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# Fuzzy multi criteria decision making approach for performance measurement of advanced manufacturing systems

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**Abstract**

In today's competitive environment, a right performance measurement system of manufacturing firms plays a critical role in achieving competitive advantages. To overcome disadvantages of traditional performance measurement and to achieve competitive advantages goals, this paper attempts to present a new approach based on fuzzy analytic hierarchy process for performance measurement of advanced manufacturing systems under activity based costing (ABC) system. The proposed decision method aggregates the experts' judgments for the ABC criteria weights, and the measuring performance of companies which applied advanced manufacturing systems. The proposed approach is applied to measure performance of advanced manufacturing systems as an experiment and results are provided. Also, the proposed approach can effectively handle complex, ambiguity and fuzzy environment involved in measuring performance of advanced manufacturing systems.

**Keywords**: Fuzzy set; multi criteria decision making; performance measurement; manufacturing system.

## Introduction

Developments and improvements in manufacturing systems have meaningfully increased the competition, both in the domestic and the international markets (Chuang *et al.*, 2009; Romero, 2010). The advanced manufacturing systems are computer-oriented technologies applied in manufacturing, design, and etc. According to Beaumont *et al.* (2002), advanced manufacturing technology involves computer-aided design (CAD), computer numerical control machines, direct numerical control machines, robotics, flexible manufacturing system (FMS), automated storage and retrieval system (ASRS), automated material handling systems (MHS), automated guided vehicles, bar coding, rapid prototyping, material requirement planning, statistical process control, manufacturing resource planning (MRP), enterprise resource planning (ERP), activity-based costing (ABC), and office automation. Evaluating AMSs often include multiple, conflicting objectives, tangible and intangible factors. Application of traditional cost accounting and financially oriented traditional performance measurement methods does not fully account for the benefits arising from intangible factors of AMS evaluation (Kahraman *et al.*, 2000).

In today's competitive environment, most of manufacturing firms attempt meeting demand, increasing quality, decreasing costs, and delivery rate. Factors such as flexibility, quality, time and innovativeness together with cost determine competitive advantage and define the competition pattern (Dangayach & Deshmukh, 2005; Swink & Nair, 2007). According to Brown (2000) if a willingness of the firm is to remain in business, there is no other option between whether to invest in technology or not. The firm can merely choose the type and extend of process technological investment. To overcome this challenging, the willingness of most companies is to adopt and invest in an advanced manufacturing system (AMS) that emphasizes quality, delivery, and flexibility to meet customers' requirements simultaneously (Kim *et al.*, 1997; Boyle, 2006).

Performance indicators for evaluating performance of manufacturing systems can improve manufacturing competitive success. To overcome disadvantages of traditional performance measurement and to achieve competitive goals, selection of a range of performance indicators appropriate for manufacturers should be made based on a company's strategic intentions that suit competitive environments and the nature of business (Yang *et al.*, 2009).

Udo and Ehie (1996) prepared a common overview of tangibles and intangible factors that should be taken into account in the evaluation process. Raafat (2002) presented a comprehensive review on justification of AMS using 231 articles. Beskese *et al.* (2004) gave a model for quantification of flexibility in AMSs based on fuzzy logic. A study of classification approaches to justify AMSs is by Kolli *et al.* (1992). They classified existing methods into two major methods: single-criterion and multi-criteria under deterministic and nondeterministic environment. Park and Kim (1995) employed the activity-based costing concept, to make an investment decision among several alternatives of advanced manufacturing technology (AMT).

Many research have been focused on various models of evaluation and selection of AMSs from simple financial analysis methods, such as Net Present Value (NPV) method, Return on Investment (ROI), and Internal Rate of return (IRR) (for example, Sullivan *et al.*, 2003), to more complex multi-criteria mathematical programming methods. However, the need for a structured methodology for evaluation AMSs is felt. The insufficiency of traditional financial analysis and appraising measures lies on their non-stochastic nature. The conventional financial analysis methods do not appear to be suitable on their own for the evaluation of advanced manufacturing technologies investments due to the nonmonetary impacts posed by the manufacturing System (Duran & Aguilo, 2008). Anyway, financial analysis (NPV, ROI, IRR, and etc.) can lead to incorrect results in most of real-world applications.

Since intangible factors cannot be obtained in quantitative terms, many articles have concentrated on merging the qualitative and quantitative aspects for evaluating the advantages and benefits of AMSs. Wabalickis (1988) presented an overview of the potential benefits derived from a FMS implementation based on the analytic hierarchy process (AHP). Stam and Kuula (1991) developed a two-phase decision procedure that uses the AHP method and multi-objective mathematical programming to select an FMS. Although AHP is variously used in selection problems of FMS, but it suffers from a number of disadvantages. Boucher *et al.* (1997) argued that AHP is often criticized for the way the criteria weights are elicited, rank reversal problem, inappropriateness of the crisp ratio representation, and problems faced in the comparison process when the number of criteria and/or the number of alternatives increase. In addition, Bayazit (2005) presented an AHP approach for selecting a FMS. Rezaie *et al.* (2009a) and Rezaie *et al.* (2010) proposed a method for evaluating the flexible manufacturing systems based on a model incorporating two decision models namely “Data Envelopment Analysis (DEA)” and “Analytical Hierarchy Process (AHP)”. Rehman and Subash Babu (2009) also used the AHP tool to alternative reconfigurable manufacturing systems. Recently, fuzzy multi criteria decision-making (MCDM) techniques are extensively applied to evaluate benefits of AMSs. Perego and Rangone (1998) gave a reference framework for the application of three major categories of fuzzy MADM approach in the assessment and selection of AMS. Karsak and Tolga (2001) presented a fuzzy MCDM approach to select the most suitable AMS alternative from a set of mutually exclusive alternatives regarding both economic evaluation criterion and strategic criteria such as flexibility, quality improvement. Chuu (2009) developed a fuzzy multiple attribute decision-making applied in the group decision-making to improve advanced manufacturing technology selection process. They developed a new fusion method of fuzzy information to managing information assessed in different linguistic scales (multi-granularity linguistic term sets) and numerical scales. Abdel-Kader and Dugdale (2001) proposed a fuzzy MADM approach for the evaluation of investments in advanced manufacturing technology. They applied mathematics of the analytic hierarchy process and fuzzy set theory to integrate the two major dimensions of financial and non-financial factors. Chan *et al.* (2006) proposed an integrated decision support system, which incorporates different justification methods (e.g., strategic, economic, and analytic evaluations) for assessing tangible benefits, like cost, and intangible benefits, like quality, of different alternatives by a fuzzy MCDM method.

To handle the complexity of the current industrial context, new control strategies devised for continuous improvement, on the one hand, the multi-criteria performance expression aspects, and the modeling of their relationships (Berrah *et al.*, 2004). To achieve this aim, the performance measurement systems (PMSs) which are instruments to support decision-making can be applied. Then, in order to support the decision, the set of performances has to be processed so as to compare the different situations (Berrah *et al.*, 2008). Thus PMSs require by nature the use of MCDM methods (Santos *et al.*, 2002).

Recently, many studies have applied new performance measurement systems with respect to the ABC system (Banker *et al.*, 2008; Askarany *et al.*, 2010). The ABC system firstly was introduced by Cooper and Kaplan (1988) to clearly define the correlation between cost drivers and objectives, and consequently rationalize the cost sharing problems. ABC could be useful for companies by supplying clear, accurate and associated cost information in a well-timed and suitable manner and managers can control by activities which derive from costs.

Activities can be measured by valuable performance attributes such as quality, flexibility, customers' satisfaction, and cost and the managers often are interested in seeing how effectively activities are performed from the integrated viewpoint instead of separated viewpoint (Kim *et al.*, 1997).

Generally, after reviewing all of the literature in AMSs' performance measurement, we cannot find a structured approach for this problem in fuzzy environment. The problem of performance measurement of the AMSs under ABC system can be formulated as the multi-criteria decision making (MCDM) problem. As the existing environment is full of ambiguities, we apply the fuzzy AHP method for evaluation and measurement of the AMSs under ABC system.

In our study, we have proposed a methodology based on the existing decision making and fuzzy tools. The distinguishing feature of our study is that, using the principle of ABC systems are used to define and present the major criteria to PMS of advanced manufacturing systems. Furthermore, experts' judgment is used for determining the relative importance of the performance measurement s' criteria. Our proposed methodology can be used by a cross-functional team of engineers for evaluating performance of advanced manufacturing systems.

**The proposed methodology**

*Table 1. List of criteria for Measuring Performance of AMSs under Activity Based Costing*

| Criteria | Explanation |
|---|---|
| Quality of an activity | Quality of an activity can be defined quality as fitness for use (Juran and Gyrna, 1980). In AMSs, fitness for use is capability to perform the operations with low waste, high productivity, and minimal downtime. In general, the quality of an activity can be measured by the quality of available resources associated with activity. The higher percentage of defective products and rework lead to the lower quality of the activity. |
| Completion time of an activity | Criterion of the completion time of an activity is indirect criterion of cost, quality, and internal or external customer service. Shorter time of an activity to perform means that lesser the resources it requires and firm can rapidly react to extensively changes in customers' requirements as a competitive advantage. |
| Setup time of an activity | Setup time is the time to make ready the equipment to produce different product/parts. Reduction in setup time is desired and leads to reduced inventory level, improved quality, and faster customer response and may have a positive impact on flexibility and cost of manufacturing. |
| Efficiency of an activity | The efficiency of an activity can be defined as the relationship between the level of resource applied and what has been achieved. In general, when a company intend to investigate its activities, it is required to exploit the efficiency of an activity concept in order to visualize and quantify cost behavior |

Here we describe our proposed methodology to performance measurement for advanced manufacturing systems by the fuzzy AHP. The first step of our methodology is to identify the criteria using the ABC systems which are going to be used for measuring performance of the AMSs.

The traditional performance measurement systems are locate in a particular place accounting information, standards, and represent financial data. Kaplan (1991) emphasized that The traditional performance measurement systems have limitation and disadvantages in several aspects: Relevant information is received too late for corrective actions to be taken, the information is reported at too aggregated a level, the information is distorted by unnecessary allocations, and excessive attention is devoted to financial measures at the expense of operating measures. The performance measurement system can be defined as the set of criteria applied to quantify both the efficiency and effectiveness of actions. An effective manufacturing performance measurement system should be both explicit and objective, and provide a means for continuously improving a system (Yang *et al.*, 2009). Since overhead costs in general occupy higher percentage of the manufacturing cost rather than direct costs in an AMS, a PMS introduced in this paper tries control the manufacturing cost through improved performance of the activity by applying ABC systems. The principle of ABC systems attempt to meet the requirement of the new performance measurement systems (Yang *et al.*, 2009). This means that ABC systems allot the costs of an organization's activities more perfectly to its products and product lines. ABC systems are designed by first identifying the activities performed by each support and operating department and then computing the unit costs of performing these activities (Glad *et al.*, 1996). Hence, to develop a PMS, it is required to define performance measures/performance criteria of the activity.

In our study, the performance criteria based on the ABC system of Kim *et al.* (1997) have been adapted. Table 1 contains the list of criteria which are adapted from Kim *et al.* (1997). It also contains brief explanation for each criterion. Our proposed hierarchical structure for

*Fig. 1. The hierarchical structure for measuring performance of AMSs under activity based costing*

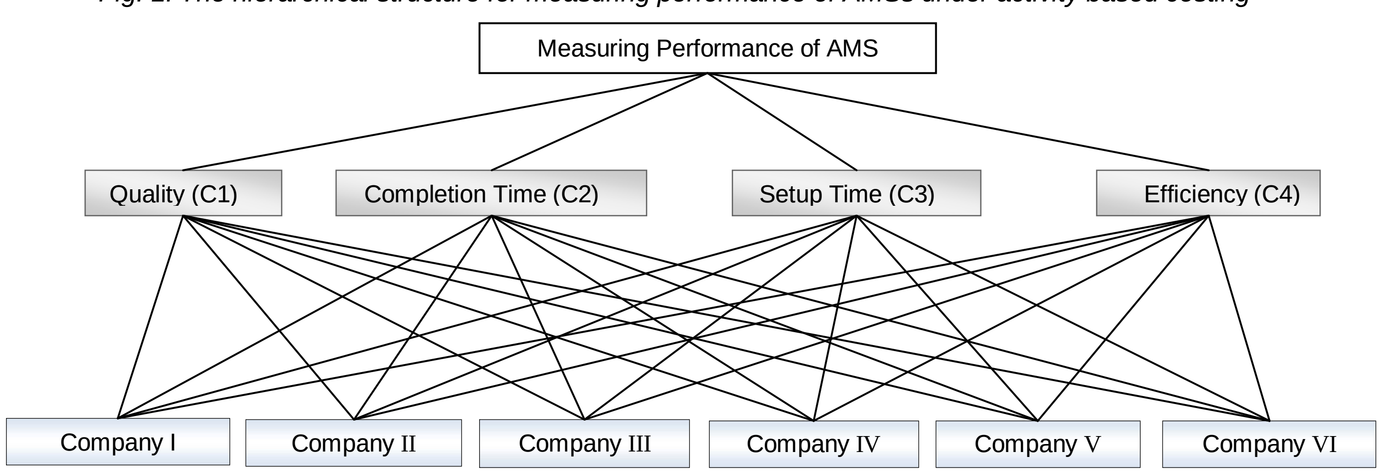

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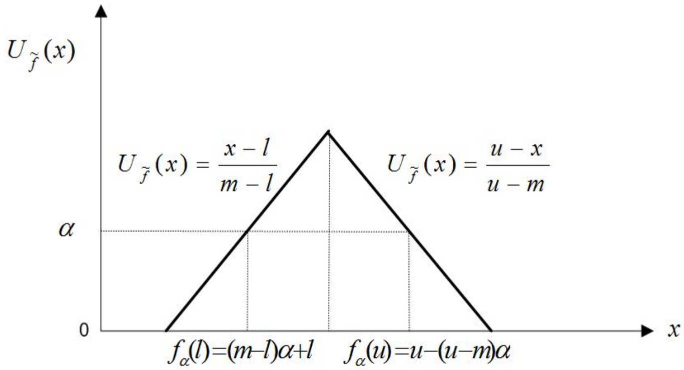
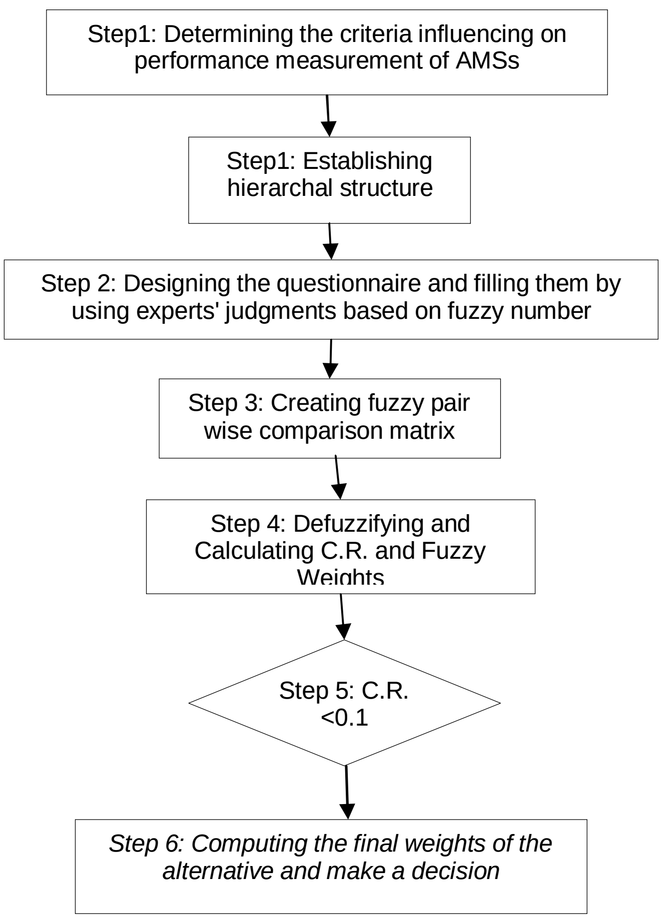
*Fig. 2. Left and right representation of triangular fuzzy numbers*




measuring the performance of AMSs consists of three levels. Level A, the objective level, demonstrates the final objective of the whole hierarchical structure, which is Measuring Performance of AMSs based on ABC systems. Level B contains the measurement criteria. In this paper, four criteria are considered in level B. These criteria are "quality of an activity", "completion time of an activity", "setup time of an activity", and "efficiency of an activity". Level C contains the alternatives or companies which are going to be measured and prioritized based on their performance. In this paper we have selected six companies (company I, II, III, IV, V, and VI). The proposed hierarchical structure is shown in Fig.1.

*Fig. 3. The steps of the proposed methodology in uncertainty environment*




*Fuzzy analytic hierarchy process (fuzzy AHP)*

Multi-criteria decision-making is one of the useful approaches for dealing with problems having conflicting objectives. AHP is one of the MCDM method introduced by Saaty (1980). The classical AHP method does not consider uncertainty conditions. Since fuzzy concept is a useful tool for explaining uncertainty, the fuzzy AHP method is used for coping with this limitation. the fuzzy AHP method has been applied in various researches for making decision in different fields such as evaluating and selecting of simulation software package (Azadeh *et al.*, 2010), Evaluating Effective Factors of Implementing Knowledge Management (Rezaie *et al.*, 2009b), Evaluating Risk of Information Technology Projects (Iranmanesh *et al.*, 2008), assigning productive operators' in cellular manufacturing systems (Azadeh *et al.*, 2011), strategic analysis of healthcare service quality (Buyukozkan *et al.*, 2011), risk assessment of implementing green initiatives in the fashion supply chain (Wang *et al.*, 2011) and so on. The fuzzy AHP method is explained in the following. A proposed methodology based fuzzy AHP to performance measurement of the advanced manufacturing systems using ABC system is depicted in Fig.2.

The steps of Fuzzy AHP approach are as follows:

In this paper, triangular fuzzy numbers are used as the membership function, which is illustrated in Fig.3. Triangular fuzzy numbers are used, since they help the decision maker make easier decisions (Kaufmann and Gupta, 1988). Membership function of a triangular fuzzy number can be found in equation (1) and is usually notated by the triplet (*l, m, u).*

$$U(x) = \begin{cases} \dfrac{x-l}{m-l} & l \le x \le m \\ \dfrac{u-x}{u-m} & m \le x \le u \\ 0 & \text{Otherwise} \end{cases} \qquad (1)$$

The AHP method proposed by Saaty (1980) uses pair-wise comparisons shown in equation (2). Number $a_{ij}$ shows the relative importance of criterion $i$ ($c_i$) in comparison with criterion $j$ ($c_j$) in Saaty's scale (1980).

$$A = \left[a_{ij}\right] = \begin{array}{c} \\ c_1 \\ c_2 \\ \vdots \\ c_n \end{array} \begin{array}{c} \begin{array}{cccc} c_1 & c_2 & \dots & c_n \end{array} \\ \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \end{array} \qquad (2)$$

Where

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*Table 2. Random index used to compute consistency ratio (C.R.)*

| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R.I. | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.4 | 1.45 | 1.49 |

$a_{ij} = 1 : \forall i = j;\ a_{ij} = \frac{1}{a_{ji}} : \forall i \neq j$

Fuzzy AHP replaces crisp $a_{ij}$ by triangular fuzzy numbers. Because each number in the matrix shows the experts' opinions, fuzzy number is the best solution to show experts' judgments. To analyze the data and achieve the consensus of the experts, eigenvector method proposed by Buckley (1985) is used here. As mentioned before, triangular fuzzy number can be represented by the triplet (*l, m, u).* As shown in equation (3)-(6) *l, m,* and *u* show the minimum possible, most likely and the maximum possible value of a fuzzy number, respectively. Triangular fuzzy number $\tilde{U}_{ij}$ is constructed as the following:

$$\tilde{U}_{ij} = (l_{ij}, m_{ij}, u_{ij}) : l_{ij} \leq m_{ij} \leq u_{ij}, l_{ij}, m_{ij}, u_{ij} \in [1/9, 9] \quad (3)$$

$$l_{ij} = \min(B_{ijk}) \quad (4)$$

$$m_{ij} = \sqrt[n]{\prod_{1}^{n} B_{ijk}} \quad (5)$$

$$u_{ij} = \max(B_{ijk}) \quad (6)$$

In which $B_{ijk}$ shows relative importance of criteria $c_i$ and $c_j$ given by expert *k*.

*Table 3. The linguistic scale and corresponding triangular fuzzy numbers*

| Fuzzy number | Linguistic scales | Scale of fuzzy number |
|---|---|---|
| $\tilde{1}$ | Equally important | (1, 1, 1) |
| $\tilde{3}$ | Weakly important | (2, 3,4) |
| $\tilde{5}$ | Essentially important | (4, 5,6) |
| $\tilde{7}$ | Very strongly important | (6, 7,8) |
| $\tilde{9}$ | Absolutely important | (8, 9, 9) |
| $\tilde{2},\tilde{4},\tilde{6},\tilde{8}$ | Intermediate values | (x- 1, x, x+1 ) |

The linguistic scale and corresponding triangular fuzzy numbers are illustrated in Table 2 based on saaty's scale (1980).

The fuzzy matrix $\tilde{A}$ in equation (7) will be used in the remaining steps of Fuzzy AHP. The number $\tilde{a}_{ij}$ is a triangular fuzzy number that represents the relative importance of criteria $c_i$ and $c_j$ based on experts' judgments according to equation (3)-(6):

$$\tilde{A} = [\tilde{a}_{ij}] = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_n \end{array} & \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \tilde{a}_{1n} \\ 1/\tilde{a}_{12} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{1n} & 1/\tilde{a}_{2n} & \cdots & 1 \end{bmatrix} \end{array} \quad (7)$$

There are different methods to defuzzify fuzzy numbers. In this paper, the method proposed by Liou and Wang (1992) is used to defuzzify fuzzy matrix $\tilde{A}$ into crisp matrix $g_{\alpha,\beta}$ as shown in equation (8)-(9):

$$g_{\alpha,\beta}(\tilde{a}_{ij}) = [\beta . f_\alpha(l_{ij}) + (1-\beta).f_\alpha(u_{ij})],\ 0 \leq \alpha, \beta \leq 1 \quad (8)$$

$$g_{\alpha,\beta}(\tilde{a}_{ij}) = 1/g_{\alpha,\beta}(\tilde{a}_{ji}),\ 0 \leq \alpha, \beta \leq 1 : i > j \quad (9)$$

Because of presenting explicitly preferences (*α*) and risk tolerance (*β*) of the decision maker, decision makers can more thoroughly understand the risk they face in different circumstances.

The single pair wise comparison matrix is expressed in (10).

$$g_{\alpha,\beta}(\tilde{A}) = g_{\alpha,\beta}([\tilde{a}_{ij}]) = \begin{array}{c c} & \begin{array}{cccc} C_1 & C_2 & \dots & C_n \end{array} \\ \begin{array}{c} C_1 \\ C_2 \\ \vdots \\ C_n \end{array} & \begin{bmatrix} 1 & g_{\alpha,\beta}(\tilde{a}_{12}) & \dots & g_{\alpha,\beta}(\tilde{a}_{1n}) \\ 1/g_{\alpha,\beta}(\tilde{a}_{12}) & 1 & \cdots & g_{\alpha,\beta}(\tilde{a}_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ 1/g_{\alpha,\beta}(\tilde{a}_{1n}) & 1/g_{\alpha,\beta}(\tilde{a}_{2n}) & \cdots & 1 \end{bmatrix} \end{array} \quad (10)$$

To determine the consistency of the matrix, Saaty (1980) suggests consistency index (*C.I.*) and consistency rate (*C.R.*). Random index (*R.I.)* represents the average consistency index over numerous random entries of the same order reciprocal matrices. If $C.R. < 0.1$, the estimation is accepted; otherwise, a new comparison matrix is solicited. The value of *R.I.* depends on the value of *n* and should be selected from Table 3.

To find the Consistency Index (*C.I.*), eigen-value of the matrix $\tilde{A}$ should be found first. The number $\lambda_{\max}$ is defined as the eigen-value of the matrix $g_{\alpha,\beta}$ calculated by equation (11):

$$\det(g_{\alpha,\beta}(\tilde{A}) - \lambda . I) = 0 \quad (11)$$

The value maximum of $\lambda$ is $\lambda_{\max}$. The final weight (*W*) of matrix can be calculated by equation (12):

$$[g_{\alpha,\beta}(\tilde{A}) - \lambda_{\max}].W = 0 \quad (12)$$

In which *W* is the eigenvector of matrix $g_{\alpha,\beta}$ and $0 \leq \alpha, \beta \leq 1$. After finding $\lambda_{\max}$, values of *C.I.* and *C.R.* can be calculated from equation (13)-(14):

$$C.I. = \frac{\lambda_{\max} - n}{n-1} \quad (13)$$

$$C.R. = \frac{C.I.}{R.I.} \quad (14)$$

**Experiments and results**

In this paper we have selected six companies (company I, II, III, IV, V, and VI). The decision makers can change, add or omit the alternatives (along with its competitors) with respect to the context for which they are going to use AMSs for producing same products. After

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establishing the hierarchical structure for Measuring Performance of AMS, now we can apply fuzzy AHP method to measure the performance of AMSs in six companies under ABC system. According to equation (2)-(6), based on Table 4, the fuzzy decision matrix for the considered criteria to performance measurement of AMSs under ABC system is attained from a verbal questionnaire filled by fourteen different experts and then converted to fuzzy numbers based on Saaty's scale (1980). In this paper $\alpha$ and $\beta$ are considered equal to 0.5. Selecting $\alpha = 0.5$ indicates that environmental uncertainty is steady; additionally $\beta = 0.5$ indicates that a future attitude would be fair.

After building the fuzzy matrix, the matrix of Table 4 should be defuzzified. The matrix can be defuzzified based on equation (8)-(9) as an example:

*Table 4. Aggregated fuzzy pair-wise comparison of criteria for measuring performance of AMSs*

| | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| $C_1$ | (1,1,1) | (0.2,1.785,7) | (1,3.347,8) | (0.167,1.842,6) |
| $C_2$ | - | (1,1,1) | (0.25,4.145,8) | (0.125,1.123,4) |
| $C_3$ | - | - | (1,1,1) | (0.167,0.673,83) |
| $C_4$ | - | - | - | (1,1,1) |

$$f_{o.5}(l_{12}) = (1.785 - 0.2)\times 0.5 + 0.2 = 0.9925$$

$$f_{o.5}(u_{12}) = 7 - (7 - 1.785)\times 0.5 = 4.3925$$

$$g_{o.5,0.5}(a_{12}) = [0.5\times 0.9925 + (1\text{-}0.5)\times 4.3925] = 2.6925$$

And finally:

$$g_{o.5,0.5}(a_{21}) = 1 / g_{o.5,0.5}(a_{12}) = 1/2.6925 = 0.3714$$

The final defuzzified matrix is shown in Table 5.

$$\det(A-\lambda I)=0 \Rightarrow \begin{bmatrix} 1-\lambda & 2.6925 & 3.9235 & 2.4627 \\ 0.3714 & 1-\lambda & 4.135 & 1.5928 \\ 0.2549 & 0.2418 & 1-\lambda & 1.1282 \\ 0.4061 & 0.6278 & 0.8864 & 1-\lambda \end{bmatrix} = 0 \qquad (15)$$

After solving (15), $\lambda_{\max}$ will be 4.1844. So by using (12) *W* will be:

$$\det(A-\lambda I)=0 \Rightarrow \begin{bmatrix} -3.1844 & 2.6925 & 3.9235 & 2.4627 \\ 0.3714 & -3.1844 & 4.135 & 1.5928 \\ 0.2549 & 0.2418 & -3.1844 & 1.1282 \\ 0.4061 & 0.6278 & 0.8864 & -3.1844 \end{bmatrix} = 0 \qquad (15)$$

$$(A-\lambda I)W = 0 \Rightarrow \begin{bmatrix} -3.1844 & 2.6925 & 3.9235 & 2.4627 \\ 0.3714 & -3.1844 & 4.135 & 1.5928 \\ 0.2549 & 0.2418 & -3.1844 & 1.1282 \\ 0.4061 & 0.6278 & 0.8864 & -3.1844 \end{bmatrix} \times \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ W_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad (16)$$

After solving (16), *W* will be:

$$W_C = [0.4755,\ 0.2703, 0.1098, 0.1445]$$

As a result of the above mentioned calculations the weights of four criteria of level B i.e. quality of an activity, completion time of an activity, setup time of an activity, efficiency of an activity are 0.4755, 0.2703, 0.1098, and 0.1445.

Then *C.I.* is calculated as the following:

$$C.I. = \frac{\lambda_{\max} - n}{n-1} = \frac{4.1844-4}{4-1} = 0.0614 \quad , C.R. = \frac{C.I.}{R.I.} = \frac{0.0614}{0.89} = 0.069 \leq 0.0.8$$

The results show that the decision matrix for the second level of the proposed hierarchical structure is consistent. The calculated weights of the whole hierarchical structure are demonstrated in Table 6.

The consistency ratios of the other decision matrices have been also calculated using equation 13 and 14. The consistency ratios of all the matrices are below 0.1 which proves their consistency.

The final weights of the alternatives for performance measurement, which are calculated by equation (17) using data of Table 6, are as follows: 0.2279 for Company I, 0.2085 for Company II, 0.0921 for Company III, 0.1891 for Company IV, 0.1941 for Company V and 0.0884 for Company VI.

According to the obtained results, the Company I has the highest weight and its performance is ranked first position among other manufacturers according to the experts' judgment. Fig.4 shows the comparison of weights of six companies in different level of ABC criteria.

*Table 5. Final defuzzified matrix of criteria to measure the performance of AMSs*

| | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| C1 | 1 | 2.6925 | 3.9235 | 2.4627 |
| C2 | 0.3714 | 1 | 4.135 | 1.5928 |
| C3 | 0.2549 | 0.2418 | 1 | 1.1282 |
| C4 | 0.4061 | 0.6278 | 0.8864 | 1 |

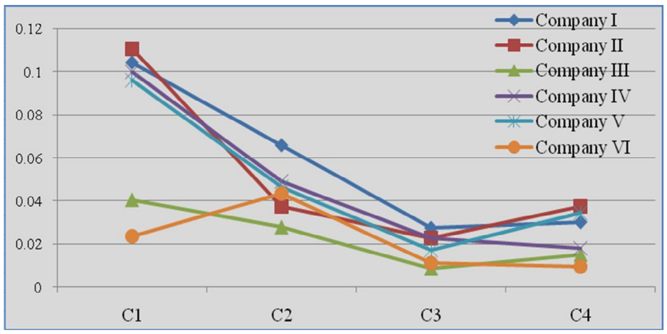
*Table 6. Summaries of results for level 2 to level 3*

| Criteria | Weights for level 2 | Weights for level 3 | | | | | |
|---|---|---|---|---|---|---|---|
| | | Company I | Company II | Company III | Company IV | Company V | Company VI |
| C1 | 0. 4755 | 0.2191 | 0.2331 | 0.0853 | 0.2099 | 0.0502 | 0.2023 |
| C2 | 0.2703 | 0.2439 | 0.1389 | 0.1032 | 0.1808 | 0.1614 | 0.1718 |
| C3 | 0.1098 | 0.2504 | 0.2068 | 0.0781 | 0.2058 | 0.1039 | 0.1550 |
| C4 | 0.1445 | 0.2094 | 0.2591 | 0.1042 | 0.1233 | 0.0656 | 0.2385 |

$$\begin{bmatrix} 0.4755 & 0.2703 & 0.1098 & 0.1445 \end{bmatrix}_{1\times 4} \times \begin{bmatrix} 0.2191 & 0.2331 & \dots & 0.2023 \\ 0.2439 & 0.1389 & \cdots & 0.1718 \\ \vdots & \vdots & \ddots & \vdots \\ 0.2094 & 0.2591 & \dots & 0.2385 \end{bmatrix}_{4\times 6}$$

$$= \begin{bmatrix} 0.2279 & 0.2085 & 0.0921 & 0.1891 & 0.1941 & 0.0884 \end{bmatrix} \quad (17)$$

*Fig. 4. Comparison of weights of six companies*




Therefore, companies' performance under ABC system for benchmarking is in the following order: Company I, Company II, Company V, Company IV, Company III, and Company VI.

**Conclusion**

In this paper, a structured methodology for measuring and evaluating performance of advanced manufacturing systems under activity based costing criteria based on fuzzy analytical hierarchy process is proposed as a multi criteria decision making tools for those who work in the field of manufacturing and accounting. Using fuzzy theory for measuring performance can reduce ambiguities and uncertainties that are inherent in the measuring of performance. Various ABC criteria were considered such as "quality of an activity", "completion time of an activity", "setup time of an activity", and "efficiency of an activity". Six different companies which had implemented AMSs were considered in this paper that could be substituted by other existing alternatives based on the application and type of AMS for measuring performance. Finally, an experiment was conducted to apply this methodology in measuring performance as a case by using judgments of fourteen experts who had worked in the AMS field and then the results were represented. For the extension of this work, other fuzzy AHP methods or deffuzification methods for measuring the performance of AMSs can be used. Also, other criteria instead of ABC criteria may be applied to the proposed approach of this study. Additionally, various methods of multi-criteria decision making such as TOPSIS and Data Envelopment Analysis (DEA) in fuzzy environment can be considered.

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