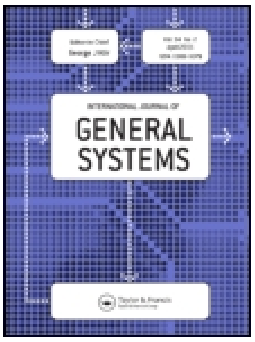

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A combined fuzzy AHP-simulation approach to CAD software selection

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In this paper, a combined approach, where the fuzzy analytic hierarchy process (AHP) and simulation come together, is presented to select the best computer-aided design (CAD) software out of the available options in the market. The fuzzy AHP is used due to the vagueness and uncertainty of the judgements of a decision maker(s), because the crisp pair-wise comparison in the conventional AHP seems to be insufficient and imprecise to capture the right judgements of the decision maker(s). In this study, first the fuzzy AHP is used to reduce a possible number of alternatives for the CAD system to an acceptable level for further study, simulation analysis. Secondly, a simulation generator as an integrated part of the fuzzy AHP is used to try the remaining alternatives, on the generated model of a real-life product organisation in which the final alternative will be used. The results of simulation experiments are obtained, and then evaluated to reach to the ultimate CAD alternative.

Keywords: computer-aided design (CAD); fuzzy logic; analytic hierarchy process (AHP); discrete-event simulation; benchmarking

1. Introduction

Manufacturing organisations in the developing countries are under intense competitive pressures. Major changes are being experienced with respect to resources, markets, manufacturing processes and product strategies. As a result of international competition, only the most productive and cost-effective industries survive. Manufacturing organisations are thus faced with the need to optimise the way in which they function in order to achieve the best possible performance within given constrains. This is a difficult task, both in terms of understanding the nature of the problem and the most effective solution strategies, and in forming and implementing plans that develop from this understanding. Many of the efforts in this direction are being carried forth under the banner of a computer-integrated manufacturing (CIM) system.

A CIM system is capital intensive due to hardware and software requirements. As a result, it is essential that it achieves high levels of flexibility and productivity compared to traditional manufacturing systems. Modelling and analysis to gain a better understanding of the system complexities and to predict system performance are critical in the system design stage, and often valuable for the system management. Modern manufacturing systems tend to be tightly coupled. They are characterised by a high degree of automation, low levels of work-in-process inventory and various forms of supervisory control.

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A computer-aided design (CAD) system, as a critical part of a CIM system, realises all kinds of design and engineering-related activities in a product development environment using the computer technology. A CAD system provides many advantages of fast and reliable design and engineering, concurrent engineering, reverse engineering and so on. But companies have had many problems in implementing such systems, one of which is the selection of the most appropriate CAD system based on their needs and future expectations. This issue has also received substantial attention in recent years, due to the high initial investment cost of such systems as well as the unprecedented mixture of success and horror stories on their implementations. In addition, the CAD software selection problem is a multiple-criteria decision-making problem (MCDM) which requires a strong method to evaluate a list of alternatives in terms of a set of criteria. Therefore, in this study, the analytic hierarchy process (AHP) as an MCDM method is selected due to the fact that it has been widely used to solve various MCDM problems in the literature as well as in practice.

The conventional AHP developed by Saaty (1981) has been used for various kinds of MCDM problems for years. But in the conventional AHP, the pair-wise comparisons for each level with respect to the goal of the best alternative selection are conducted using a nine-point scale. So, the application of Saaty's AHP has some shortcomings as follows (Saaty 1981): (1) the AHP method is mainly used in nearly crisp decision applications, (2) the AHP method creates and deals with a very unbalanced scale of judgement, (3) the AHP method does not take into account the uncertainty associated with the mapping of one's judgement to a number, (4) ranking of the AHP method is rather imprecise and (5) the subjective judgement, selection and preference of decision makers have great influence on the AHP results.

In addition, a decision maker's requirements on evaluating a process always contain ambiguity and multiplicity of meaning. Furthermore, it is also recognised that human assessment of qualitative attributes is always subjective and thus imprecise. Therefore, the conventional AHP seems to be inadequate to capture a decision maker's requirements explicitly. In order to model this kind of uncertainty in human preference, fuzzy sets could be incorporated with the pair-wise comparison as an extension of AHP, referred to as fuzzy AHP. The use of fuzzy AHP and simulation methods together looks interesting because, to the best of our knowledge, there are only a few works bringing both methods together in the literature.

In short, in this paper, first, the fuzzy AHP is used to reduce the possible number of alternatives for the CAD system to an acceptable level for further study, simulation analysis. Secondly, a simulation generator as an integrated part of the fuzzy AHP is used to try the remaining alternatives on the generated model of a real-life product organisation, in which the final alternative will be used. The results of simulation experiments are obtained and then evaluated to reach to the ultimate CAD alternative. In the final section, a case study is presented to help readers clearly understand how the proposed approach is implemented. This case study was realised in a leading company in Turkey, which designs and manufactures all kinds of cutting tools.

2. Related research

The fuzzy set theory is a mathematical theory designed to model the vagueness or imprecision of human cognitive processes which was pioneered by Zadeh (Lootsma 1997). This theory is basically a theory of classes with unsharp boundaries. What is important to recognise is that any crisp theory can be fuzzified by generalising the concept of a set within that theory to the concept of a fuzzy set. Fuzzy set theory and fuzzy logic have been applied in a great variety of applications, which are reviewed by several authors (Klir and Yuan 1995; Zimmermann 1996).

The key idea of the fuzzy set theory is that an element has a degree of membership in a fuzzy set (Negoita 1985; Zimmermann 1996). The membership function represents the grade of membership of an element in a set. The membership values of an element vary between 1 and 0. Elements can belong to a set in a certain degree and elements can also belong to multiple sets. A fuzzy set allows the partial membership of elements. Transition between membership and non-membership is gradual. The membership function maps the variation of the value of linguistic variables into different linguistic classes. The adaptation of the membership function for a given linguistic variable under a given situation is achieved in three ways: (a) experts' previous knowledge about the linguistic variable; (b) using simple geometric forms having slopes (triangular, trapezoidal or s-functions) as per the nature of the variable and (c) by a trial and error learning process.

As one of the most commonly used MCDM methods, the AHP was first developed for decision-making by Saaty (1981) and extended by Marsh *et al.* (1991) who have developed a more specific method directly for design decision-making. Marsh's AHP has three steps ordering the factors (or criteria) of a decision such that the most important ones receive the greatest weight. Zahedi (1986) provided an extensive list of references on the AHP methodology and its applications.

In this study, fuzzy logic and the AHP method (referred to as the fuzzy AHP) are integrated to use their advantages on the CAD software selection problem. Although there are many works on the fuzzy AHP in the current literature, some related works are briefly presented as follows: Kahraman *et al.* (2003) used fuzzy AHP to select the best supplier firm providing the most satisfaction for the attributes determined. Kuo *et al.* (2002) developed a decision support system using the fuzzy AHP to locate a new convenience store. Murtaza (2003) presented a fuzzy version of AHP to the country risk assessment problem. Kahraman *et al.* (2004) developed an analytical tool using fuzzy AHP to select the best catering firm providing the most customer satisfaction. Weck *et al.* (1997) evaluated alternative production cycles using the extended fuzzy AHP method. Lee *et al.* (2001) proposed a fuzzy AHP approach in modular product design complemented with a case example to validate its feasibility in a real company. Bozdag *et al.* (2003) used fuzzy group decision-making to evaluate CIM system alternatives. Piippo *et al.* (1999) used a group decision support system for a real-life CAD-system selection application for an industrial company. Cheng and Mon (1994) evaluated a weapon system by AHP based on fuzzy scales. Kwong and Bai (2002) suggested a fuzzy AHP approach to determine the importance of customer requirements in quality function deployment (QFD). They proposed a new approach that can improve the imprecise ranking of customer requirements, which is based on the conventional AHP. They also used the extent analysis method and the principles for the comparison of fuzzy numbers to determine the important weights for the customer requirements in QFD. In another study, Buyukozkan *et al.* (2004) compared the fuzzy AHP methods in the literature (Table 1) which have important differences in their theoretical structures. This comparison includes advantages and disadvantages of each method.

In addition, Bozbura and Beskese (2007) prioritised the organisational capital measurement indicators using the AHP. Chan and Kumar (2007) used fuzzy extended AHP for global supplier development considering risk factors. Erensal *et al.* (2006) determined key capabilities in technology management using the fuzzy AHP. Ayag and Ozdemir (2006) utilised the fuzzy AHP for the machine tool selection problem.

Table 1. Comparison of various fuzzy AHP methods (Buyukozkan *et al.* 2004).

Sources	*Main characteristics*	*Advantages (A)/disadvantages (D)*
Van Laarhoven and Pedrycz (1983)	• Direct extension of Saaty's AHP method with triangular fuzzy numbers • Lootsma's logarithmic least square method is used to derive fuzzy weights and fuzzy performance scores	• (A) The opinions of multiple decision makers can be modelled in the reciprocal matrix • (D) There is not always a solution to the linear equations • (D) The computational requirement is tremendous, even for a small problem • (D) It allows only triangular fuzzy numbers to be used
Buckley (1985)	• Direct extension of Saaty's AHP method with trapezoidal fuzzy numbers • Uses the geometric mean method to derive fuzzy weights and performance scores	• (A) It is easy to extend to the fuzzy case • (A) It guarantees a unique solution to the reciprocal comparison matrix • (D) The computational requirement is tremendous
Boender (1989)	• Modifies van Laarhoven and Pedrycz's method • Presents a more robust approach to the normalisation of the local priorities	• (A) The opinions of multiple decision makers can be modelled • (D) The computational requirement is tremendous
Chang (1996)	• Synthetical degree values • Layer simple sequencing • Composite total sequencing	• (A) The computational requirement is relatively low • (A) It follows the steps of crisp AHP. It does not involve additional operations • (D) It allows only triangular fuzzy numbers to be used
Cheng (1996)	• Builds fuzzy standards • Represents performance scores by membership functions • Uses entropy concepts to calculate aggregate weights	• (A) The computational requirement is not tremendous • (D) Entropy is used when probability distribution is known. The method is based on both probability and possibility measures

Dağdeviren and Yüksel (2008) developed a fuzzy AHP model for behaviour-based safety management. Cebeci and Ruan (2007) used a fuzzy AHP for a multi-attribute comparison of Turkish quality consultants. Karsak and Özogul (2009) proposed an integrated decision-making approach for the ERP system selection problem. Vaidya and Kumar (2006) reviewed the applications of the AHP in various fields. William *et al.* (2009) undertook a literature review for MCDM approaches for supplier evaluation and selection and listed the works of fuzzy AHP in various fields.

Furthermore, the use of modelling and simulation techniques together in a manufacturing environment is not a new issue. A large number of simulation studies have been done so far, whereas new simulation software with outstanding graphics capabilities parallel with computer technology is developed. Next, some of these studies are briefly presented. Pruett and Vasudev (1990) modelled a whole manufacturing organisation of a company and developed a system called MOSES that allowed users to evaluate their ideas on the modelled manufacturing organisation using the simulation technique. Love and Barton (1996) developed a simulator for a whole production system in a CIM environment in order to both analyse various design strategies and evaluate them based on a financial basis. They applied it to a company and modelled all its business and manufacturing functions and their relationships on each other. The effects of design changes in these functions were examined with the assistance of this simulator. Shang and Tadikamalla (1993) developed an approach to maximise the output of CIM. This approach also included a statistical technique decreasing the calculation time of a large number of simulation experiments because of the complexity of the manufacturing system. Biemans and Vissers (1991) advised a reference model to develop a CIM architecture including the required steps in its implementation. First of all, the authors divided a whole production environment into units. In other words, they defined the whole manufacturing system as a structure consisting of these divided units. Botzer and Etzion (1995) developed a hierarchical optimisation model to integrate different databases existing in a CIM system. Wunderli *et al.* (1996) defined multi-base agents, each of which provides an interface system between CAx systems in order to integrate them to lead to a whole CIM system.

In the literature, to the best of our knowledge, there are a few studies in which the AHP and simulation methods were used together as follows: Levary and Wan (1999) developed a methodology for ranking entry mode alternatives encountered by individual companies considering foreign direct assessment. The methodology deals with the risks and uncertainties related to foreign direct investment. The AHP was used to solve the MCDM problem using input from the company's management. A simulation approach is incorporated into the AHP to handle the uncertainty considerations encountered in a foreign direct investment environment. Ayag (2002) developed an AHP-based simulation model for implementation and analysis of computer-aided systems (CAx). Ayag (2005a, 2005b) also proposed integrated approaches (i.e. AHP-based simulation, fuzzy AHP-based simulation) to evaluate design options in terms of a set of criteria in a new product development (NPD) environment.

3. Proposed approach

In this paper, a combined fuzzy AHP-simulation approach for the CAD software selection problem is proposed. The steps of this approach are outlined in Figure 1.

In practice, both the fuzzy AHP and simulation techniques have quite time-consuming implementation steps, especially if they are carried out manually. For instance, in a fuzzy AHP study, as the number of criteria and alternatives increase, the dimension of the problem naturally expands such as an evaluation matrix with large number of the columns and lines. This means a too long and boring calculation process. Also for a simulation study, to build the model of a manufacturing system manually takes considerable time and effort. Therefore, in this study, computer software was developed to facilitate the efforts required for both techniques. This software makes all the required and time-consuming calculations of the fuzzy AHP automatically and models an entire production system of a company via a simulation generator. The generator writes the required files automatically for the target simulation language, SIMAN, one of the most commonly used languages in simulation studies. It also allow users to understand the results of simulation experiments, who do not have deep experience or knowledge of simulation, modelling and computer programming. This software has three different modules: (a) *a user interface* connected to a user bidirectionally, which also enables the user to make the fuzzy AHP and simulation studies via the data-driven user interface, (b) *the fuzzy AHP* and (c) *the model and*

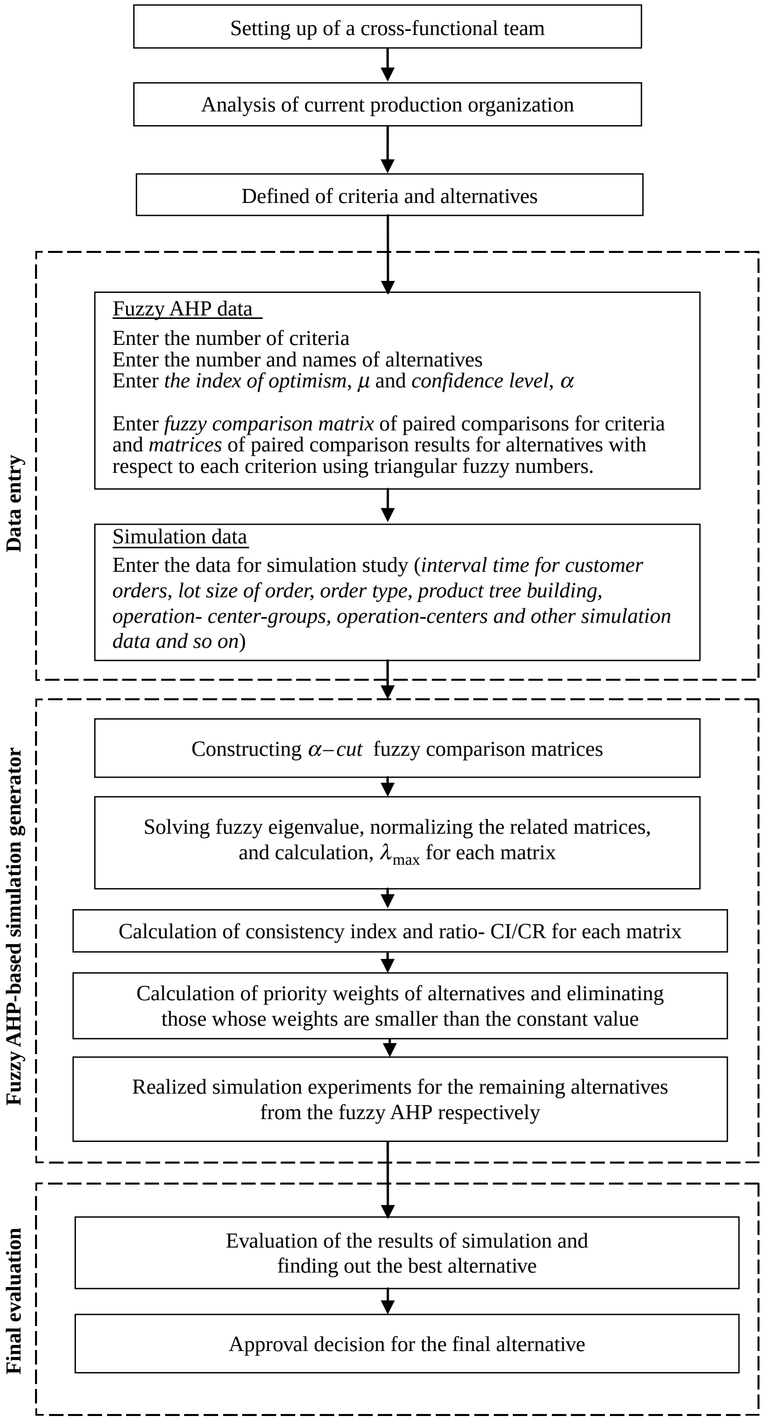

Figure 1. A combined approach to the CAD software selection problem.

experimental file generator. In its user interface part, the user enters all the requested data for a study through a data-driven interactive tool in a user friendly environment after reading the instructions given in detail on the screen. These modules are illustrated in Figure 2.

Next, the steps of the proposed approach outlined in Figure 1 are presented in more detail.

3.1 *Setting up of a cross-functional team (Step I)*

A cross-functional team consisting of the key persons in the related departments of a company (i.e. product design and development, IT department and manufacturing) is set up by the company's top management. At least one member from the top management should be in the team so that s/he can follow up the evaluation process much more closely.

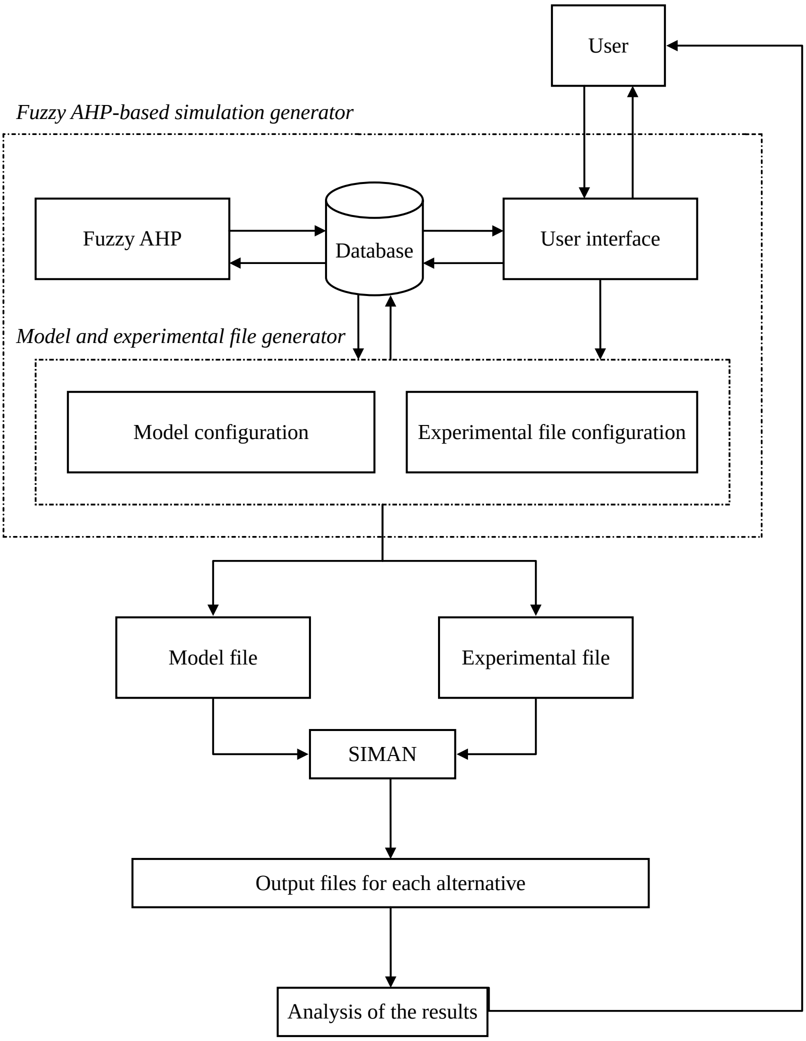

Figure 2. Fuzzy AHP-integrated simulation analysis with a simulation generator.

3.2 *Analysis of current production organisation (Step II)*

The current production organisation of a company should be examined to gather data required by a simulation generator in order to model the organisation. The analysis aims to measure the benefits of each alternative on the generated model of a real-life product organisation to find out the best one providing the most benefits. So the team should analyse the relevant departments and the tasks carried out by them, which might be more likely affected during the study.

3.3 *Defined criteria and alternatives (Step III)*

Some criteria and alternatives should be defined to solve the problem. These criteria, that may change from one company to another, should be defined by the team according to the needs and expectations of the company. The team first should make a list of possible alternatives in the market, and then eliminate those that are extreme in order to build a shorter list. These alternatives can be easily obtained from both their vendors and other sources. These criteria and alternatives will be used in the fuzzy AHP method.

3.4 *Data entry (Step IV)*

The user as a member of the team enters all the requested data for the fuzzy AHP study through a data-driven interactive tool (or user interface) in user friendly environment after reading the instructions given in detail on the screen. The user also enters the data in the same way as for the simulation study. These data are shown in Figure 1. All data both entered via the user interface and created during the analysis are kept in a database so that they can be easily reached for future works. This database also contains easily accessible data, which can be updated at any time by the user regarding the changes that might take place during the analysis, or rise from real-life conditions.

3.5 *Fuzzy AHP-based simulation generator (Step V)*

In this step, first, all necessary fuzzy calculations (i.e. constructing $\alpha -$ cut fuzzy comparison matrices (FCMs), solving fuzzy eigenvalues, calculation of priority weights for each alternative after normalising matrices of priority weights for both criteria and alternatives) for the CAD software selection problem are carried out. The results of the process are presented to the user in more detail in an understandable format. Then, the system eliminates low-weighted alternatives based on an elimination scale in order to reduce the number of alternatives for further study and simulation. Secondly, a real-life production organisation of a company is automatically modelled by a simulation generator, and simulation experiments for each alternative are carried out easily to reach the final decision. These works are explained in detail next.

3.5.1 *Fuzzy AHP*

In this section, first, the fuzzy representation of pair-wise comparison and secondly, the steps of the fuzzy AHP approach are presented as follows:

Fuzzy representation of pair-wise *comparison.* A hierarchy of the CAD software selection problem needs to be established before performing the pair-wise comparison of AHP. After constructing a hierarchy for the problem, the decision maker(s) is asked to compare the elements at a given level on a pair-wise basis to estimate their relative

Table 2. Definition and membership function of fuzzy number (Ayag 2005b).

Intensity of importance[a]	*Fuzzy number*	*Definition*	*Membership function*
1	$\tilde{1}$	Equally important/preferred	(1, 1, 2)
3	$\tilde{3}$	Moderately more important/preferred	(2, 3, 4)
5	$\tilde{5}$	Strongly more important/preferred	(4, 5, 6)
7	$\tilde{7}$	Very strongly more important/preferred	(6, 7, 8)
9	$\tilde{9}$	Extremely more important/preferred	(8, 9, 10)

[a] Fundamental scale used in pair-wise comparison (Saaty 1989)

importance in relation to the element at the immediate proceeding level. In conventional AHP, the pair-wise comparison is made using a ratio scale. A frequently used scale is the nine-point scale (Saaty 1989, Table 2), which shows the participants' judgements or preferences among the options such as equally important, weakly more important, strongly more important, very strongly more important and absolutely more important. Even though the discrete scale of 1–9 has the advantages of simplicity and ease of use, it does not take into account the uncertainty associated with the mapping of one's perception or judgement to a number.

In this study, triangular fuzzy numbers, $\tilde{1}$ to $\tilde{9}$, are used to represent subjective pair-wise comparisons of a selection process in order to capture the vagueness. A fuzzy number is a special fuzzy set $F = \{(x, \mu_F(x)), x \in R\}$, where x takes its values on the real line, $R: -\infty < x < +\infty$ and $\mu_F(x)$ is a continuous mapping from R to the closed interval [0, 1]. A triangular fuzzy number is denoted as $\tilde{M} = (l, m, u)$, where $l \leq m \leq u$ has the following triangular type membership function;

$$\mu_F(x) = \begin{cases} o & x < l \\ x - l/m - l & l \leq x \leq m \\ u - x/u - m & m \leq x \leq u \\ o & x > u. \end{cases}$$

Alternatively, by defining the interval of confidence level α, the triangular fuzzy number can be characterised as

$$\forall \ \alpha \in [0, 1] \quad \tilde{M}_\alpha = [l^\alpha, u^\alpha] = [(m - l)\alpha + l, -(u - m)\alpha + u]. \tag{1}$$

Some main operations for positive fuzzy numbers are described by the interval of confidence by Kaufmann and Gupta (1985), as given below

$$\forall \ m_L, m_R, n_L, n_R \in R^+, \ \tilde{M}_\alpha = \left[m_L^\alpha, m_R^\alpha\right], \ \tilde{N}_\alpha = \left[n_L^\alpha, n_R^\alpha\right], \ \alpha \in [0, 1],$$

$$\tilde{M} \oplus \tilde{N} = \left[m_L^\alpha + n_L^\alpha, m_R^\alpha + n_R^\alpha\right], \ \tilde{M} \Theta \tilde{N} = \left[m_L^\alpha - n_L^\alpha, m_R^\alpha - n_R^\alpha\right],$$

$$\tilde{M} \otimes \tilde{N} = \left[m_L^\alpha n_L^\alpha, m_R^\alpha n_R^\alpha\right], \ \tilde{M}/\tilde{N} = \left[m_L^\alpha / n_L^\alpha, m_R^\alpha / n_R^\alpha\right].$$

The triangular fuzzy numbers, $\tilde{1}$ to $\tilde{9}$, are utilised to improve the conventional nine-point scaling scheme. In order to take the imprecision of human qualitative assessments into consideration, the five triangular fuzzy numbers are defined with the corresponding membership function, as shown in Figure 3.

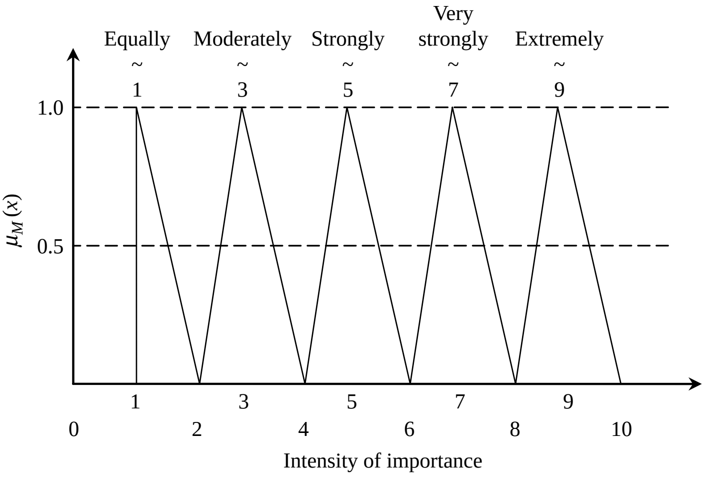

Figure 3. Fuzzy membership function for linguistic values for attributes or alternatives.

The steps of fuzzy AHP approach. The AHP method is known as an eigenvector method. It indicates that the eigenvector corresponding to the largest eigenvalue of the pair-wise comparisons matrix provides the relative priorities of the factors, and preserves ordinal preferences among the alternatives. This means that, if an alternative is preferred to another, its eigenvector component is larger than that of the other. A vector of weights obtained from the pair-wise comparison matrix reflects the relative performance of the various factors. In the fuzzy AHP, triangular fuzzy numbers are utilised to improve the scaling scheme in the judgement matrices, and interval arithmetic is used to solve the fuzzy eigenvector (Cheng and Mon 1994). The five-step procedure of this approach is given as follows:

Step 1. Comparing the performance score. Triangular fuzzy numbers $(\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9})$ are used to indicate the relative strength of each pair of elements in the same hierarchy.

Step 2. Constructing the FCM. By using triangular fuzzy numbers, via pair-wise comparison, the fuzzy judgement matrix $\tilde{A}(a_{ij})$ is constructed as given below:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \dots & \dots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \dots & \dots & \tilde{a}_{2n} \\ \dots & \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots & \dots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \dots & \dots & 1 \end{bmatrix},$$

where $\tilde{a}_{ij}^{\alpha} = 1$, if i is equal to j, and $\tilde{a}_{ij}^{\alpha} = \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$ or $\tilde{1}^{-1}, \tilde{3}^{-1}, \tilde{5}^{-1}, \tilde{7}^{-1}, \tilde{9}^{-1}$, if i is not equal to j.

$\tilde{a}_{ij}^{\alpha}$ indicates the elements of the FCM, $\tilde{A}$ with the value of α, the index of confidence, for $0 < \alpha \leq 1$.

Step 3. Solving fuzzy eigenvalues. A fuzzy eigenvalue, $\tilde{\lambda}$, is a fuzzy number solution to

$$\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}, \tag{2}$$

where is an $n \times n$ fuzzy matrix containing fuzzy numbers $\tilde{a}_{ij}$ and $\tilde{x}$ is a non-zero $n \times 1$ fuzzy vector containing fuzzy numbers $\tilde{x}_i$. To perform fuzzy multiplications and additions using the interval arithmetic and $\alpha -$ cut, the equation $\tilde{A}\tilde{x} = \tilde{\lambda}\tilde{x}$ is equivalent to

$$\left[a^{\alpha}_{i1l}x^{\alpha}_{1l}, a^{\alpha}_{i1u}x^{\alpha}_{1u}\right] \oplus \cdots \oplus \left[a^{\alpha}_{inl}x^{\alpha}_{nl}, a^{\alpha}_{inu}x^{\alpha}_{nu}\right] = \left[\lambda x^{\alpha}_{il}, \lambda x^{\alpha}_{iu}\right],$$

where

$$\tilde{A} = [\tilde{a}_{ij}], \ \ \tilde{x}^{t} = (\tilde{x}_1, \ldots, \tilde{x}_n),$$

$$\tilde{a}^{\alpha}_{ij} = \left[a^{\alpha}_{ijl}, a^{\alpha}_{iju}\right], \ \ \tilde{x}^{\alpha}_{i} = \left[x^{\alpha}_{il}, x^{\alpha}_{iu}\right], \ \ \tilde{\lambda}^{\alpha} = \left[\lambda^{\alpha}_{l}, \lambda^{\alpha}_{u}\right],$$

for $0 < \alpha \leq 1$ and all i, j, where $i = 1, 2, \ldots, n, j = 1, 2, \ldots, n$.

$\alpha -$ cut is known to incorporate the experts or decision maker(s) confidence over his/her preference or the judgements. Degree of satisfaction for the judgement matrix $\tilde{A}$ is estimated by the index of optimism μ. The larger value of index μ indicates the higher degree of optimism. The index of optimism is a linear convex combination (Lee 1999) defined as

$$\tilde{a}^{\alpha}_{ij} = \mu a^{\alpha}_{iju} + (1 - \mu)a^{\alpha}_{ijl}, \quad \forall \ \mu \in [0, 1]. \tag{3}$$

Although α is fixed, the following matrix can be obtained after setting the index of optimism, μ, in order to estimate the degree of satisfaction.

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}^{\alpha}_{12} & \cdots & \cdots & \tilde{a}^{\alpha}_{1n} \\ \tilde{a}^{\alpha}_{21} & 1 & \cdots & \cdots & \tilde{a}^{\alpha}_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \tilde{a}^{\alpha}_{n1} & \tilde{a}^{\alpha}_{n2} & \cdots & \cdots & 1 \end{bmatrix}.$$

The eigenvector is calculated by fixing the μ value and identifying the maximal eigenvalue.

Step 4. Normalisation of the matrices: Normalisation of both the matrix of paired comparisons and calculation of priority weights (approx. criterion weights), and the matrices and priority weights for alternatives are also done before calculating $\lambda_{\max}$. In order to control the result of the method, the consistency ratio for each of the matrices and overall inconsistency for the hierarchy are calculated. The deviations from consistency are expressed by the following equation consistency index, and the measure of inconsistency is called the consistency index (CI);

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}. \tag{4}$$

The consistency ratio (CR) is used to estimate directly the consistency of pair-wise comparisons. The CR is computed by dividing the CI by a value obtained from a table of random consistency index (RI)

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{5}$$

If the CR is less than 0.10, the comparisons are acceptable. otherwise not. RI is the average index for randomly generated weights (Saaty 1981)

Step 5. Calculation of priority weights for each alternative. After normalisation, the priority weight of each alternative can be obtained by multiplying the matrix of evaluation ratings by the vector of criterion weights and summing over all criteria. Expressed in conventional mathematical notation (Saaty 1981):

Weighted evaluation for alternative

$$k = \sum_{i=1}^{t} (\text{criteria weight}_i \times \text{evaluation rating}_{ik}), \tag{6}$$

for $i = 1, 2, \ldots, t$ (t: total number of criteria).

After calculating the weight of each alternative, the overall consistency index is calculated to make sure that it is smaller than 0.10 for consistency on judgements.

3.5.2 *Determining the constant value and reducing the number of alternatives*

The reducing process uses a constant value to eliminate the alternatives, the fuzzy weights of which are smaller than this value. This value is determined using an elimination scale. This scale is constructed as follows: (1) if the number of alternatives is less than or equal to 4, there is no need to use a constant value and no need to reduce alternatives, (2) if the number of alternatives is between 5 and 12, discard the alternatives that have scores less than 0.10 and (3) if the number of alternatives is between 13 and 24, discard the alternatives that have scores less than 0.05.

3.5.3 *Simulation generator*

In this section, a simulation generator is used for measuring the benefits of each remaining alternative of the fuzzy AHP on the generated model of a real-life manufacturing organisation. Therefore, first, *an operation-based structure* is defined for building an entire production organisation. All data are entered into the system via a data-driven interactive tool by the user. And then, the simulation generator automatically builds the model of a real-life product organisation and writes its model and experimental files in the target simulation language SIMAN. And then, the generated model is run first for the current system and second for each alternative, which is assumed as a scenario. Each scenario uses the data obtained from the benchmarking process for each alternative. The results of simulation experiments are obtained and evaluated to reach the ultimate solution. The code generator was written in QBasic and run on PC platform.

Gathering the data. Six different ways can be defined to get all the required data for the simulation experiments, such as: (1) similar studies realised in the literature can provide more important information for a new system analysis; (2) feedback taken from well-experienced employees who know both their old system well and a new system (to get the correct information, first they should believe that a new system will bring very important benefits to the company, as well as to themselves); (3) decisions made by a decision maker or a member of the top management who has authority to realise a new system; (4) data obtained from the vendor and his experience;(5) other companies that realised the same or a similar new system; (6) information obtained from the benchmarking process that tries the benefits of any candidate system on the product organisation of the company.

The ways mentioned above have some disadvantages besides their advantages, such as that information from the literature or the studies realised earlier was obtained under certain conditions. Although they are very useful for simulation experiments, their correctness and confidences can be discussed. So, first of all, a sensitive analysis should discover under which conditions they were obtained. In addition, this process can be a time-consuming activity. Although employees working in a relevant department of a company are one of the most important sources of necessary information about an old system leading to implement a new system, their views can be subjective and may not reflect the real values. Information from a vendor may not be enough due to the fact that it has less information on their customers' applications than required. Companies using the same or similar systems can also provide significant information. But each company has different production systems. So information obtained from other user companies can barely be used to get a rough view of point for the analysis. Finally, all of the ways mentioned above have some disadvantages, as well as their advantages. But gathering correct and trustworthy data to use in a simulation study is one of the most important parts of this study. So, of all the ways, the benchmarking technique realised on the company's outstanding activities provides more valuable and trustworthy information than the others, but the others can roughly be used to test the acceptability of the results of a benchmarking process. Therefore, the benchmarking technique is selected to gather data for each alternative. There are two ways described here regarding the use of benchmarking technique: (1) the deterministic samples – these samples, the results of which are certainly known, are selected and applied for each alternative to measure its performance based on the criteria (cost, time, quality, etc.) on the company's product organisation; (2) the stochastic samples – these samples representing heavy-load conditions of the company production organisation are taken into consideration to evaluate the performance of the same alternative under extreme conditions.

Modelling a product organisation. A typical *operation centre structure* is defined in Figure 4 as a cornerstone of a manufacturing system to build a whole system. An operation centre as a member of *operation centre group* could be sales/marketing or product planning and control manufacturing or warehousing, etc., which are the main functions of a production organisation, whereas information flow (input and output) defines the priorities among them. It can be assumed that this production organisation consists of the

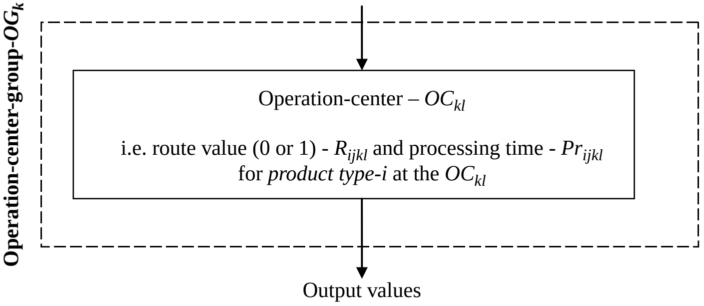

Figure 4. An *operation centre structure* as a cornerstone of a manufacturing system.

operation centre groups, and their operation centres with input and output values and the tasks carried out by these centres.

All the data regarding the organisation to be modelled are kept in a database so that they can be easily updated if any changes happen regarding any parameter of the operation centre and operation-centre-groups.

The most effective functions that directly affect the performance of a product organisation are taken into account for this study. The information transfer times are ignored due to the fact that it is assumed that they do not affect the overall performance of a product organisation. All data are gathered from a real-life system under certain assumptions. Assumptions relate the model behaviour to the physical system behaviour by serving two purposes: (1) the first purpose is to identify system details not included in the model because they do not influence performance, (2) the second purpose is to define how the included details are represented in the model. The following is a list of the key assumptions made for this study: (a) there is only material flow modelled, (b) absence of employees is not included and (c) rework is not included. The simulation generator needs the matrices of routes set up and process times for each alternative. The values regarding process and set-up times are based on the data gathered from the real-life system, and fitted to the certain parametric distributions for the simulation analysis to generate random variables during the experiments. Table 3 shows the notations used, as Table 4 shows components of the database.

User interface. A user interface is designed and implemented. It is an interactive data-driven tool. Input is taken through the keyboard from the user to supply the simulation generator with the necessary information. The user interface was tested and validated extensively for different cases. Some operational data are generated from the basic descriptions after the user completes data entry.

Simulation report generation. The simulation generator creates custom report specifications within the experimental file. Results of a simulation run are divided into three major sections with the following headings: tally variables, discrete-change variables and counters. Under the tally variables section, observation-based statistics are listed. Average coefficient of variation, minimum, maximum and the number of observations are reported for each item. The discrete-change variables section lists time-based statistics. Average, coefficient of variation, minimum, maximum and final values are reported for each variable. The final section reports the counter variables such as the number of orders completed, the number of units designed and the number of units manufactured.

Verification and validation of the simulation generator. Various steps were taken to verify and validate both the generated SIMAN files (model and experimental) and the

Table 3. Notations – Summary.

P_i	Product type – i ($i = 1,2,3,\ldots,m$)
m	Number of products
t	Number of operation centre groups
v	Number of operation centres
OG_k	Type of operation centre group ($k = 1,2,3,\ldots,t$)
OC_{kl}	Type of operation centre in the operation centre group – OG_k ($l = 1,2,3,\ldots,v$)
R_{ijkl}	Route value (0 or 1) for product type – i at the operation centre – OC_{kl}
Pr_{ijkl}	Processing time for product type – i at the operation centre – OC_{kl}
TO_{kll}	Transfer time between operation centres at the same operation centre group
TG_{kk}	Transfer time between operation centre groups

Table 4. Components of the database.

Fuzzy AHP
Number of criteria (2–50)
Number of alternatives (2–24)
Names of alternatives
Matrix of paired comparison for criteria using triangular fuzzy numbers
Matrix of paired comparison of alternatives with respect to each criterion using triangular fuzzy numbers
Fuzzy scaling system
Simulation
Customer order
Interval time (days) – exponential
Lot size of order – uniform (1–10)
Type of the order (or product) – discrete
Operation-centre-groups
Types of the groups for all (i.e. marketing, product planning and control, design, manufacturing, etc. groups)
Numbers of groups (1–24)
Transportation times between operation-centre-groups – constant (5 min)
Operation centres
Types of operation centres in each group (i.e. order processing, process planning, CAD design, etc.)
Numbers of operation centres in each group (1–12)
Initial buffer and buffer capacity (for input and output queue) on each operation centre in group
Transportation times between operation centres in the same group – constant (1 min)
Processing time product i at the operation centre [Normal]
Route value matrix of product i at the operation centre [0 or 1]
Processing time matrix of product – i at the operation centre
Experiments
Simulation date, model and user's name
Maximum number of concurrent entities in the system
Number of simulation runs to execute
Warm-up period of simulation
Beginning time of the first run
Maximum length of each run
Option for initialising the system status between runs [YES/NO]
Option for discarding previous observations between runs [YES/NO]
Option for detailing trace report of the processing entities [YES/NO]

results obtained from the simulation runs. Several examples were generated using the user interface. The generated files were verified manually for their logical and structural correctness. If the data taken via the user interface is employed to describe a product organisation system, then the simulation generator creates the files for the SIMAN simulation language. Several performance measures such as queue lengths, resource utilisation and cycle times are included as standard items in the output results to validate the simulation models. Finally, a few small models' logic is validated using the TRACE capability of SIMAN. All results indicated a valid and robust simulation generator.

Limitations of the simulation generator. The simulation generator is written using QBasic. It has no model size restrictions and generates simulation programs that can be run in all versions of SIMAN. Advantages of simulation generators are well known but there are also several limitations. O'Keefe and Haddock (1991) indicate that the disadvantages for the user occur in three areas: (1) perceived ease of use, (2) weaknesses resulting from the underlying language and (3) limitations of the generator.

Furthermore, if the assumptions made in developing a simulation generator is not explicitly stated by the developer and not understood by the user, the results can be invalid. The simulation generator is easy to use, but it requires a large amount of data. It also requires basic statistical skills. The same arguments can be made for the design of the simulation experiment and for the analysis of the simulation results. There are a few weaknesses resulting from the underlying language, SIMAN. SIMAN does not have real subroutine capabilities, so several modules must be repeated many times causing long model files. However, this can be viewed as an advantage since the code is more readable in its current form.

3.6 *Final evaluation (Step VI)*

In this step, the results of simulation experiments realised for each alternative are evaluated and compared with each other based on a set of performance criteria, used for measuring the benefits of each alternative. The alternative that provides the most benefits is found to be the ultimate CAD software alternative. Then, it is presented to the company's management for approval to kick off further actions.

4. Case study

In the previous sections, a fuzzy AHP-based simulation approach has been presented to evaluate a set of CAD software alternatives. In this section, a case study is realised to prove its applicability and validity in order to make this approach more understandable and clearer for everyone. Therefore, a manufacturing system of a leading cutting tool manufacturer in Turkey, which designs and manufactures all kinds of standard, semi-custom and custom cutting tools (i.e. twist drills, reamers, taps, nuts, carbide-tipped tool holders, centre drills, masonry drills) for national and international markets, was taken into consideration.

First, a cross-functional team was set up to select the best CAD software among its possible alternatives. This team consisted of five persons, four of them were from the product development, IT, product planning and control departments; the fifth person was from the management, the director of research and development (R&D). Then, the company's current production organisation was analysed, and all the business and manufacturing functions were determined, which could affect the overall performance of the organisation. The products that are designed and manufactured in the company are also classified in three categories such as N (standard products), S (semi-standard products) and P (custom products). A German-based software called INTEPS was used as a production planning and control system, which controls all the business functions from the customer order to shipping order and also includes accounting and finance departments except for the design functions done separately and manually without any support of computer technology. One of the most important departments in the organisation is the product design and engineering department, which can be directly affected by the study. In this department, different kinds of the tasks (i.e. custom-tailored design based on customer specifications, giving of code and drawing numbers to products, revision of drawings, preparation of production tables used in similar products, archiving of drawings, classification of samples coming from customer and so on) are carried out. The company's manufacturing site includes several multi-axis NC-controlled machines, as well as conventional ones. In addition, there are five manufacturing facilities divided up as per the product groups, except for the heat treatment department, which provides services to all of them:

Table 5. FCM for the criteria using triangular fuzzy numbers.

Criteria	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
C1	1	$\tilde{1}$	$\tilde{5}$	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{9}$
C2	$\tilde{1}^{-1}$	1	$\tilde{3}$	$\tilde{3}$	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$
C3	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{1}$	$\tilde{1}$	$\tilde{3}$	$\tilde{7}$
C4	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	1	$\tilde{1}$	$\tilde{5}$	$\tilde{5}$
C5	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	1	$\tilde{1}$	$\tilde{1}$
C6	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}^{-1}$	1	$\tilde{1}$
C7	$\tilde{9}^{-1}$	$\tilde{3}^{-1}$	$\tilde{7}^{-1}$	$\tilde{5}^{-1}$	$\tilde{1}^{-1}$	$\tilde{3}^{-1}$	1

(1) drills, (2) cutters, (3) taps, (4) saws and (5) carbide-tipped tool holders. Second, the team defined seven critical criteria (i.e. system cost, ease of use, compatibility, efficiency and effectiveness, concurrent engineering, updating/added feature and technical support and service) and carried out the fuzzy AHP study and used triangular fuzzy numbers $\tilde{1}-\tilde{9}$ to express the preference in the pair-wise comparisons. Then, the required data was entered into the software for analysis and the FCMs obtained for each level using geometric means of the pair-wise comparisons. In Tables 5 and 6, the pair-wise comparison matrix (FCM$_0$) of the criteria for each level and the pair-wise comparison matrix (FCM$_1$) of the alternatives with respect to the first criteria, *system cost*, are presented as an example by using triangular fuzzy numbers ($\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$). The other pair-wise comparison matrices of the alternatives for the remaining criteria were also constructed by following the same procedure.

The lower limit and the upper limit of the fuzzy numbers with respect to the α were defined as follows by applying Equation (1):

$$\tilde{1}_\alpha = [1, 3-2\alpha],\ \ \tilde{3}_\alpha = [1+2\alpha, 5-2\alpha],\ \ \tilde{3}_\alpha^{-1} = \left[\frac{1}{5-2\alpha}, \frac{1}{1+2\alpha}\right],$$
$$\tilde{5}_\alpha = [3+2\alpha, 7-2\alpha],\ \ \tilde{5}_\alpha^{-1} = \left[\frac{1}{7-2\alpha}, \frac{1}{3+2\alpha}\right],\ \ \tilde{7}_\alpha = [5+2\alpha, 9-2\alpha],$$
$$\tilde{7}_\alpha^{-1} = \left[\frac{1}{9-2\alpha}, \frac{1}{5+2\alpha}\right],\ \ \tilde{9}_\alpha = [7+2\alpha, 11-2\alpha],\ \ \tilde{9}_\alpha^{-1} = \left[\frac{1}{11-2\alpha}, \frac{1}{7+2\alpha}\right].$$

We substituted the values $\alpha = 0.5$ and $\mu = 0.5$ from the above expression into FCMs using Equation (3), and obtained all the α-cut FCMs (Tables 7 and 8) (Equation (2) was used to calculate eigenvectors for all comparison matrices). We determined the index of optimism, $\mu = 0.5$, based on the optimism of the decision maker because it reflects a moderate situation. If its various values are applied, different variations in the results indicate some possible mistakes of the estimation process (human impact).

Table 6. FCM for the alternatives with respect to the first criterion – *system cost (C1)* – using triangular fuzzy numbers.

Alternatives	*A1*	*A2*	*A3*	*A4*	*A5*
A1	1	$\tilde{1}$	$\tilde{3}$	$\tilde{5}$	$\tilde{7}$
A2	$\tilde{1}^{-1}$	1	$\tilde{1}$	$\tilde{3}$	$\tilde{3}$
A3	$\tilde{3}^{-1}$	$\tilde{1}^{-1}$	1	$\tilde{3}$	$\tilde{9}$
A4	$\tilde{5}^{-1}$	$\tilde{3}^{-1}$	$\tilde{3}^{-1}$	1	$\tilde{1}$
A5	$\tilde{7}^{-1}$	$\tilde{3}^{-1}$	$\tilde{9}^{-1}$	$\tilde{1}^{-1}$	1

Table 7. α-cut FCM for the criteria ($\alpha = 0.5$).

Criteria	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*
C1	1	[1, 2]	[4, 6]	[1, 2]	[2, 4]	[4, 6]	[8, 10]
C2	[1/2, 1]	1	[2, 4]	[2, 4]	[1, 2]	[1, 2]	[2, 4]
C3	[1/6, 1/4]	[1/4, 1/2]	1	[1, 2]	[1, 2]	[2, 4]	[6, 8]
C4	[1/2, 1]	[1/4, 1/2]	[1/2, 1]	1	[1, 2]	[4, 6]	[4, 6]
C5	[1/4, 1/2]	[1/2, 1]	[1/4, 1/2]	[1/2, 1]	1	[1, 2]	[1, 2]
C6	[1/6, 1/4]	[1/4, 1/2]	[1/4, 1/2]	[1/6, 1/4]	[1/2, 1]	1	[1, 2]
C7	[1/10, 1/8]	[1/4, 1/2]	[1/8, 1/6]	[1/6, 1/4]	[1/2, 1]	[1/4, 1/2]	1

Table 8. α-cut FCM for the alternatives with respect to the first criterion – *system cost (C1)* ($\alpha = 0.5$).

Alternatives	*A1*	*A2*	*A3*	*A4*	*A5*
A1	1	[1, 2]	[2, 4]	[4, 6]	[6, 8]
A2	[1/2, 1]	1	[1, 2]	[2, 4]	[2, 4]
A3	[1/4, 1/2]	[1/2, 1]	1	[2, 4]	[8, 10]
A4	[1/6, 1/4]	[1/4, 1/2]	[1/4, 1/2]	1	[1, 2]
A5	[1/8, 1/6]	[1/4, 1/2]	[1/10, 1/8]	[1/2, 1]	1

Let $FCM_1^{0.5} = A_1$, the matrix of pair-wise comparison of the alternatives with respect to the first criteria, *system cost* (FCM_1). We first calculated the eigenvalue of the matrix $\mathbf{A}_1$ by solving the characteristic equation of $\mathbf{A}_1$, $\det(A_1 - \lambda I) = 0$. Then, we calculated all λ values for $\mathbf{A}_1$ (λ_1, λ_2, λ_3, λ_4, λ_5).

The largest eigenvalue of matrix $FCM_1^{0.5}, \lambda_{\max}$, was calculated to be 5.429. The dimension of the matrix, n, is 5 and the random index, RI(n), is 1.12 (RI – function of the number of criteria). Then we calculated the consistency index and the consistency ratio of the matrix using Equations (4) and (5) as follows (Table 9):

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} = \frac{5.429 - 5}{4} = 0.107, \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.107}{1.12} = 0.096 < 0.10.$$

We also calculated the consistency ratios for all the matrices and found that they were less

Table 9. Eigenvector for comparison matrix of the alternatives with respect to the first criterion – *system cost (C1).*

Alternatives	*A1*	*A2*	*A3*	*A4*	*A5*	*e-Vector*
A1	1.000	1.500	3.000	5.000	7.000	0.399
A2	0.750	1.000	1.500	3.000	3.000	0.236
A3	0.375	0.750	1.000	3.000	9.000	0.232
A4	0.208	0.375	0.375	1.000	1.500	0.078
A5	0.146	0.375	0.113	0.750	1.000	0.055
					$\lambda_{\max}$	*5.429*
					CI	*0.107*
					RI	*1.12*
					CR	*0.096 < 0.1*

than 0.10. As the result of these calculations, we proved that the consistency of the judgements in each comparison matrix was acceptable.

Similarly, for the matrix $FCM_0^{0.5} = A_0$, we first calculated the matrix of pair-wise comparisons of the criteria for each level. Then, we calculated the eigenvalue of the matrix $\mathbf{A}_0$ as follows by solving the characteristic equation of $\mathbf{A}_0$, $\det(A_0 - \lambda I) = 0$, and then we calculated all λ values for $\mathbf{A}_0$ ($\lambda_1, \lambda_2, \ldots, \lambda_7$) (Table 10).

Then, we calculated $\lambda_{\max} = 7.667$, CI = 0.111 = (7.667-7)/6, RI = 1.32 and CR as 0.084, less than 0.10, and we saw that the consistency of the judgements in the comparison matrix was acceptable.

Finally, we obtained the final weights of five alternatives with respect to the goal using the formula as follows and ranked them by weight.

$$\sum_{i=1}^{7} (\text{attribute weight}_i \times \text{evaluation rating}_{iA}).$$

In addition, we calculated the overall consistency index to make sure that it was smaller than 0.10 for consistency on all judgements. Table 11 shows the results of the fuzzy AHP.

At the beginning, there were five alternatives and they were ranked by weight as seen in Table 11. Two of them (CIMATRON and UNIGRAPHICS) were eliminated based on the elimination scale, because their scores (0.085, 0.059) were less than 0.100. Only three alternatives (CATIA, I-DEAS and Pro–ENGINEER) remained for further study, simulation experiments.

By using the data in Table 12, the company's current product organisation was modelled using the data-driven user interface. The user, a member of the team, introduced the data in the table to the system, and then they were stored in the database. These data were obtained from the company's real-life product organisation and used to build its simulation model. To prove the accuracy of the data, the TRACE command, one of the SIMAN output commands, was used to verify the generated model. This command allows the following of the step-by-step running of a model on a time basis in order to see on how well the model is running in comparison with the real-life system. In addition, for the validity of the model, extreme conditions from the real-life system were taken into consideration to understand how well the model represented it.

Formal, qualitative and observation characteristics were examined on the model (1996). Furthermore, *t*-distribution was used to prove the validity of simulation model using the 'product cycle time for all products' variable at 95% confidence level.

Table 10. Eigenvector for comparison matrix of the criteria.

Criteria	*C1*	*C2*	*C3*	*C4*	*C5*	*C6*	*C7*	*e-Vector*
C1	1.000	1.500	5.000	1.500	3.000	5.000	9.000	0.310
C2	0.750	1.000	3.000	3.000	1.500	1.500	3.000	0.203
C3	0.208	0.375	1.000	1.500	1.500	3.000	7.000	0.141
C4	0.750	0.375	0.750	1.000	1.500	5.000	5.000	0.158
C5	0.375	0.750	0.375	0.750	1.000	1.500	1.500	0.091
C6	0.208	0.375	0.375	0.208	0.750	1.000	1.500	0.055
C7	0.113	0.375	0.146	0.208	0.750	0.375	1.000	0.042
							$\lambda_{\max}$	*7.667*
							CI	*0.111*
							RI	*1.32*
							CR	*0.084 < 0.1*

Table 11. Final ranking of CAD software alternatives.

Alternative	*C1 (0.310)*	*C2 (0.203)*	*C3 (0.141)*	*C4 (0.158)*	*C5 (0.091)*	*C6 (0.055)*	*C7 (0.042)*	*Overall e-Vector*
CATIA	0.399	0.394	0.459	0.498	0.505	0.424	0.487	0.437
I-DEAS	0.236	0.300	0.203	0.182	0.185	0.247	0.203	0.230
Pro-ENGINEER	0.232	0.176	0.193	0.173	0.134	0.143	0.159	0.189
CIMATRON	0.078	0.069	0.090	0.090	0.110	0.114	0.079	$0.085 < 0.100$[a]
UNIGRAPHICS	0.055	0.061	0.055	0.057	0.066	0.072	0.072	$0.059 < 0.100$[a]
CR	*0.096*	*0.087*	*0.088*	*0.084*	*0.097*	*0.082*	*0.072*	

Overall consistency index: $0.094 < 0.100$ ok.

[a] The alternatives are eliminated. Only the first three are taken for further study, simulation analysis.

Table 12. Cells and their tasks and process times for each product type.

Operation centres *Tasks*	*Process times (day)*		
	N type	*S type*	*P type*
• Customer			
• Quoting	N (0.2, 0.1)	N (1.2,0.5)	N (3, 0.8)
• Warehousing and shipping	N (0.1, 0.2)	N (0.6,0.2)	N (1, 0.4)
• Production planning and control			
• Create work order	0.1	0.16	0.22
○ Calculating net orders	0.15	0.2	0.25
○ Preparing monthly reports	0.5	1.2	2.0
• Manual design ands drafting			
○ Designing carbide-tipped tool holders		N (1.6,0.5)	N (4, 0.4)
○ Designing all kinds of cutting tools		N (1.1,0.5)	N (3, 0.6)
• Tool design			
○ New tool and fixture design for an order		N (4,1)	N (7, 1.8)
○ Preparing tool and fixture manufacturing drawings		N (3,0.6)	N (5, 1.2)
○ Revising tool and fixtures as per product changes	N (1, 0.2)	N (1.6,0.5)	N (3, 0.8)
• NC codes (Carbide-tipped tool holders)			
○ Manual NC Code generation		N (3,1.5)	N (6, 0.7)
○ NC code preparation and transfer to CNC machines		0.3	0.5
• Method studies		N (2.5,0.4)	N (4, 0.8)
• Process planning			
○ Preparing manual process plans for new orders		N (0.6,0.2)	N (1, 0.2)
• Soft operations before heat treatment	N (4, 0.5)	N (12,2.5)	N(18,3.5)
• Heat treatment	N (1, 0.2)	N (3,0.5)	N (4, 0.8)
• Operations after heat treatment	N (2, 0.2)	N (6,1.5)	N(10,0.4)
• Carbide-tipped tool holder manufacturing	N (1, 0.2)	N (1.6,0.5)	N (3, 0.8)
• Quality control	N (0.1, 0.2)	N (0.4,0.2)	N (1, 0.2)

Simulation duration was selected as 300 working days (approx. 1 year) so that the required data could be obtained statistically from the experiments. The results were exported to Excel® as an ASCII file using the SIMAN output command, so that they could be represented graphically. To find the warm-up period or transition period, the PLOT command of the SIMAN output analysis module was used on the average product cycle time of all products', and the warm-up period duration was found to be 90 days. To calculate the confidence intervals, FILTER and INTERVALS commands were also used for each performance criteria (Pegden 1990).

Simulation experiments. Each alternative remaining from the fuzzy AHP was accepted as a scenario in the simulation experiments. The generator used the required data obtained from the benchmarking process for each alternative (Table 13). The process times for standard (N) product types were assumed to be fixed. For each alternative, the user modified the relevant model parameters of the current product organisation using Table 13 and ran the updated model again to get the results.

Simulation results. After doing the experiments for three alternatives, the results were obtained. Table 14 shows the benefit comparisons of CAD alternatives on the company's current production organisation. As seen in Table 14, the comparisons of the average cycle

Table 13. Data for the simulation study.

	Current system		*CAD supported system*					
	Process time (day)							
			CATIA		*I-DEAS*		*PRO−ENGINEER*	
Tasks	*S*	*P*	*S*	*P*	*S*	*P*	*S*	*P*
Design for all products	N (1.1, 0.5)	N (3, 0.6)	N (1.0, 0.5)	N (1.5, 0.4)	N (1.2, 0.2)	N (2.0, 0.5)	N (0.9, 0.2)	N (2.1 0.4)

Note: Process times are assumed to fit into normal distribution.

Table 14. Comparison of the average cycle times (all values rounded up).

Performance criteria	*Current system*	*Scenario I CATIA*	*Scenario II I-DEAS*	*Scenario III PRO–ENGINEER*
Average product cycle time for all products (day)	59.5	50.4 (% 15)	53.4 (% 10)	54.2 (% 9)
Average design cycle time for all products (day)	0.75	0.37	0.4	0.42

Note: The alternative satisfies to the company management if the criteria ‘product cycle time for all products’ is less than 7.5 weeks (52.5 days). The values in the brackets show the improvement degree of the scenarios comparison with the current system.

times of three alternatives after eliminating warm-up period data in 90 days are presented. In the table, the best value of performance criteria, *product cycle time for all products*, was obtained for the alternative *CATIA* (50.4 days) with 15% improvement in comparison with the current system (59.5 days). This alternative also satisfied the company management, because the criteria ‘product cycle time for all products’ is less than 7.5 weeks (52.5 days).

In this final step, the ultimate CAD software alternative, CATIA, was presented to the company’s top management for approval to start further actions.

5. Conclusions

In this paper, in a combined approach, the fuzzy AHP and simulation are combined for the CAD software selection problem. First, the fuzzy AHP is used to reduce a possible number of alternatives for a CAD system to an acceptable level for further study, simulation analysis. Secondly, a simulation generator as an integrated part of the fuzzy AHP is used to try the remaining alternatives, on the generated model of a real-life product organisation in which the final alternative will be used. The results of simulation experiments are obtained and then evaluated to reach the ultimate CAD alternative. Furthermore, software is presented to make all the calculations required for both fuzzy AHP and simulation studies easy and quicker via a data-driven user interface and the related database.

The proposed approach in this study is limited in its range of application, because it consists of a simulation generator that is mainly developed for a narrow field of manufacturing (Aytug and Dogan 1998). To expand the range of a simulation generator, the model builder should review the generator to include new issues on modelling a manufacturing environment. Depending on the purpose of the study, if necessary, the builder can also add more issues such as modelling of machine breakdown, absence of employees and so on. The simulation generator also produces the files required by the SIMAN simulation language. It has no model size restrictions and generates simulation programmes that can be run in all versions of SIMAN. The fuzzy AHP method has also no restriction (i.e. the number of alternatives and the number of criteria).

Using the fuzzy AHP approach to evaluate alternatives for a CAD system resulted in the following two major advantages: (1) fuzzy numbers are preferable to extend the range of a crisp comparison matrix of the conventional AHP method, as human judgement in the comparisons of selection criteria and CAD software alternatives is really fuzzy in nature, (2) adoption of fuzzy numbers can allow decision maker(s) to have freedom of estimation regarding the CAD software selection problem. In other words, the conventional AHP of Saaty uses a nine-point scale to make pair-wise comparisons. The AHP method does not take into account the uncertainty associated with the mapping of one’s judgement to a number. But the fuzzy AHP, especially in this work, the decision maker(s) uses fuzzy triangular numbers to express their judgements using an interval of confidence. More reliable judgements are obtained and interval arithmetic is used to solve the fuzzy eigenvector.

In future research, a knowledge-based system (KBS) can be adapted to this approach to interpret the outputs of the simulation experiments automatically via a user interface. A KBS creates a rule-based database to interpret the results of simulation experiments, makes the comments using its inference engine and presents them to the user.

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