

Goal	1st level criteria	2nd level criteria	3rd level criteria	4th level criteria
Agile supplier evaluation and selection	f_1	f_{11}	f_{111}	f_{1111}
				f_{1112}
				f_{1113}
			f_{112}	f_{1121}
				f_{1122}
				f_{1123}
				f_{1124}
		f_{12}	f_{121}	f_{1211}
				f_{1212}
				f_{1213}
				f_{1214}
			f_{122}	f_{1221}
				f_{1222}
		f_{13}	f_{131}	f_{1311}
				f_{1312}
			f_{132}	f_{1321}
	f_2	f_{21}	f_{211}	f_{2111}
				f_{2112}
			f_{212}	f_{2121}
			f_{213}	f_{2131}
			f_{214}	f_{2141}
				f_{2142}
			f_{215}	f_{2151}
				f_{2152}
			f_{216}	f_{2161}
				f_{2162}
		f_{22}	f_{221}	f_{2211}
			f_{222}	f_{2221}

Table II. The four-level general hierarchical structure of criteria

Step 4: normalization of alternative suitability vs qualitative criteria.

Values (or suitability) of alternatives vs different quantitative criteria need to be normalized because they have different units. If only benefit (or cost) qualitative criteria are used, normalization can be omitted. In this model, suitability of alternatives vs quantitative criteria can be classified into benefit (*B*) and cost (*C*) ones. The normalization of the suitability can be accomplished by applying the following two formulas:

$$r_{x_1x_2\ \ldots\ x_it} = \frac{S_{x_1x_2\ \ldots\ x_it}}{\max_t\left\{S_{x_1x_2\ \ldots\ x_it}\right\}}, \tag{5}$$

$$r_{x_1x_2\ \ldots\ x_it} = \frac{\min_t\left\{S_{x_1x_2\ \ldots\ x_it}\right\}}{S_{x_1x_2\ \ldots\ x_it}}. \tag{6}$$

Here $r_{x_1x_2\ \ldots\ x_it}$ denotes the normalized value of $S_{x_1x_2\ \ldots\ x_it}$. Also $S_{x_1x_2\ \ldots\ x_it}$ denotes the suitability value of alternative t vs criterion $f_{x_1x_2\ \ldots\ x_i}$.

Step 5: synthetic evaluation.

The additive weighted evaluation matrices in the structure can be obtained by using multiplication and addition to aggregate the evaluation matrices and their corresponding weights matrices as follows:

$$\begin{aligned} M_{x_1x_2\ldots x_{(i-1)}} &= W_{x_1x_2\ldots x_{(i-1)}} \times R_{m_{x_1x_2\ldots x_{(i-1)}}\times p} \\ &= \left[\sum_{x_i=1}^{m_{x_1x_2\ldots x_{(i-1)}}} w_{x_1x_2\ldots x_i}.r_{x_1x_2\ldots x_i1} \sum_{x_i=1}^{m_{x_1x_2\ldots x_{(i-1)}}} w_{x_1x_2\ldots x_i}.r_{x_1x_2\ldots x_i2}\cdots \right. \\ &\qquad \left. \sum_{x_i=1}^{m_{x_1x_2\ldots x_{(i-1)}}} w_{x_1x_2\ldots x_i}.r_{x_1x_2\ldots x_it}\cdots \sum_{x_i=1}^{m_{x_1x_2\ldots x_{(i-1)}}} w_{x_1x_2\ldots x_i}.r_{x_1x_2\ldots x_ip}\right] \\ &= \left[r_{x_1x_2\ldots x_{(i-1)}1} r_{x_1x_2\ldots x_{(i-1)}2}\ldots r_{x_1x_2\ldots x_{(i-1)}t}\ldots r_{x_1x_2\ldots x_{(i-1)}p}\right] \end{aligned} \tag{7}$$

Here $M_{x_1x_2\ldots x_{(i-1)}}$ is a $1\times p$ vector with the additive weighted evaluations of the p alternatives over the criteria set $f_{x_1x_2\ldots x_i}, W_{x_1x_2\ldots x_{(i-1)}}$ is the vector of the corresponding criteria weights and $R_{m_{x_1x_2\ldots x_{(i-1)}}\times p}$ is a matrix with the suitability of the alternatives on the criteria. $w_{x_1x_2\ldots x_{(i-1)}}$ is derived by Equation (3), t represents alternative $t.r_{x_1x_2\ldots x_it}$ is defined from Equation (4) when $f_{x_1x_2\ldots x_i}$ is a qualitative criterion with no sub-criteria, from Equations (5) and (6) when $f_{x_1x_2\ldots x_i}$ is a quantitative criterion with no sub-criteria, or from $\sum_{x_{(i+1)}=1}^{m_{x_1x_2\ldots x_i}} w_{x_1x_2\ldots x_{(i+1)}}.r_{x_1x_2\ldots x_{(i+1)}t}$ when $f_{x_1x_2\ldots x_i}$ is not further analyzed into lower-level sub-criteria. $\sum_{x_i=1}^{m_{x_1x_2\ldots x_{(i-1)}}} w_{x_1x_2\ldots x_i}.r_{x_1x_2\ldots x_it}$ denotes the additive weighted evaluation value, $r_{x_1x_2\ldots x_{(i-1)}t}$, of sub-criterion $f_{x_1x_2\ldots x_{(i-1)}}$ of $f_{x_1x_2\ldots x_{(i-2)}}$ from alternative t, and is the corresponding element of the $x_{(i-1)}$th row and the tth column in $R_{m_{x_1x_2\ldots x_{(i-2)}}\times p}$. The aggregation at every level of the hierarchy is done similarly to Equation (7).

The final additive weighted evaluation matrix can then be derived by the following equation based on the rule of back propagation as follows:

$$\begin{aligned} M = W \times R_{m\times p} &= \left[\sum_{x_1=1}^{m} w_{x_1}.r_{x_1 1} \sum_{x_1=1}^{m} w_{x_1}.r_{x_1 2}\ldots \sum_{x_1=1}^{m} w_{x_1}.r_{x_1 t}\ldots \sum_{x_1=1}^{m} w_{x_1}.r_{x_1 p}\right] \\ &= \left[r_1 r_2 \ldots r_t \ldots r_p\right] \end{aligned} \tag{8}$$

Here M represents the set of final additive weighted evaluation of all the m major criteria from p alternatives, and is the $1\times p$ evaluation matrix. Here $R_{m\times p}$ represents a $m\times p$ matrix. Also w_{x_1} and r_{x_1t} are the corresponding elements in W and $R_{m\times p}$, respectively. w_{x_1} is derived by Equation (3). Now, r_{x_1t} is derived from Equation (4) when f_{x_1} is a qualitative criterion with no sub-criteria, from Equations (5) and (6) when f_{x_1} is a quantitative criterion with no sub-criteria, or from $\sum_{x_2=1}^{m_{x_1}} w_{x_1x_2}.r_{x_1x_2t}$ when f_{x_1} is not further analyzed into lower-level sub-criteria. Also $\sum_{x_1=1}^{m} w_{x_1}.r_{x_1t}$ denotes the final additive weighted evaluation value, r_t, of the major criterion f_{x_1} from alternative t. The better performance the alternative, the higher the evaluation value; therefore the alternative that has the highest evaluation value should be chosen.

3.2 Data collection

In order to illustrate application potential of the fuzzy embedded MLMCDM methodology in comparison with Fuzzy-TOPSIS as well as Fuzzy-MOORA; a case industrial research has been conducted for supplier evaluation and selection in an ASC. A case study has been conducted in a famous automobile manufacturing company located at Tamil Nadu, India. The company's footprint in India has been growing steadily since its inception in 2005. Marked by an impressive rise in sales, award-winning quality from locally-built products, an expanding range of innovative cars and a rapidly evolving dealer network, the growth underlines the strategic importance of India to the said company. Guided by its global Brand commitment "Innovation and Excitement for Everyone" the company delivers cutting-edge technology, Innovative design and a rewarding experience to all its customers. In India, the case company has been constantly expanding innovative and exciting product offerings across hatchback, sports car, SUV and sedan segments.

Evaluation of suppliers' require an evaluation platform (criteria hierarchy) consisting of various performance indices. Main performance indices may further be divided into a number of sub-indices and sub-sub-indices and so on. Literature depicts a variety of criteria hierarchies proposed by pioneers to facilitate supplier selection in ASC. For example, Zhou *et al.* (2008) considered the following main criteria (delivery date, quality of after sale service, product quality, enterprise reputation, and technical level) for partner evaluation model of the ASC. Wu and Barnes (2014) suggested: production and logistics management, partnership management, technology and knowledge management, marketing capability, industrial and organizational competitiveness, human resource management, financial capability as key performance criterions for agile partner selection. Kahraman and Kaya (2010) proposed a set of main criteria (quality, delivery, agility, performance, management, and service) for supplier selection in ASC. Each main criterion has further been divided into various sub-criterions. In this present work, the following criterions (adapted from Seyedhoseini *et al.*, 2010): flexibility, responsiveness, competency, and cost have been considered as main criterions for agile supplier selection as they consist of general as well as agility-related criterions both and the hierarchy is not industry specific. Therefore, this GHC has been utilized; industry management has been requested to explore this to conduct a case research toward examining application potential of three MCDM tools in solving agile supplier selection problems.

Two-level GHC consisting four main criteria (Level I indices) and a total of 11 sub-criteria (Level II indices) has been explored, as shown in Table III.

A committee of five DMs (experts: D_1, D_2, D_3, and D_4) has been formed to collect necessary evaluation data. A set of four candidate suppliers: A_1, A_2, A_3, and A_4, have been chosen for evaluation as well as selection purpose. Here, it has been assumed that the criteria as well as sub-criteria are independent. The DMs' opinions have been collected in terms of linguistic variable which have further been converted into equivalent triangular fuzzy numbers.

The procedural steps of the entire selection module have been illustrated as follows:

Step 1: preparation of GHC toward suppliers' selection and evaluation (Table III).

Step 2: formation of a committee of DMs. A committee of five DMs has been formed to get expert opinion against relative importance weights of all main criteria (Level I indices) as well as sub-criteria (Level II indices); and the ratings of individual sub-criteria. The sub-criterions (Level II indices) have been divided into qualitative and quantitative ones.

Step 3: selection of appropriate linguistic scales and corresponding fuzzy representations.

Human judgment of the DMs has been collected in terms of linguistic variables. A five-member linguistic terms set (unimportant, UI; slightly important, SI; fairly important, FI; important, I; very important, VI) (adapted from Chu and Varma, 2012) has been used in order to represent importance weight of various evaluation criteria (both at Level I and Level II of the criteria hierarchy). Similarly, for assessment of performance ratings against individual Level II sub-criterions; a five-member linguistic terms set (unsatisfactory, U; poor, P; medium, M; satisfactory, S; excellent, E) (adapted from Chu and Varma, 2012) has been explored. These linguistic data have been converted into appropriate triangular fuzzy representative values in accordance with the fuzzy scale chosen, as shown in Table IV.

Step 4: collection of expert judgment through linguistic terminology.

After finalization of the appropriate linguistic scale and corresponding fuzzy representative value; DMs have been asked to explore aforesaid linguistic scale (Table IV) in order to provide their expert opinion toward importance weight of all the criteria (both at Level I and Level II). Expert opinion has been furnished in Table V. Similarly, the ratings of individual Level II indices in relation to four candidate

Table III. General hierarchal criteria (GHC) for agile supplier selection

Goal	Main-criteria (Level I indices)	Sub-criteria (Level II indices)
Agile supplier evaluation and selection	Flexibility, C_1	Sourcing flexibility, C_{11}
		Manufacturing flexibility, C_{12}
		Delivery flexibility, C_{13}
	Responsiveness, C_2	Sourcing responsiveness, C_{21}
		Manufacturing responsiveness, C_{22}
		Delivery responsiveness, C_{23}
	Competency, C_3	Cooperation and internal-external balance, C_{31}
		Capabilities of human resources, C_{32}
	Cost, C_4	Sourcing cost, C_{41}
		Manufacturing cost, C_{42}
		Delivery cost, C_{43}

Table IV. Linguistic scale for assignment of important weight and performance rating of suppliers' evaluation indices and corresponding fuzzy representative scale

Linguistic scale (for weight)	Triangular fuzzy numbers	Linguistic scale (for ratings)	Triangular fuzzy numbers
Unimportant (UI)	(0, 0.1, 0.3)	Unsatisfactory (U)	(0, 0, 0.25)
Slightly important (SI)	(0, 0.2, 0.5)	Poor (P)	(0, 0.25, 0.5)
Fairly important (FI)	(0.3, 0.45, 0.7)	Medium (M)	(0.25, 0.5, 0.75)
Important (I)	(0.5, 0.7, 0.8)	Satisfactory (S)	(0.5, 0.75, 1.0)
Very important (VI)	(0.7, 0.9, 1.0)	Excellent (E)	(0.75, 1.0, 1.0)

Source: Chu and Varma (2012)

Criteria/indices	DM_1	DM_2	DM_3	DM_4	DM_5
Main-criteria (Level I indices)					
Flexibility, C_1	VI	I	I	VI	I
Responsiveness, C_2	I	I	FI	FI	I
Competency, C_3	FI	VI	VI	FI	FI
Cost, C_4	SI	FI	I	I	FI
Sub-criteria (Level II indices)					
Sourcing flexibility, C_{11}	VI	I	I	VI	VI
Manufacturing flexibility, C_{12}	I	FI	I	I	FI
Delivery flexibility, C_{13}	FI	FI	FI	SI	SI
Sourcing responsiveness, C_{21}	I	I	I	I	I
Manufacturing responsiveness, C_{22}	I	VI	I	FI	FI
Delivery responsiveness, C_{23}	I	SI	VI	SI	SI
Cooperation and internal-external balance, C_{31}	VI	I	FI	VI	I
Capabilities of human resources, C_{32}	FI	I	VI	I	VI
Sourcing cost, C_{41}	VI	I	VI	FI	VI
Manufacturing cost, C_{42}	VI	I	FI	FI	FI
Delivery cost, C_{43}	SI	I	SI	I	VI

Table V. Expert opinion expressed in linguistic values for assignment of importance weight of evaluation indices

suppliers have been collected (for qualitative as well as quantitative criteria, separately); which have been shown in Tables VI and VII, respectively. For qualitative criteria, ratings have been obtained from DM's viewpoint (human judgment); and, for quantitative criteria, performance estimates (ratings) have been obtained directly from suppliers/vendors data base.

4. Results

The various stages of data analysis have been described below.

Sub-criteria (subjective)			A_1					A_2		
	DM_1	DM_2	DM_3	DM_4	DM_5	DM_1	DM_2	DM_3	DM_4	DM_5
C_{11}	S	E	E	S	E	M	M	M	S	P
C_{12}	M	M	E	E	S	S	E	E	S	S
C_{13}	S	S	S	E	S	S	P	S	S	S
C_{21}	E	M	E	M	M	M	M	E	P	P
C_{22}	S	S	S	S	S	M	M	M	M	P
C_{23}	M	E	S	S	S	E	S	E	E	E
C_{31}	S	S	P	S	P	M	S	S	S	M
C_{32}	M	E	E	M	E	E	S	S	S	M
Sub-criteria (subjective)			A_3					A_4		
	DM_1	DM_2	DM_3	DM_4	DM_5	DM_1	DM_2	DM_3	DM_4	DM_5
C_{11}	E	E	M	S	M	S	P	S	M	M
C_{12}	P	M	M	M	M	S	M	S	M	S
C_{13}	S	M	S	S	M	S	S	S	S	S
C_{21}	E	M	S	S	E	M	M	S	S	M
C_{22}	M	E	S	P	E	S	E	S	E	S
C_{23}	E	S	S	M	S	S	S	S	M	M
C_{31}	M	M	P	M	S	P	P	S	M	M
C_{32}	S	S	S	S	E	E	E	E	S	S

Table VI. Expert opinion expressed in linguistic values for assignment of performance rating of subjective evaluation indices for individual supplier alternatives

4.1 Agile supplier selection through FMLMCDM module

Step 1: aggregation and defuzzification.

Now, linguistic data have been converted into representative triangular fuzzy numbers as described in *Step 3*; and, then aggregated and defuzzified using the theory of COA defuzzification method (Figures A1-A3 and Equations (A1)-(A3) in Appendix) and Equations (3) and (4) for importance weights of all criteria and ratings of candidate suppliers under qualitative criteria. For the defuzzification purpose, COA method has been utilized. The defuzzified result of importance weight of the criteria has been shown in Table VIII; and rating of suppliers under qualitative criteria presented in Table IX.

Step 2: normalization of suppliers rating under quantitative criteria.

The ratings of supplier under quantitative criteria (Table VII) have been normalized, because the unit of the quantitative criteria may be different for criteria wise. The normalization has been done using the Equations (5) and (6) and the normalized data has been tabulated in Table X.

Step 3: final evaluation and ranking of suppliers.

For the final evaluation, the additive weighted method as represented in Equations (7) and (8) have been utilized and evaluation values have been obtained (shown in Table XI) based on the back propagation rules from Level II to Level I as depicted in the criteria-hierarchical structure as shown in Table III. Table XII exhibits final evaluation values in regards of performance of the four supplier alternatives; and, the alternatives

Table VII. Suppliers rating under quantitative sub-criteria

Alternatives	C_{41} (\$)	C_{42} (\$)	C_{43} (\$)
A_1	4,000	10,000	5,000
A_2	3,000	8,500	6,000
A_3	5,000	12,000	5,500
A_4	5,000	9,200	4,000

Table VIII. Average weight of individual Level I indices (main-criteria) as well as individual Level II indices (sub-criteria)

Evaluation indices	Aggregated defuzzified weight
Main-criteria	
C_1	0.7532
C_2	0.5949
C_3	0.6351
C_4	0.5051
Sub-criteria	
C_{11}	0.7932
C_{12}	0.5949
C_{13}	0.3763
C_{21}	0.6732
C_{22}	0.6349
C_{23}	0.4451
C_{31}	0.7144
C_{32}	0.7144
C_{41}	0.7544
C_{42}	0.5951
C_{43}	0.5349

have been ranked according to this final evaluation values obtained. A larger value indicates the better performance of the candidate alternative. The alternative corresponding to the highest final evaluation value has been assumed the best performing alternative and to be selected. From Table XI, it has been observed that the alternative supplier A_1 has the first rank because; it provides the highest evaluation score 3.1826; which has been selected as the best performed supplier suitable for the case agile organization. The alternative A_3 assumes a score of 3.0917, which appears as the second highest value. Therefore A_3 has been ranked second followed by alternatives A_4 and A_2 which appear as the third and the fourth rank with the score of 2.9433 and 2.7952, respectively. The final ranking order of agile supplier alternatives becomes: $A_1 > A_3 > A_4 > A_2$.

4.2 Agile supplier selection through Fuzzy-TOPSIS

The decision-making module exploring Fuzzy-TOPSIS requires a single set of criteria values (along with their weights) with respect to a finite number of possible alternatives. However, the GHC adapted in this case study is a multi-levelled one. In order to transform expert opinion into a compatible decision matrix (consisting of a set of criteria at single level), fuzzy operational rules need to be explored. Here, expert opinion (Table V) in

	Aggregated defuzzified rating			
Sub-criteria	A_1	A_2	A_3	A_4
C_{11}	0.8592	0.5000	0.7236	0.5500
C_{12}	0.7236	0.8236	0.4500	0.6500
C_{13}	0.7872	0.6500	0.6500	0.7500
C_{21}	0.6768	0.4872	0.7736	0.6000
C_{22}	0.7500	0.4500	0.6736	0.8236
C_{23}	0.7372	0.8936	0.7372	0.6500
C_{31}	0.5500	0.6500	0.5000	0.4500
C_{32}	0.7592	0.7372	0.7872	0.8592

Table IX. Rating of candidate suppliers under qualitative criteria

	Quantitative sub-criterions		
Alternatives	C_{41}	C_{42}	C_{43}
A_1	0.8	0.83	0.83
A_2	0.6	0.71	1.0
A_3	1.0	1.0	0.92
A_4	1.0	0.77	0.67

Table X. Normalized values of suppliers rating under quantitative criteria

Alternatives	Final evaluation score	Supplier ranking order
A_1	3.1826	1
A_2	2.7952	4
A_3	3.0917	2
A_4	2.9433	3

Table XI. Final evaluation values of candidate suppliers and corresponding ranking order

Table XII.
Aggregated fuzzy weight of criteria

	Aggregated fuzzy weight
Main criteria	
C_1	(0.58,0.78,0.88)
C_2	(0.42,0.60,0.76)
C_3	(0.46,0.63,0.82)
C_4	(0.32,0.50,0.70)
Sub criteria	
C_{11}	(0.62,0.82,0.92)
C_{12}	(0.42,0.60,0.76)
C_{13}	(0.18,0.35,0.62)
C_{21}	(0.50,0.70,0.80)
C_{22}	(0.46,0.64,0.80)
C_{23}	(0.24,0.44,0.66)
C_{31}	(0.54,0.73,0.86)
C_{32}	(0.54,0.73,0.86)
C_{41}	(0.58,0.77,0.90)
C_{42}	(0.42,0.59,0.78)
C_{43}	(0.34,0.54,0.72)

linguistic terms against priority weight of individual criteria and sub-criteria (at Levels I and II, respectively) has been transformed into appropriate triangular fuzzy numbers in accordance with Table IV. Aggregated fuzzy weights of individual criteria have been computed and furnished in Table XII. Similarly, linguistic ratings of subjective sub-criterions (at Level II) as assigned by the DM (Tables VI-VII) (for alternatives A_1, A_2, A_3, and A_4) have been transformed into appropriate triangular fuzzy numbers as per Table IV. Aggregated fuzzy ratings have been computed and presented in Table XIII.

The numeric values (ratings) of objective sub-criterions (from Table VII) have been fuzzified to construct a fuzzy decision-making matrix in combination with the data of Table XIII. Objective sub-criteria values have been normalized first, using the following:

$$x_i'\big|_{j=1,2,3} = \frac{x_{i\min}}{x_i}\bigg|_{j=1,2,3} (i = 1, 2, 3, 4) \quad (9)$$

Table XIII.
Aggregated fuzzy rating of alternatives with respect to different sub-criteria

Sub-criteria	Aggregated fuzzy rating A_1	A_2	A_3	A_4
C_{11}	(0.65,0.90,1.00)	(0.25,0.50,0.75)	(0.50,0.75,0.90)	(0.30,0.55,0.80)
C_{12}	(0.50,0.75,0.90)	(0.60,0.85,1.00)	(0.20,0.45,0.70)	(0.40,0.65,0.90)
C_{13}	(0.55,0.80,1.00)	(0.40,0.65,0.90)	(0.40,0.65,0.90)	(0.50,0.75,1.00)
C_{21}	(0.45,0.70,0.85)	(0.25,0.50,0.70)	(0.55,0.80,0.95)	(0.35,0.60,0.85)
C_{22}	(0.50,0.75,1.00)	(0.20,0.45,0.70)	(0.45,0.70,0.85)	(0.60,0.85,1.00)
C_{23}	(0.50,0.75,0.95)	(0.70,0.95,1.00)	(0.50,0.75,0.95)	(0.40,0.65,0.90)
C_{31}	(0.30,0.55,0.80)	(0.40,0.65,0.90)	(0.25,0.50,0.75)	(0.20,0.45,0.70)
C_{32}	(0.55,0.80,0.90)	(0.50,0.75,0.95)	(0.55,0.80,1.00)	(0.65,0.90,1.00)
C_{41}	(0.75,0.75,0.75)	(1.00,1.00,1.00)	(0.60,0.60,0.60)	(0.60,0.60,0.60)
C_{42}	(0.85,0.85,0.85)	(1.00,1.00,1.00)	(0.71,0.71,0.71)	(0.92,0.92,0.92)
C_{43}	(0.80,0.80,0.80)	(0.67,0.67,0.67)	(0.73,0.73,0.73)	(1.00,1.00,1.00)

Since all the objective sub-criterions are non-beneficial (cost) in nature; the LB normalization formula has been adapted so that the normalized value comes in the range $0 < x_i' \leqslant 1$. After normalization the sub-criterions can be treated as beneficial (HB); because normalized value 1 is the most desired value. Also, a real number *a* can be written in terms of a triangular fuzzy number like (*a*, *a*, *a*); the normalized values of sub-criterions C_{41}, C_{42}, and C_{43} have been fuzzified. Now, based on fuzzy weighted average rule (Equation (1)), computed fuzzy performance rating of individual main-criteria (at Level I) (C_1, C_2, C_3, and C_4) have been obtained for all candidate alternatives (Table XIV), which has been treated as the final fuzzy decision matrix. Since all sub-criterions (C_{11}-C_{43}) have been treated as beneficial in nature; hence, further normalization is not required at all. The weighted (normalized) decision matrix has been constructed next and shown in Table XV. The positive ideal solution A^+ and the negative ideal solution A^- have been determined and shown in Table XVI.

Now, the distance of each alternative from the positive ideal solution and the negative ideal solution has been calculated and shown in Table XVII. Finally, the

Table XIV. Calculated rating of alternatives with respect to main criteria

Criteria	Computed fuzzy rating A_1	A_2	A_3	A_4
C_1	(0.31,0.83,1.82)	(0.21,0.65,1.65)	(0.20,0.63,1.57)	(0.19,0.62,1.67)
C_2	(0.25,0.73,1.76)	(0.17,0.59,1.48)	(0.27,0.75,1.72)	(0.24,0.70,1.73)
C_3	(0.27,0.68,1.35)	(0.28,0.70,1.47)	(0.25,0.65,1.39)	(0.27,0.68,1.35)
C_4	(0.44,0.80,1.43)	(0.51,0.91,1.61)	(0.37,0.67,1.21)	(0.45,0.81,1.48)

Table XV. Weighted normalized decision matrix

Criteria/alternative	A_1	A_2	A_3	A_4
C_1	(0.18,0.65,1.60)	(0.12,0.51,1.45)	(0.12,0.49,1.38)	(0.11,0.49,1.47)
C_2	(0.11,0.44,1.33)	(0.07,0.36,1.13)	(0.11,0.45,1.31)	(0.10,0.42,1.31)
C_3	(0.12,0.43,1.11)	(0.13,0.44,1.21)	(0.12,0.41,1.14)	(0.12,0.43,1.11)
C_4	(0.14,0.40,1.00)	(0.16,0.45,1.13)	(0.12,0.33,0.84)	(0.14,0.41,1.03)

Table XVI. Positive ideal solution and negative ideal solution

Criteria	A^+	A^-
C_1	(0.18,0.65,1.60)	(0.11,0.49,1.47)
C_2	(0.11,0.44,1.33)	(0.07,0.36,1.13)
C_3	(0.13,0.44,1.21)	(0.12,0.41,1.14)
C_4	(0.12,0.33,0.84)	(0.16,0.45,1.13)

Table XVII. Separation measure, closeness coefficient and ranking order of alternatives

Alternatives	d_i^+	d_i^-	CC_i	Ranking order
A_1	0.113	0.200	0.638	1
A_2	0.255	0.046	0.154	4
A_3	0.167	0.222	0.571	2
A_4	0.183	0.132	0.419	3

closeness coefficient (CC_i) for each of the supplier alternatives has been determined. The final ranking order of agile supplier alternatives becomes: $A_1 > A_3 > A_4 > A_2$; same as obtained in FMLMCDM approach in the previous section.

4.3 Agile supplier selection through Fuzzy-MOORA

Starting with the final fuzzy decision matrix (Table XIV) as constructed during Fuzzy-TOPSIS analysis, has been normalized first using vector normalization to obtain the normalized fuzzy decision matrix (Table XVIII). In the next step, the weighted normalized decision matrix has been formed and shown in Table XIX. Therefore, overall ratings of all criteria for each alternative have been calculated. Nest, overall performance index (S_i) has been determined for each alternative (Table XX). Since, all criterions have been treated as beneficial in nature; the defuzzified values of overall performance index $S_i = (S_i^{a+}, S_i^{b+}, S_i^{c+})$ have been utilized to rank the alternative suppliers. The overall performance indices have been arranged in the descending order and ranked best to worst, i.e., the alternative with the highest overall performance index is the best choice (Table XX). The ranking order becomes as $A_1 > A_2 > A_4 > A_3$; however, it was $A_1 > A_3 > A_4 > A_2$ in FMLMCDM approach as well as Fuzzy-TOPSIS obtained in the previous sections.

5. Discussions and managerial implications

In current highly volatile marketplace, ASC needs to be highly flexible so that the ever-changing customer requirements in terms of product quality, quantity and

	Normalized ratings of main-criteria			
Alternatives	C_1	C_2	C_3	C_4
A_1	(0.085,0.226,0.498)	(0.069,0.199,0.480)	(0.085,0.215,0.431)	(0.130,0.233,0.419)
A_2	(0.057,0.177,0.449)	(0.047,0.162,0.405)	(0.090,0.223,0.469)	(0.150,0.265,0.472)
A_3	(0.055,0.172,0.429)	(0.073,0.205,0.470)	(0.080,0.207,0.443)	(0.109,0.196,0.353)
A_4	(0.053,0.170,0.457)	(0.066,0.192,0.472)	(0.085,0.215,0.431)	(0.131,0.239,0.433)

Table XVIII. Normalized fuzzy decision matrix

	Weighted normalized ratings of main-criteria			
Alternatives	C_1	C_2	C_3	C_4
A_1	(0.049,0.177,0.438)	(0.029,0.120,0.364)	(0.039,0.135,0.353)	(0.042,0.117,0.293)
A_2	(0.033,0.138,0.396)	(0.020,0.097,0.308)	(0.041,0.140,0.384)	(0.048,0.133,0.331)
A_3	(0.032,0.134,0.378)	(0.031,0.123,0.358)	(0.037,0.130,0.363)	(0.035,0.098,0.247)
A_4	(0.031,0.133,0.402)	(0.028,0.115,0.359)	(0.039,0.135,0.353)	(0.042,0.119,0.303)

Table XIX. Weighted normalized decision matrix

Alternatives	Overall rating of alternative suppliers	Defuzzified value (by COA method)	Ranking order
A_1	(0.159, 0.548, 1.449)	0.6866	1
A_2	(0.142, 0.508, 1.418)	0.6562	2
A_3	(0.134, 0.485, 1.346)	0.6240	4
A_4	(0.139, 0.502, 1.417)	0.6527	3

Table XX. Suppliers overall ratings and final ranking order product variety within a particular time period can satisfactorily be fulfilled. This entire event is somehow related to the evaluation and selection of appropriate supplier. Therefore, the need for developing an agile supplier selection module is definitely a challenging task. In aforesaid work, an efficient suppliers' evaluation module has been described for ASC. A two-level GHC has been adapted here. The selection model presented here has been aimed to aid the DMs/ industry management toward successful survival in turbulent and competitive business environment. In this context, a FMLMCDM methodology has been adapted to facilitate agile supplier selection event. The application potential of FMLMCDM approach has been compared to that of Fuzzy-TOPSIS as well as Fuzzy-MOORA. The most appropriate supplier appears same in all three cases. This infers that the methods are compatible and competent on one another. However, their working principles various and procedural steps differ. That is why; the ranking order obtained from Fuzzy-MOORA differs from that of FMLMCDM approach as well as Fuzzy-TOPSIS. In such a case, dominance theory may be applied to determine the final ranking order of candidate alternatives. A comprehensive comparison on aforesaid three approaches has been summarized in Table XXI.

The aforesaid approaches can simultaneously consider qualitative (subjective) as well as quantitative supplier selection criterions. Managers can adopt and implement these frameworks in existing ASC system in order to undergo proper evaluation as well as selection of appropriate agile suppliers that in term may be helpful in achieving competitive advantage in the tough business place.

6. Conclusions and future scopes

The effective and competent supplier selection model is one of the most important issues in modern SC system. ASC system can overcome that issues and function as per present requirement. In supplier selection, the MCDM is utmost important at different management levels in association with consideration of with several criteria as well as sub-criteria. In the present work, FMLMCDM method has been attempted and compared with Fuzzy-TOPSIS as well as Fuzzy-MOORA to resolve the said MCDM situation. MLMCDM provides the systematic and easy-to explore solution for selection of suppliers, machines, tools, techniques, and service which has consists of various hierarchical level criteria, sub-criteria, sub-sub criteria, and so on. The ranking of supplier is made through additive weighted methodology by back propagation rules. In addition to that the COA approach has been adapted to defuzzify aggregated importance weight and supplier rating under qualitative criteria. Finally, based on the evaluation scores the candidate alternatives suppliers are ranked. The limitations and future research directions have been pointed out below.

The GHC, also called evaluation index system, toward evaluating potential supplier in ASC, has been adapted from the knowledge of past literature. The evaluation index system mostly consists of two levels comprising various evaluation indices (both at levels I and II). This GHC has been provided to the case industry personnel to assist in gathering decision data. However, aforementioned criteria hierarchy has not been standardized. It has not been tested whether these criteria hierarchy is industry-specific (e.g. manufacturing or service sector) or may tend to vary from one industry/organization to another depending on the particular SC construct/product/service.

The hierarchy levels of this case study have been consisted two levels only which covered only the main-criteria (Level I indices) as well as sub-criteria

Sl. no.	FMLMCDM	Proposed Fuzzy-TOPSIS	Proposed Fuzzy-MOORA
1	Works on multi-level multi-criteria model. Each main criterion is divided into sub-criteria; each sub-criterion is divided into sub-sub-criteria and so on	Explores a set of criterions at single level	Explores a set of criterions at single level
2	Can consider both subjective as well as objective data	Proposed approach can consider only subjective (fuzzy) data. Objective (if it is there) data needs to be fuzzified first	Proposed approach can consider only subjective (fuzzy) data. Objective (if it is there) data needs to be fuzzified first
3	Fuzzy appropriateness rating as well as fuzzy priority weight needs to be defuzzified first. Then by layer-wise (higher level to lower level of the criteria hierarchy), a unique supplier selection score is computed	Based on "Fuzzy Weighted Average" rule appropriateness ratings as well as priority weights of sub-criteria (at higher level) are utilized to compute appropriateness rating of a criterion (at higher/preceding level)	Based on "Fuzzy Weighted Average" rule appropriateness ratings as well as priority weights of sub-criteria (at higher level) are utilized to compute appropriateness rating of a criterion (at higher/preceding level)
3	The unique supplier selection score is used to rank the alternative suppliers	It computes an ideal solution and anti-ideal solution set. Then separation distances of each alternative with respect to ideal and anti-ideal solution are computed. Finally, a closeness coefficient is computed to rank the alternative suppliers	It computes an overall performance index which is the difference between sum of all beneficial criteria values and sub of all non-beneficial criteria values. Suppliers are ranked based on the overall performance index
4	Fuzzy operational rules are not utilized here. Because, initially all fuzzy data are converted into representative crisp values (defuzzified values). At every stage exploration of defuzzified values may increase chance of error	Fuzzy operational rules are utilized here. Defuzzification of a fuzzy number is not required at all.	Fuzzy operational rules are utilized here only to convert a multi-level criteria hierarchy into a single set of criterions. Defuzzification is required only to obtain crisp weights of main criterions

Table XXI.
Difference between three MCDM approaches adapted in this paper: FMLMCDM, Fuzzy-TOPSIS and Fuzzy-MOORA

(Level II indices). Another example of two-level criteria hierarchy could be obtained in (Gunasekaran *et al.*, 2001). It can also be extended into higher level (e.g. Chan and Qi, 2003) of complicated hierarchy structure as future scope of work.

Different defuzzification approaches possess different formulas which produce different defuzzification values. Different defuzzification values may likely lead to different final evaluation values and may lead to different ranking outcome.

The linguistic scale and corresponding representative fuzzy numbers scale thus chosen for collecting expert opinion (human judgment) have been taken from existing literature. However, sensitivity of these scales has not been tested. In the proposed fuzzy-based decision support systems, fuzzy numbers with a trapezoidal membership functions have been explored. It is felt necessary to investigate which fuzzy number (corresponding membership function like triangular, trapezoidal, Gaussian, bell shaped) is capable of providing the most reliable result.

Three decision support systems (FMLMCDM, Fuzzy-TOPSIS, Fuzzy-MOORA) have been attempted here toward appraising suppliers' selection in ASC. Application feasibility of FMLMCDM module has been compared to that of Fuzzy-TOPSIS as well as Fuzzy-MOORA. Apart from these, other fuzzy-based MCDM approaches like Fuzzy-VIKOR, Fuzzy-AHP, etc., could be applied to validate application potential of the FMLMCDM approach.

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Further reading

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(The Appendix follows overleaf.)

Appendix

	Definition	References
Main-criteria		
Flexibility	Flexibility is the organization's ability to meet an increasing variety of customer expectations without excessive costs, time, organizational disruptions, or performance losses	Slack (1983), Beach *et al.* (2000), Zhang *et al.* (2003)
Responsiveness	Ability to react purposefully and within an appropriate time scale to customer demand or changes in the marketplace, to bring about or maintain competitive advantage	Lin *et al.* (2006a, b), Holweg (2005)
Competency	Competency is the ability to efficiently and effectively reach enterprises' aims and goals. In other words, competency is the measurable or observable knowledge, skills, abilities and behaviors critical to successful job performance	Lin *et al.* (2006a, b)
Cost	It is the cost of product/service demanded by the supplier	
Sub-criteria		
Sourcing flexibility	The availability of a range of options and the ability of the purchasing process to effectively exploit them so as to respond to changing requirements related to the supply of purchased components	Swafford *et al.* (2008), Beach *et al.* (2000)
Manufacturing flexibility	The ability to produce a variety of products in the quantities that customers demand while maintaining high performance. It is strategically important for enhancing competitive position and winning customer orders	Swafford *et al.* (2008), Zhang *et al.* (2003)
Delivery flexibility	The ability to exploit various dimension of speed of delivery	Slack (1983) (Source: www.uky.edu/~dsianita/611/fms.html)
Sourcing responsiveness	It is the responsiveness of the sources available in an organization for the effective utilization of resource and customer satisfaction	Gindy *et al.* (1999)
Manufacturing responsiveness	The ability of a manufacturing system to make a rapid and balanced response to the predictable and unpredictable changes of today's manufacturing environments	Gindy *et al.* (1999)
Delivery responsiveness	It is the response time taken to deliver the customized product and services	Gindy *et al.* (1999)
Cooperation and internal-external balance	It is the management strategy of the organization to improve the performance of the organization	Monczka *et al.* (2009)

(*continued*)

Table AI.
Description/definition of various main-criteria and sub-criteria

	Definition	References
Capabilities of human resources	HR capability describes the extent to which the firms viewed skilled and innovative human resources, training competent employees, and human resources commitment as their source of competitive advantage	Karami (2004)
Sourcing cost	The cost incurred in the procurement practices aimed at finding, evaluating and engaging suppliers of good and services	
Manufacturing cost	The cost which is directly involve in the manufacturing of the products	
Delivery cost	It is the cost incurred to the customer for the delivery of the purchased product	

Table AI.

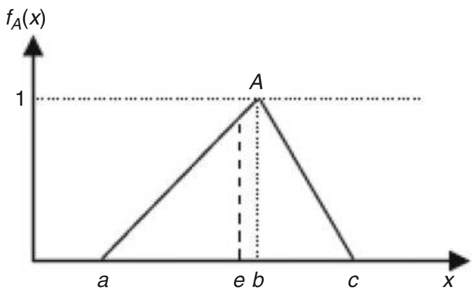

Figure A1. Triangular fuzzy number *a* and its defuzzification value *e* when ab > bc

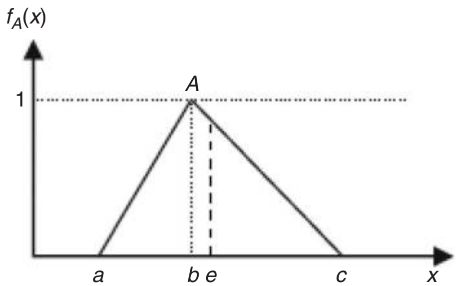

Figure A2. Triangular fuzzy number *a* and its defuzzification value *e* when ab < bc

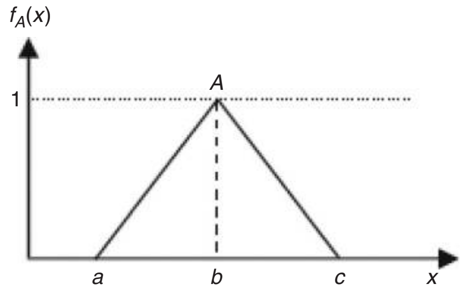

Figure A3. Triangular fuzzy number *a* and its defuzzification value *e* when ab=bc

The defuzzification formulas for fuzzy number $A=(a,b,c)$ by using COA, i.e., $I_L(A)=I_R(A)$, are presented in the following three situations:

(a) If $\overline{ab} > \overline{bc}$ as shown in Figure A1.

Thus, according to Figure A1, e is derived from "$I_L(A)=I_R(A)$" as:

$$e = a+\frac{1}{2}\left[2a^2-2ab-2ac+2bc\right]^{\frac{1}{2}} \tag{A1}$$

(b) If $\overline{ab} < \overline{bc}$ as shown in Figure A2.

Thus, according to Figure A2, e is derived from "$I_L(A)=I_R(A)$"as:

$$e = c-\frac{1}{2}\left[2c^2+2ab-2ac-2bc\right]^{\frac{1}{2}} \tag{A2}$$

(c) If $\overline{ab} = \overline{bc}$ as shown in Figure A3.

According to Figure A3, the defuzzification value e equals to b. Thus, e is derived from "$I_L(A)=I_R(A)$" as:

$$e = \frac{1}{2}(a+c). \tag{A3}$$

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