Non-traditional machining process selection using integrated fuzzy AHP and QFD techniques: a customer perspective

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With the advancement in material science and engineering, hard as well as difficult to cut materials are coming to the fore on regular basis. Machining such advanced materials with higher geometrical accuracy by conventional means is almost impossible. Thus, demand for higher accuracy with desired surface finish leads us to a large pool of non-traditional machining (NTM) processes. However, zeroing-in for a particular NTM process, for a particular operation and for a case-specific machining, is a cumbersome task. In order to make this task simpler for a decision-maker, the present research uses, fuzzy analytic hierarchy process to calculate the relative importance of various NTM processes taking product and process characteristics as the comparison basis. Finally, an overall score of various NTM processes have been obtained using quality function deployment methodology based on various shape features and work material combination. Also, the variations in the process capability features have been taken into consideration. Analysis of the present research study shows that electrochemical machining process has an edge over the other NTM processes with respect to surface finish, corner radii, minimum surface damage depth, and production time.

Keywords: non-traditional machining; fuzzy analytic hierarchy process; quality function deployment; multi-objective decision-making

1. Introduction

With the growing applications of hard and difficult-to-machine materials in turbine, aviation, tool and die making industries, there is a need of machining materials with high precision and surface finish. There are basically two machining techniques namely traditional and non-traditional, of which traditional machining involves direct interaction of tool and workpiece. As such, this technique cannot be utilized to machining of difficult-to-cut materials, since hardness becomes the limiting factor. Therefore, the option left with is non-traditional machining (NTM) process. Thus, NTM processes turns out to be extremely useful for such applications as there is no direct contact of tool and the workpiece. The traditional methods of machining involve chip formation so their accuracy and surface finish get deteriorated. Moreover, according to Taguchi (Jain, 2002) high precision and accuracy cannot be simultaneously achieved by means of traditional machining methods, where the material is removed in the form of chips. On the other hand, development of new materials along with innovative and complex product design.
vies to test the capabilities of traditional machining methods. As such the enhanced and efficient process capabilities of NTM processes make them very much acceptable for the manufacturing industries. However, the presence of a large number of NTM processes with their boundless capacities makes the exact choice to be very complicated and taxing. Further, the process characteristics of a particular NTM process may not perfectly match with the customer’s requirement of machining a particular material.

In the existing literature, researchers have employed various methods for NTM process selection like computer-aided selection procedure using 16-digit classification code. The coding system uses a computer program and database for the process of elimination (Cogun, 1993, 1994). A systematic methodology for selecting optimal NTM process under constrained material and machining conditions followed with development of expert system for automation of selection process based on analytic hierarchy process (AHP) (Chakraborty & Dey, 2006). A method-combining technique for order preference by similarity to ideal solution (TOPSIS) integrated with AHP method (Chakladar & Chakraborty, 2008; Yurdakul & Ççoğun, 2003) has proposed for appropriate NTM selection for a specific work material and shape feature combination. Further, the authors went on to develop an expert system on the proposed methodology. Chakraborty and Dey (2007) studied the NTM process selection using quality function deployment (QFD) by taking into account the product and process characteristics for machining a particular shape feature on a specific material and then also developed an expert system based on this. A three-tier information system was also developed for NTM selection that encompasses real time web-based knowledge base system (Chandraseelan, Jehadeesan, & Raajenthiren, 2008). Further, the digraph approach was used for a specific set of NTM processes evaluation and also developed an expert system based on it (Chakladar, Das, & Chakraborty, 2009).

Later on Das and Chakraborty (2011) worked on analytic network process (ANP)-based approach for NTM process selection and also a commendable work has been done on multi-objective optimization on the basis of ratio analysis method to solve six different decision-making problems covering NTM process selection (Chakraborty, 2011). Karande and Chakraborty (2012) considered four NTM processes selection problem using an integrated approach of preference ranking organization method for enrichment evaluation (PROMETHEE) and geometrical analysis for interactive aid method to act as a visual aid to the process engineers. An integrated approach using AHP and TOPSIS was used for NTM process selection (Choudhury et al., 2013) for selecting the best NTM process.

Keeping in view of the customer’s requirement, selecting a particular NTM process from the pool of NTM processes for a desired shape feature and work material combination remains a critical issue. A particular NTM process may be highly acceptable for a given set of requirements, but it may fail to prove its acceptability under another set of conditions. In order to address all such issues, there is a need for devising a method for careful selection of most suitable NTM process for the requirement-based application of the product.

When it comes to machining a particular product on the most appropriate NTM process, then a decision-maker is influenced by a large number of interdependent and conflicting attributes (Chakraborty & Dey, 2007). Under such situations, the existence of large number of multi-objective, multi-attribute decision-making methods are useful to the decision-maker. There are few papers which have used integrated approach of fuzzy analytic hierarchy process (FAHP) and QFD for different types of problems. However, it is not yet utilized for selection of NTM process. Thus, this paper attempts to address such decision-making problem by integrating FAHP and QFD for selecting best suited NTM process based on a set of product characteristics and process characteristics. This
paper starts with the explanation of FAHP and QFD method which is then followed by brief explanation of product and process characteristics. Further, a methodology has been proposed based on a hybrid model of FAHP and QFD to solve a case study. There are few papers which do integrate the FAHP and QFD; but in the present paper, QFD has been implemented for the identification of the technical requirements (TRs), whereas FAHP has been used to find weightage of individual TRs so that problem arising from the traditional QFD model can be avoided.

2. FAHP method

Of the various multi-criteria decision-making (MCDM) tools, AHP offers subjective judgment of one criteria over the other. AHP, as developed by Saaty (1988), uses eigen-value approach for the pairwise comparison. The three fundamental steps of AHP are:

1. Structuring a decision-making problem in the form of hierarchy,
2. Performing pairwise comparisons between alternatives and the criteria,
3. Synthesizing the priorities for developing an overall evaluation of decision alternatives.

A large number of work has already been carried out for solving various decision-making problems using AHP (e.g. Chan, Kumar, Tiwari, Lau, & Choy, 2007; Dağdeviren & Yüksel, 2008; Kahraman, Ruan, & Doğan, 2003; Kulak & Kahraman, 2005). The methodology is especially suitable for analyzing complex multi-parameter alternatives, which includes subjective criteria. The technique stresses on the calculation of priority weights of various influencing attributes.

Even though AHP can deal well with the expert’s knowledge and his perceptions of preferences, but still it cannot perfectly reflect the decision-maker’s thought with the crisp numbers. Conventional AHP method may fail to provide accurate judgments if there exists certain degree of fuzziness in the problem (Bouyssou et al., 2000). Quiet often in MCDM problems, the data is imprecise, since the decision-maker may be unwilling to express his/her views precisely (Nobakht & Roghanian, 2013) and finding solution of such problems means coping with indefiniteness. Since the conventional AHP cannot perfectly reflect the human thinking style so to avoid the involved risks, the FAHP, an extension of AHP, helps in solving the hierarchical fuzzy problems (Özdagolu & Özdagoloğlu, 2007). More importantly if the available information/evaluation is certain enough then AHP should be used, otherwise FAHP should be used. Thus, for uncertain environments, fuzzy numbers have to be used for the evaluation and for this FAHP approach proves out to be more appropriate method in tackling multi-criteria decision-making problems (Kabir & Hasin, 2011). The fuzzy extension of AHP utilizes a nine-level scale of judgments, which are expressed through the triangular fuzzy numbers (TFNs) to characterize the relative significance among hierarchy’s criteria (Zhu, Jing, & Chang, 1999). The use of TFNs is rather simple and easy to calculate. It is also very helpful in a decision-making problem, where the available information is subjective and imprecise (e.g. Chang & Yeh, 2002; Chang, Yeh, & Wang 2007; Kahraman et al., 2003; Zimmermann, 1996). In real practice, membership function of triangular form is most often used for representing the fuzzy numbers. And it can be characterized by a triplet of real numbers \( K = (a, b, c) \), where \( a \) represents lower bound limit, \( c \) the upper bound limit, and \( b \) being the median value. Although in literature, there exists a number of scales, but in this paper, the authors propose to utilize the one which is rather simple.
and correspond better to the preference scale of crisp AHP as outlined in Table 1. Since, FAHP integrates the fuzzy theory (Zadeh, 1965) into AHP environment so it has been implemented to solve the problem of NTM process selection as the available information was imprecise.

Further Equation (1) defines the fuzzy membership function $\mu_K(y)$

$$
\mu_K(y) = \begin{cases} 
0, & \text{if } y < a \\
\frac{y-a}{b-a}, & a \leq y \leq b \\
\frac{b-y}{b-c}, & b \leq y \leq c \\
0, & \text{if } y > c 
\end{cases}
$$

(1)

Considering two TFNs, $K_1$ and $K_2$, where $K_1 = (a_1, b_1, c_1)$ and $K_2 = (a_2, b_2, c_2)$. Then, their basic operational laws are as follows:

$$
K_1 \oplus K_2 = (a_1, b_1, c_1) \oplus (a_2, b_2, c_2) = (a_1 + a_2, b_1 + b_2, c_1 + c_2)
$$

(2)

$$
K_1 \otimes K_2 = (a_1, b_1, c_1) \otimes (a_2, b_2, c_2) = (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2)
$$

(3)

$$
(a_1, b_1, c_1)^{-1} = (1/c_1, 1/b_1, 1/a_1)
$$

(4)

The extent analysis method for estimating the synthetic degree value was originally introduced by Chang (1996). In this research study, Chang extent analysis has been utilized, since compared to other FAHP approaches, it is rather simple. While there are certain problems which are associated with Chang extent analysis and it was pointed out by Wang, Luo, and Hua (2007), and has been illustrated by taking help of three numerical examples. Further Wang et al. (2007) have suggested some corrections with suitable suggestions in the paper. As suggested by Wang et al. (2007), the authors have considered the corrections in Chang’s extent analysis. Here, it is worth mentioning that for ranking of the fuzzy numbers, authors are using total integral value method (Liou & Wang, 1992). Let $K_{ij} = (a_{ij}, b_{ij}, c_{ij})$ be a TFN. Then, the steps involved in calculations of FAHP are as follows:

**Step 1:** A pairwise comparison of attributes is formed using the fuzzy numbers, which is made of lower, mid, and upper bound values in a particular level of hierarchy structure as shown in Figure 1.

**Step 2:** The fuzzy synthetic extent value for the $i$th object is defined as:

### Table 1. Fuzzy scale of preferences (Anagnostopoulos, Gratziou, & Vavatsikos, 2007).

| Linguistic variables         | Crisp AHP | TFS          | Reciprocal TFS |
|-----------------------------|-----------|--------------|----------------|
| Equally                     | 1         | (1,1,1)      | (1,1,1)        |
| Equally to Moderately       | 2         | (1,2,3)      | (1/3,1/2,1)    |
| Moderately                  | 3         | (2,3,4)      | (1/4,1/3,1/2)  |
| Moderately to Strongly       | 4         | (3,4,5)      | (1/5,1/4,1/3)  |
| Strongly                    | 5         | (4,5,6)      | (1/6,1/5,1/4)  |
| Strongly to Very Strongly    | 6         | (5,6,7)      | (1/7,1/6,1/5)  |
| Very Strongly               | 7         | (6,7,8)      | (1/8,1/7,1/6)  |
| Very Strongly to Extremely   | 8         | (7,8,9)      | (1/9,1/8,1/7)  |
| Extremely                   | 9         | (8,9,9)      | (1/9,1/9,1/8)  |
\[ SE_i = \sum_{j=1}^{n} K_{ij} \otimes \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} K_{ij} \right]^{-1} \]  \hspace{1cm} (5)

\[ \sum_{j=1}^{n} K_{ij} = \left( \sum_{j=1}^{n} a_{ij}, \sum_{j=1}^{n} b_{ij}, \sum_{j=1}^{n} c_{ij} \right) \]  \hspace{1cm} (6)

subjected to

\[ \sum_{i=1}^{m} \sum_{j=1}^{n} K_{ij} = \left( \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}, \sum_{i=1}^{m} \sum_{j=1}^{n} b_{ij}, \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \right) \]  \hspace{1cm} (7)

\[ \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} K_{ij} \right]^{-1} = \left( \frac{1}{\sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}}, \frac{1}{\sum_{i=1}^{m} \sum_{j=1}^{n} b_{ij}}, \frac{1}{\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}} \right) \]  \hspace{1cm} (8)

However, according to the suggestion of Wang et al. (2007), Equation (8) can be corrected to

\[ \left[ \sum_{i=1}^{m} \sum_{j=1}^{n} K_{ij} \right]^{-1} = \left( \frac{1}{\sum_{j=1}^{n} a_{ij} + \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}}, \frac{1}{\sum_{j=1}^{n} b_{ij} + \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij}}, \frac{1}{\sum_{j=1}^{n} c_{ij} + \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ij}} \right) \]  \hspace{1cm} (8a)

The TFN value of \( SE_i \) is calculated using the above-mentioned set of formula.
Step 3: The degree of possibility is then calculated by comparing the values of $SE_i$ and can be better expressed as

\[
V(SE_j \geq SE_i) = \text{Height}(SE_i \cap SE_j) = \mu SE_j(z)
\]

\[
= \begin{cases} 
1, & \text{if } b_j \geq b_i \\
0, & \text{if } a_i \geq c_j \\
\frac{a_i - c_j}{(b_j - c_j) - (b_i - a_i)}, & \text{otherwise}
\end{cases}
\]

(9)

The highest intersection point $P$ has $p$ as the ordinate and it lies somewhere in between $\mu SE_j$ and $\mu SE_i$ as shown in Figure 2. To compare $SE_i$ and $SE_j$, both the values of $V(SE_j \geq SE_i)$ and $V(SE_i \geq SE_j)$ are required.

Step 4: The minimum degree of possibility $p(i)$ is then calculated as

\[
V(SE_j \geq SE_i) \quad \text{for } i,j = 1,2,\ldots,k
\]

\[
V(SE \geq SE_1,SE_2,SE_3,\ldots,SE_k), \quad \text{for } i = 1,2,3,\ldots,k
\]

\[
= V[(SE \geq SE_1) \text{ and } (SE \geq SE_2) \text{ and } \ldots(SE \geq SE_k)]
\]

\[
= \min V(SE \geq SE_i) \text{ for } i = 1,2,3,\ldots,k
\]

(10)

Assuming that

\[
 p^*(A_i) = \min V(SE \geq SE_i); \quad \text{for } i = 1,2,3,\ldots,k
\]

Then, the weight vector is given by

\[
W^* = (p^*(A_1),p^*(A_2),\ldots,p^*(A_n))^T
\]

(11)

where $A_i(i = 1,2,3,\ldots,n)$ are the $n$ elements.

Step 5: With the help of normalization, the normalized weight vectors are then obtained.

\[
W = (p(A_1),p(A_2),\ldots,p(A_n))^T
\]

(12)

where $W$ thus obtained is a non-fuzzy number.

But, according to the suggestions by Wang et al. (2007), the degree of possibility as calculated by extent analysis method does not truly reflect the priorities, and so it cannot

![Figure 2. Highest intersection between $\mu SE_j$ and $\mu SE_i$ is at point $P$.](image)
be used to find out the relative importance values. Hence, the authors are not taking the Equations from (9) to (12) into account for the calculation purposes. However, the problem can be dealt with if total integral value as developed by Liou and Wang (1992) is considered for finding the priorities of synthetic extent. The equation for finding the total integral value is

\[
J_T^j(SE_j) = \frac{1}{2} \alpha (b_j + c_j) + \frac{1}{2} (1 - \alpha)(a_j + b_j) = \frac{1}{2} [\alpha c_j + b_j + (1 - \alpha)a_j]
\]  

(13)

where \(\alpha\) represents the degree of optimism of the decision-maker and its value can range from 0 to 1.

Then, the normalized priority vector \(W = (w_1, w_2, \ldots, w_n)^T\), a non fuzzy number, is calculated by following equation:

\[
w_j = \frac{J_T^j(SE_j)}{\sum_{j=1}^{n} J_T^j(SE_j)}
\]

(14)

Thus, for the calculations of FAHP equation number (5), (6), (7), and (8a) will be considered. While for finding the priority values Equations (13) and (14) will be considered.

3. QFD process

QFD was developed by Akao (1990) and his works were first implemented by Mitsubishi Industries in 1972. QFD is an efficient approach for product planning and development based on the customer requirement and technical requirement (TR). The main goal of QFD is to translate the subjective quality criteria as quoted by the customer into objective ones so that it can be quantified and can be suitably used for the design and manufacture of the product.

QFD is a structured approach for product planning and development. Using it, the development team can clearly specify the customer’s requirement and then it evaluates each proposed product systematically so as to identify the degree to which it meets the set requirements of customer (Hauser & Clausing, 1988; Wasserman, 1993).

The first phase for the implementation of QFD involves formation of house of quality (HOQ) matrix as named by Hauser and Clausing (Kahraman et al., 2003). HOQ is used to display the relationship between the voice of customers, i.e. customer requirement (WHATs) and the quality characteristics or TR (HOWs) (Chan & Wu, 2002; Chuang, 2001; Govers, 2001). In the present paper, HOQ is developed in its simplest form, whereby the technical correlation and planning matrices have been removed from the HOQ. QFD, when combining WHATs and HOWs with competitive analysis (WHYs), represents a customer-driven and market-oriented process for decision-making (Cohen 1995). Also, the voices of customers have been considered as the product characteristics, while the TRs have been considered to be process characteristics.

4. Product characteristics

As outlined by Chakraborty and Dey (2007), the very characteristic of QFD provides better judgment amongst different attributes or criteria easier as well as help to examine those criteria influencing the selection of the suitable NTM process. In order to meet the customer’s requirement fully, the decisive criteria can be linked to various achievable
independent product characteristics. The product characteristics which have been considered in this paper are:

(a) Workpiece material (WPM).
(b) Shape feature (ShFe).
(c) Surface finish (SF).
(d) Minimum surface damage depth (SDD).
(e) Tolerance (T).
(f) Corner radii (CR).
(g) Production time (PT).
(h) Product economy (PE).

In order to avoid repetition in analysis all of the above-mentioned product characteristics have been assumed to be independent of each other. Since the product characteristics can have a range of priority values, so the application of FAHP becomes essential to calculate the weights of individual product characteristics.

5. Process characteristics

The optimal NTM process selection decision depends on the extent to which its process characteristics are able to meet desired product characteristics. Thus, the process characteristics that are responsible for achieving the required product characteristics are listed as follows:

(a) Material application: It defines the frequency at which a particular NTM process is to be used for a given material.
(b) Shape application: It shows the capability of a NTM process for the generation of a specific shape on a particular material.
(c) Capital investment: It is the total initial cost and related investment needed for the installation of a particular NTM process.
(d) Tooling and fixtures: If a NTM process needs replacement of any tooling and fixture then it is covered under this product characteristic.
(e) Power requirement: It is power rating of a particular NTM process.
(f) Efficiency: It is ratio of the amount of energy applied for the material removal on NTM to the amount of input energy given to machine.
(g) Process capability: It is the capability of a particular NTM process to achieve high precision and surface finish, maximize material removal rate (MRR), minimize surface damage depth.
(h) Tool consumption: This characteristic takes care of the tool-changing requirement for machining a particular product and also takes care of any cost involved with it.

6. The QFD matrix

In today’s world, a company puts great thrust to the customer’s requirements, a company’s job in implementation of QFD is to integrate the customer requirements to TRs in a feasible manner. To start with, the QFD team first lists down the TRs which are most likely to affect the customer requirements. The customer’s insight on competitor’s product provides help to fix technical targets. And if in case, there remain any discrepancies between the
customer’s perception and the QFD team’s correlation of customer requirement and TR, then it can be easily understood by QFD matrix. The response of a company to various customer requirements may be understood by having a look at the vertical part of QFD matrix. In the proposed paper, customer requirements are considered equivalent to the product characteristics, while the TRs correspond to the process characteristics.

7. Proposed methodology

The proposed methodology encompasses the integration of FAHP and QFD for a NTM process selection problem for a particular shape feature and work material combination. The steps as outlined by Bhattacharya, Sarkar, and Mukherjee (2005) for integration of AHP and QFD have been slightly modified for the said purpose and are as follows:

Step 1: Identify the various customer requirements i.e. product characteristics.
Step 2: Identify all the TRs i.e. process characteristics.
Step 3: Using the expert knowledge of a QFD team, a central relationship matrix is constructed.
Step 4: The expert judgments of the three experts are taken in a pairwise comparison matrix and then an arithmetic mean of expert judgments are calculated for individual comparison of customer requirement.
Step 5: Using FAHP, the level of importance (normalized weight vectors) of various customer requirements, i.e. product characteristics are calculated.
Step 6: Level of importance of all the individual TRs, i.e. process characteristics are calculated using equation:

$$w_q = \frac{1}{m} \sum_{p=1}^{m} R_{pq} c_p$$

where \(w_q\) is level of importance of the \(q\)th TR \((q = 1, 2, \ldots, n)\); \(R_{pq}\) is the quantified relationship between the \(p\)th customer requirement and the \(q\)th technical criteria in the central relationship matrix; and \(c_p\) is the importance weighing of the \(p\)th customer requirement.

Step 7: The level of importance of various TRs as calculated in previous step is then normalized using the equation:

$$\overline{w}_q = \frac{w_q}{\sum_{q=1}^{n} w_q} \times 100$$

Step 8: By utilizing FAHP method, the pairwise comparison between various NTM processes is done based on each TR which correspond better to original preference scale of crisp AHP (Lamata, 2004; Zhu et al., 1999) as enlisted in Table 1.
Step 9: The normalized weight vectors \((w_{pq})\) value is evaluated for each NTM process based on various TRs.
Step 10: The overall score of various NTM processes is calculated using the equation:

$$S_q = \sum_{q=1}^{n} \overline{w}_q w_{pq}$$
where $S_q$ is the overall score of the $q$th NTM process alternative ($q = 1, 2, \ldots, n$), $w_q$ is the normalized level of importance of the $q$th technical criteria ($q = 1, 2, \ldots, n$); and $w_{pq}$ is the normalized weight vector value of the $q$th alternative based on the $p$th technical criteria.

**Step 11:** Since the process capability has been sub-divided in five parts viz. surface finish, corner radii, production time, tolerance, and minimum surface damage depth, so step 10 is repeated for five times to calculate the overall scores of various NTMs on all the five capabilities.

**Step 12:** An average score of all alternatives have been calculated for ranking. The average score has been calculated by averaging the scores obtained on the basis of various process capabilities.

The various NTM processes are ranked in the descending order of the overall score calculated. Ranking order has been done on the basis of five different process capabilities parameters viz. surface finish, corner radii, production time, tolerance, and minimum surface damage depth.

### 8. Case study

In order to validate the proposed methodology a case study of a large manufacturing company will now be analyzed. The main objective of the company is to select the best-suited NTM process for a particular shape feature and work material combination so as to achieve simplicity in manufacturing and thereby increasing productivity. An expert committee consisting of a professor (E1), an industrial expert (E2) involved in NTM manufacture and a researcher (E3) considers seven alternative NTM processes from which the best suited process is to be selected. The processes considered are: ultrasonic machining (USM), abrasive jet machining (AJM), electrochemical machining (ECM), electric discharge machining (EDM), electron beam machining (EBM), laser beam machining (LBM), and plasma arc machining (PAM). The subsequent section deals with the selection process of best suited NTM process for a specific manufacturing process in the company.

The product characteristics, i.e. the customer requirements, which have been identified for specific manufacturing processes are WPM, shape feature (ShFe), surface finish (SF), minimum surface damage depth (SDD), tolerance (T), corner radii (CR), production time (PT), and product economy (PE). In the same way, eight major process characteristics, i.e. TRs, have been identified which are: material application, shape application, capital investment, tooling and fixtures, power requirement, efficiency, process capability, and tool consumption. Further, process capability has been sub-divided in five different aspects viz. surface finish, corner radii, production time, tolerance, and minimum surface damage depth.

As per the judgment of the experts from academic, industrial and research sectors, the authors form a pairwise comparison matrix of eight criteria to get their weight vectors. Table 2 of $8 \times 8$ elements, is constructed, using FAHP, to measure the normalized weight vectors for each product characteristics. These fuzzy assessment scores have been obtained from experts by using the means of questionnaire and converting their ideas in terms of linguistic variables. Experts E1, E2, and E3 gave their opinions on the evaluation of product characteristics, which are enlisted in Table 2. Fuzzy arithmetic mean was then taken for the pairwise comparison given by experts and these mean values are then used to determine the weights of criteria based on FAHP.
| Criteria | WPM                  | ShFe                  | SF                    | SDD                  | T                    | CR                    | PT                    | PE                    |
|----------|----------------------|-----------------------|-----------------------|----------------------|----------------------|-----------------------|-----------------------|-----------------------|
| WPM      | E1 (1,1,1)           | (1,1,1)               | (1,2,3)               | (2,3,4)              | (1,2,3)              | (2,3,4)               | (2,3,4)               | (6,7,8)               |
|          | E2 (1,1,1)           | (1,1,1)               | (1,1,1)               | (2,3,4)              | (1,1,1)              | (1,2,3)               | (1,1,1)               | (5,6,7)               |
|          | E3 (1,1,1)           | (1,1,1)               | (1,2,3)               | (1,2,3)              | (1,2,3)              | (1,2,3)               | (1,2,3)               | (6,7,8)               |
| ShFe     | E1 (1,1,1)           | (1,1,1)               | (1,2,3)               | (1,2,3)              | (1,2,3)              | (3,4,5)               | (3,4,5)               | (4,5,6)               |
|          | E2 (1,1,1)           | (1,1,1)               | (1,2,3)               | (1,1,1)              | (2,3,4)              | (2,3,4)               | (2,3,4)               | (3,4,5)               |
|          | E3 (1,1,1)           | (1,1,1)               | (1,2,3)               | (1,1,1)              | (2,3,4)              | (4,5,6)               | (3,4,5)               | (5,6,7)               |
| SF       | E1 (1/3,1/2,1)       | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (2,3)               | (1,2,3)               | (1,2,3)               | (3,4,5)               |
|          | E2 (1,1,1)           | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (1,1,1)              | (2,3,4)               | (2,3,4)               | (1,1,1)               |
|          | E3 (1/3,1/2,1)       | (1,1,1)               | (1,1,1)               | (1,1,1)              | (2,3,4)              | (4,5,6)               | (3,4,5)               | (4,5,6)               |
| SDD      | E1 (1/4,1/3,1/2)     | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (1/3,1/2,1)          | (1,2,3)               | (1,2,3)               | (1/5,1/4,1/3)         |
|          | E2 (1/4,1/3,1/2)     | (1,1,1)               | (1,1,1)               | (1,1,1)              | (1/3,1/2,1)          | (2,3,4)               | (2,3,4)               | (1/4,1/3,1/2)         |
|          | E3 (1/3,1/2,1)       | (1,1,1)               | (1,1,1)               | (1,1,1)              | (1/4,1/3,1/2)        | (1,1,1)               | (2,3,4)               | (1/6,1/5,1/4)         |
| T        | E1 (1/3,1/2,1)       | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (1,1,1)              | (1,2,3)               | (1,2,3)               | (3,4,5)               |
|          | E2 (1,1,1)           | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (1,1,1)              | (1,2,3)               | (1,2,3)               | (4,5,6)               |
|          | E3 (1/4,1/3,1/2)     | (1/3,1/2,1)           | (1,1,1)               | (1,1,1)              | (1,1,1)              | (1,2,3)               | (1,2,3)               | (2,3,4)               |
| CR       | E1 (1/4,1/3,1/2)     | (1/5,1/4,1/3)         | (1/3,1/2,1)           | (1,1,1)              | (1/3,1/2,1)          | (1,1,1)               | (1,1,1)               | (1,2,3)               |
|          | E2 (1,1,1)           | (1/4,1/3,1/2)         | (1/4,1/3,1/2)         | (1/4,1/3,1/2)        | (1/4,1/3,1/2)        | (1,1,1)               | (1,1,1)               | (2,3,4)               |
|          | E3 (1/3,1/2,1)       | (1/5,1/4,1/3)         | (1,1,1)               | (1,1,1)              | (1/4,1/3,1/2)        | (1,1,1)               | (1,1,1)               | (1,1,1)               |
| PT       | E1 (1/4,1/3,1/2)     | (1/5,1/4,1/3)         | (1/3,1/2,1)           | (1,1,1)              | (1/3,1/2,1)          | (1,1,1)               | (1,1,1)               | (1,2,3)               |
|          | E2 (1,1,1)           | (1/4,1/3,1/2)         | (1/4,1/3,1/2)         | (1,1,1)              | (1/4,1/3,1/2)        | (1,1,1)               | (1,1,1)               | (1,1,1)               |
|          | E3 (1/3,1/2,1)       | (1/5,1/4,1/3)         | (1/4,1/3,1/2)         | (1,1,1)              | (1/4,1/3,1/2)        | (1,1,1)               | (1,1,1)               | (1,1,1)               |
| PE       | E1 (1/8,1/7,1/6)     | (1/6,1/5,1/4)         | (1/5,1/4,1/3)         | (3,4,5)              | (5,1/4,1/3)          | (1/3,1/2,1)           | (1/3,1/2,1)           | (1,1,1)               |
|          | E2 (1/7,1/6,1/5)     | (1/5,1/4,1/3)         | (1/4,1/3,1/2)         | (2,3,4)              | (6,1/5,1/4)          | (1/4,1/3,1/2)         | (1,1,1)               | (1,1,1)               |
|          | E3 (1/8,1/7,1/6)     | (1/7,1/6,1/5)         | (1/6,1/5,1/4)         | (4,5,6)              | (1/4,1/3,1/2)        | (1,1,1)               | (1/4,1/3,1/2)         | (1,1,1)               |
After this, for the calculations of FAHP equation number (5), (6), (7), and (8a) have been considered on the mean fuzzy evaluation values as enlisted in Table 2, and hence the TFN values of eight criteria are obtained as follows:

\[
SE_1(WPM) = (14.33, 19.33, 24.33) \otimes (1/(14.33 + 117.6), 1/93.067, 1/(24.33 + 71.7)) = (0.108, 0.207, 0.253)
\]

\[
SE_2(ShFe) = (14.66, 19.33, 24) \otimes (1/(14.66 + 117.6), 1/93.067, 1/(33.24 + 71.7)) = (0.11, 0.207, 0.25)
\]

\[
SE_3(SF) = (9.77, 13, 16.66) \otimes (1/(9.77 + 117.6), 1/93.067, 1/(16.66 + 71.7)) = (0.076, 0.139, 0.188)
\]

\[
SE_4(SDD) = (6.233, 7.927, 10.194) \otimes (1/(6.233 + 117.6), 1/93.067, 1/(10.194 + 71.7)) = (0.05, 0.085, 0.124)
\]

\[
SE_5(T) = (9.861, 13.111, 16.833) \otimes (1/(9.861 + 117.6), 1/93.067, 1/(16.833 + 71.7)) = (0.077, 0.14, 0.19)
\]

\[
SE_6(CR) = (5.427, 6.538, 8.361) \otimes (1/(5.427 + 117.6), 1/93.067, 1/(8.361 + 71.7)) = (0.044, 0.07, 0.104)
\]

\[
SE_7(PT) = (5.661, 6.722, 8.388) \otimes (1/(5.661 + 117.6), 1/93.067, 1/(8.388 + 71.7)) = (0.046, 0.072, 0.104)
\]

\[
SE_8(PE) = (5.767, 7.1, 8.827) \otimes (1/(5.767 + 117.6), 1/93.067, 1/(8.827 + 71.7)) = (0.046, 0.076, 0.109)
\]

Following the integral value approach and using Equation (13) and taking degree of optimism as 0.5, the integral values are calculated. Further, normalization is performed using Equation (14) to determine the weights of criteria. Table 3 enlists both integral values and the corresponding weights of product characteristics. The weights thus obtained are non-fuzzy numbers.

| Product characteristics | Integral value (J) | Priority weight (w) |
|-------------------------|-------------------|---------------------|
| WPM                     | 0.1943556         | 0.196343            |
| ShFe                    | 0.1942672         | 0.196253            |
| SF                      | 0.1361697         | 0.137562            |
| SDD                     | 0.0862859         | 0.087168            |
| T                       | 0.1372994         | 0.138703            |
| CR                      | 0.072259          | 0.072998            |
| PT                      | 0.0737739         | 0.074528            |
| PE                      | 0.0772329         | 0.078022            |
Table 4. Scale of interrelationship.

| Scale value | Significance               |
|-------------|---------------------------|
| 0           | No relationship           |
| 1           | Very weak relationship    |
| 3           | Slightly weak relationship|
| 5           | Moderately weak           |
| 9           | Strong relationship       |

Table 4 enlists the scale values for the interrelationships existing between customer requirement and TR. These values of weights as enlisted in Table 3 are then used by QFD experts to calculate the weights of individual TRs as enlisted in Table 5. The scale of relationship has been chosen on the basis of relationship that exists between the customer requirements versus TR.

The next step would be to find out the ranking of various NTM processes viz. USM, AJM, ECM, EDM, EBM, LBM, and PAM based on various TRs. These comparisons are based on the available literatures viz. Chakraborty and Dey (2007) (Table 3) (set of comparisons value required to generate surface of revolution feature on aluminum).

**Matrix 1:** With respect to ‘material application’ (Aluminum)

\[
[T_1] = \begin{bmatrix}
(1,1,1) & (2,3,4) & (1/4,1/3,1/2) & (1/4,1/3,1/2) & (1/4,1/3,1/2) & (1/4,1/3,1/2) & (1/4,1/3,1/2) & (1/5,1/4,1/3) \\
(1/4,1/3,1/2) & (1,1,1) & (1/3,1/2,1) & (1/3,1/2,1) & (1/3,1/2,1) & (1/3,1/2,1) & (1/3,1/2,1) & (1/4,1/3,1/2) \\
(2,3,4) & (1,2,3) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(2,3,4) & (1,2,3) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(2,3,4) & (1,2,3) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(3,4,5) & (2,3,4) & (1,2,3) & (1,2,3) & (1,2,3) & (1,2,3) & (1,2,3) & (1,1,1)
\end{bmatrix}
\]

**Matrix 2:** With respect to ‘surface of revolution’

\[
[T_2] = \begin{bmatrix}
(1,1,1) & (1,1,1) & (1/4,1/3,1/2) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(1,1,1) & (1,1,1) & (1/4,1/3,1/2) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(2,3,4) & (2,3,4) & (1,1,1) & (1,2,3) & (1,2,3) & (1,2,3) & (1,2,3) & (1,1,1) \\
(1,1,1) & (1,1,1) & (1/3,1/2,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(1,1,1) & (1,1,1) & (1/3,1/2,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(1,1,1) & (1,1,1) & (1/3,1/2,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1,1,1) & (1/3,1/2,1) \\
(1,2,3) & (1,2,3) & (1,1,1) & (1,2,3) & (1,2,3) & (1,2,3) & (1,2,3) & (1,1,1)
\end{bmatrix}
\]

The same form of comparisons are performed for all the NTM processes and Table 6 enlists the weights of various NTM processes based on various TRs as has been obtained by using the method of FAHP.

The values of different TRs are then used to calculate the overall scores of various NTM processes. Overall scores have been calculated keeping in view that the process capability can be characterized under surface finish, corner radii, production time,
Table 5. QFD matrix for NTM process selection.

| Customer requirement          | Material application | Shape application | Capital investment | Tooling and fixture | Power requirement | Efficiency | Process capability | Tool consumption | Scale |
|------------------------------|----------------------|-------------------|--------------------|---------------------|-------------------|------------|-------------------|-----------------|-------|
| Workpiece material           | 9                    | 1                 |                    |                     | 5                 |            |                   |                 | 0.196343 |
| Shape feature                | 1                    | 9                 |                    |                     | 5                 |            |                   |                 | 0.196253 |
| Surface finish               | 1                    |                   |                    |                     |                   |            |                   |                 | 0.137562 |
| Surface damage depth         | 5                    |                   |                    |                     |                   |            |                   |                 | 0.087168 |
| Tolerance                    | 1                    | 9                 |                    |                     |                   |            |                   |                 | 0.138703 |
| Corner radii                 | 9                    | 3                 |                   |                     | 3                 |            |                   |                 | 0.072998 |
| Production time              | 5                    | 3                 | 3                  | 3                   | 5                 |            |                   |                 | 0.074528 |
| Production economy           | 2.100                | 2.992             | 0.702              | 1.590               | 0.234             | 0.596      | 3.951             | 3.951           | 0.078022 |
| Degree of importance for selection criteria | 16.939 | 24.126 | 5.661 | 12.823 | 1.887 | 4.808 | 31.864 | 1.887 |

Degree of importance for selection criteria (%)

Normalized degree of importance for selection criteria (%)
tolerance and minimum surface damage depth. The selection of process capability parameter is mutually exclusive in nature. Table 7 enlists the calculation of overall score of various NTM processes based on only surface finish as a process capability feature.

Table 7. Overall scores of the various NTM processes based on surface finish as process capability.

| Technical requirement                  | Weight (%) | Importance weights for NTMs | USM | AJM | ECM | EDM | EBM | LBM | PAM |
|----------------------------------------|------------|-------------------------------|-----|-----|-----|-----|-----|-----|-----|
| Material application                   | 16.939     | 0.092                         | 0.150 0.150 0.150 0.150 0.150 0.239 |
| Shape application                      | 24.127     | 0.107                         | 0.150 0.150 0.150 0.150 0.150 0.209 |
| Capital investment                     | 5.661      | 0.110                         | 0.150 0.150 0.150 0.150 0.150 0.074 |
| Tooling and fixture                    | 12.823     | 0.147                         | 0.150 0.150 0.150 0.150 0.150 0.065 |
| Power requirement                      | 1.887      | 0.192                         | 0.150 0.150 0.150 0.150 0.150 0.054 |
| Efficiency                             | 4.808      | 0.152                         | 0.150 0.150 0.150 0.150 0.150 0.213 |
| Process capability                     | 31.864     | 0.217                         | 0.150 0.150 0.150 0.150 0.150 0.058 |
| Tool consumption                       | 1.887      | 0.196                         | 0.150 0.150 0.150 0.150 0.150 0.067 |
| Overall score (%)                      | 15.077     | 13.374                        | 20.068 13.280 13.906 10.977 13.601 |

Table 8. Overall score of various NTM processes based on different process capabilities.

| Process capability                     | USM | AJM | ECM | EDM | EBM | LBM | PAM |
|----------------------------------------|-----|-----|-----|-----|-----|-----|-----|
| Surface finish                         | 0.150 0.133 0.132 0.138 0.109 0.135 |
| Corner radii                           | 0.126 0.126 0.193 0.177 0.117 0.106 0.152 |
| Production time                        | 0.136 0.094 0.203 0.164 0.111 0.103 0.184 |
| Tolerance                              | 0.153 0.097 0.162 0.170 0.144 0.113 0.158 |
| Minimum surface damage depth           | 0.139 0.143 0.203 0.134 0.120 0.107 0.151 |
| Average score                          | 0.141 0.118 0.192 0.155 0.126 0.108 0.156 |
| Overall rank                           | 4    6   1   3   5   7   2  |
While Table 8 enlists the overall scores obtained by various NTM processes based on all the different sorts of process capabilities.

9. Result and discussions

Using the proposed methodology, the problem of NTM process selection has been solved and the average scores as obtained by various NTM processes reveal that ECM is the best suited process for the required application. From the scores as enlisted in Table 8, it can be inferred that the present methodology helps not only in selecting the best suited NTM process but it also provides a basis for the comparative study of alternate NTM processes. The final results as obtained on the basis of different process capabilities are listed in Table 8. When the top three alternatives are analyzed based on different process capabilities, it is observed that ECM ranks out to be first preference for selection but in case of tolerance, it is ranked second. For aluminum machining, EDM is better suited than ECM as far as degree of tolerance is concerned. Also, PAM ranks second, if production time and minimum surface damage depth are taken into account, while it comes at third place, if corner radii and tolerance are taken into account, but it falls out at fourth rank if surface finish is considered. EDM ranks third, if production time and minimum surface damage depth are considered, while it ranks second, if corner radii are considered, also it ranks sixth if surface finish is considered as process capability. Considering the average scores of all the process capabilities into account through this proposed methodology NTM processes can be ranked as ECM > PAM > EDM > USM > EBM > AJM > LBM.

The objective of the present research work has been to search out the most appropriate NTM process from the various NTM processes in terms of their relative degree of importance depending on five distinct considered process capabilities. The results have been shown in Figure 3.

Thus, the present study amongst the various alternate NTM helps in deploying the correct available technologies by acutely focusing on the process characteristics.

In order to make the present methodology more robust, sensitivity analysis has been performed by considering the MRR measure of alternatives. The sensitivity analysis has been carried out based on mathematical model proposed by Bhattacharya, Sarkar, and Mukherjee (2002a, 2002b) as given in Equation (15).

$$SI_k = [(αPFM_k) + (1 - α)MRM_k]$$

where

$$MRM_k = \frac{1}{MRF_k \sum_{k=1}^{n} MRF^{-1}}$$

where $MRM$ is the material removal measure, $MRF$ is the material removal factor, $PFM$ is the performance factor measure, $SI$ is the sensitivity index, $α$ is the performance factor decision weight, and $n$ is the number of alternatives.

The PFM values, i.e. the priority value of each alternative is taken as the performance measure value as obtained from average score of various NTM processes. The $MRF$ values are the standard MRR values for the different alternatives and $MRMs$ have been calculated using Equation (16) to obtain a non-dimensional quantity. By doing this one can combine MRR values, i.e. cardinal measures, with the $PFM$ values, i.e. ordinal measure, as shown in Equation (15). The unit of $MRF$ is mm$^3$/min, whereas $MRM$ values are non-dimensional entities. Selection of proper value of $α$ is an important issue,
Figure 3. Graphical display of alternatives based on different process capabilities.

Figure 4. Graphical display of alternatives based on sensitivity analysis.
which needs to be jointly decided by design engineer, production manager and maintenance engineer. However, the value of $\alpha$ depends upon the decision-maker’s preference between material removal measure and performance factor measure. Thus, a sensitivity plot helps to properly analyze the effect of $\alpha$ in NTM process selection problem. So using Equation (15) variation of SI with $\alpha$ can be plotted for all alternatives as shown in Figure 4.

In Figure 4, the x-axis represents the variation in value of $\alpha$, while the y-axis represents the variation in value of SI. A closer look of the plot reveals that for $\alpha > 0.5$, the order of NTM processes are similar to that found by using FAHP and QFD, i.e. ECM > PAM > EDM > USM > EBM > AJM > LBM.

Further coefficient of variance has been calculated on the average scores as obtained from the present methodology and it was found that the coefficient of variance was 21.27%. While the coefficient of variance for the scores as obtained by Chakraborty and Dey (2007) was 17.25%. It further fortifies that the present methodology is a better method of ranking NTM processes than ranking of the NTM processes on the basis of QFD alone.

10. Conclusion

The present research work emphasizes on the selection of NTM processes taking into consideration, the product and process characteristics and utilizing the pragmatic approach of FAHP and QFD. From this research study, the following conclusions can be drawn:

(i) Based on various process capabilities viz. (a) Surface finish – ECM (20.068%) is very much applicable followed by USM (15.077%). (b) Corner radii – ECM (19.5522%) is more reliable, which is followed by EDM (17.952%). (c) Production time – ECM (20.415%) is more reliable followed by PAM (18.539%). (d) Tolerance – EDM (17.4%) which is followed by ECM (16.6446%). (e) minimum Surface damage – ECM (20.435%), which is followed by PAM (15.159%).

(ii) Also, sensitivity analysis has been carried out to verify the proposed technique. From this analysis, it is corroborated that the ranking achieved through combined method of FAHP and QFD is same as obtained in this analysis.

(iii) Based on the average scores the order of ranking as obtained by our methodology is ECM > PAM > EDM > USM > EBM > AJM > LBM. However, from the existing literature, the order was ECM > PAM > USM > EDM = LBM > EBM > AJM. Thus, it can be inferred that ranking of top two NTM processes matches well with that of past researchers. However, a little amount of discrepancies do remain with the intermediate rankings and that can be because of difference of opinions regarding the subjective judgments of the decision makers.

(iv) Co-efficient of variance on the average scores for the present methodology was 21.27% while it came out to be 17.25% for the scores as obtained by previous researchers.

Thus, for the help of a decision-maker, the proposed methodology provides an objective method for an accurate NTM process selection with proper satisfaction of overall customer requirements and the involved uncertainties. The considered case study has been used for demonstrating the application of proposed methodology.
One of the main assumptions of the proposed methodology is related with the QFD matrix, where the interrelationships between the TRs i.e. roof matrix has not been considered, since it requires a large amount of time for consensus building within the QFD team. Since the technical correlation and planning matrices have not been considered, so the QFD matrix can rather be called as priority matrix.

The development of an expert system which should be flexible enough such that its database can be updated from time to time and should be based on FAHP and QFD remains an important aspect for future scope. Also, the development of methodologies for the selection of NTM processes using other fuzzy MCDM methods, such as fuzzy ELECTRE, fuzzy PROMETHEE, and fuzzy ANP remains another aspect that needs a serious attention.

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