Application of Fuzzy TOPSIS for evaluating machining techniques using sustainability metrics

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Abstract. Sustainable processes and techniques are getting increased attention over the last few decades due to rising concerns over the environment, improved focus on productivity and stringency in environmental as well as occupational health and safety norms. The present work analyzes the research on sustainable machining techniques and identifies techniques and parameters on which sustainability of a process is evaluated. Based on the analysis these parameters are then adopted as criteria’s to evaluate different sustainable machining techniques such as Cryogenic Machining, Dry Machining, Minimum Quantity Lubrication (MQL) and High Pressure Jet Assisted Machining (HPJAM) using a fuzzy TOPSIS framework. In order to facilitate easy arithmetic, the linguistic variables represented by fuzzy numbers are transformed into crisp numbers based on graded mean representation. Cryogenic machining was found to be the best alternative sustainable technique as per the fuzzy TOPSIS framework adopted. The paper provides a method to deal with multi criteria decision making problems in a complex and linguistic environment.

1. Introduction
The most elemental definition of sustainability is the one where sustainability is defined as a quality which enables us to preserve, keep or maintain something. The definition of sustainability had a more environmental aspect to it but in the recent past sustainability has new dimensions to it such as; environment, social, economical and even technology. The idea of sustainability was introduced in the Brundtland Report (1987) with the objective of meeting the needs of the present without compromising on the resources of the future. When it comes to implementing sustainability concepts, there are multiple domains where the concepts are applicable. One such domain is manufacturing. Manufacturing plays a huge role in the human lifestyle and our dependence on manufactured products is something which cannot be ignored. It does not include only production but a number of industrial activities. This brings manufacturing to the centre stage when it comes to adopting sustainable practices for achieving the larger goal of sustainable development since at every step/stage of the process, natural resources are being consumed. This introduces the concept of sustainability and sustainable development into the realm of manufacturing. At first instance, raw material and energy consumption might come across as the only areas which need focus but a closer look reveals the additional need to consider emissions, waste generation and working conditions also into the sustainability picture [1].

Sustainable manufacturing is defined by the United States Department of Commerce as “The creation of manufactured products that use processes that minimize negative environmental impact, conserve
energy and natural resources, are safe for employees, communities and consumers and are economically sound”. The idea is to do more with less [2]. The adoption of sustainable development in manufacturing offers industry a cost effective route to improving economic, environmental, and social performance (the three pillars of sustainability). More and more organizations are incorporating methods to assess their level of sustainability and further improve on it. In India, the National Manufacturing Competitiveness Council (NMCC) provides a forum to energize the growth of manufacturing industries. A country like India, faces challenges in resource constraints and hence it becomes imperative that organizations focus on sustainable processes. However there are certain challenges faced by the small and medium enterprises (SME). It is the huge investment and lack of awareness related to the benefits associated with sustainable activities [3]. It has been observed that off late there has been an improvement in awareness and we see enterprises moving towards adopting metrics to evaluate the sustainability of their practices. It has also been observed that the rate at which measures are being implemented in manufacturing is comparatively slow. This is where technology can be harnessed. The gap between science, policy-making, and implementation has to be bridged.

With the implementation of sustainability principles in production processes, companies of all sizes have the potential to save money and improve their environmental performance even if their production stays in the same range or decreases. The source of the problem is that manufacturing companies are traditionally focused on short-term financial considerations, with little thought to the longer-term view especially when it comes to environment. However, a long term business strategy essential in order to achieve sustainable development and ultimately survival. In order to overcome the challenges facing the sector, it is vital that companies adopt sustainable production practices [4]. A review of the existing literature on sustainable machining highlights the following key focus area’s where industries need to invest resources and efforts in order to achieve better sustainability

- Minimizing waste
- Recycling and Re-usage of waste [5]
- Using resources such as materials, water and energy more efficiently,
- Avoiding or at least improving management of metalworking fluids, swarf, lubricating oils, hydraulics oils etc
- Adopting lean manufacturing and other sustainable engineering techniques [6]
- Improve working conditions
- Using best practices in machining
- Train employees about sustainable practices

Manufacturing in itself is a domain of vast proportions that encompasses different processes and techniques such as casting, metal forming, welding, metal cutting etc. Sustainability concepts can be applied in all the above mentioned area’s with the objective of improving the sustainability level of the organization. The present study focuses on the metal cutting practices in the industry and reviews the advancements in the machining processes and practices. The applicability of this study can however be extended to other manufacturing area’s as well. Research and Development in the field of machine tool-cutting tool-part interaction has resulted in innovations that have enhanced both productivity and quality of machined products. However, the current trend towards higher productivity via high-speed machining (HSM) inevitably leads to higher temperatures in both the cutting tool and the part and affecting them both. Thermal management of machining operations for enhancement of both, the tool-life and machined part quality is not new. The development of cooling and/or lubrication techniques and temperature management of the process, is still considered as a novel and emerging direction to study. Industrial metal cutting applications widely utilize conventional cooling lubrication fluids (CLF), such as: air, oils and aqueous emulsions, to counter the extremely high levels of heat generated in the cutting zone during the machining process, even though they are environment unfriendly, health hazardous and relatively costly. It has been reported that 15 % of the total machining costs are due to the use of CLF emulsions, while percentage of tool costs is a lot lower; around 4 % [7]. It is not only the cost aspect but the risks conventional cutting fluids pose to the environment and operator safety that is driving research in the area of alternative machining techniques. Conventional oil-based CLF have therefore been identified as the major non-sustainable element of the machining process. Hence
the review of literature related to alternative machining techniques reveals emergence of processes that either eliminate or optimize the use of conventional cutting fluids. For example, dry machining is an alternative technique that aims at machining without cutting fluids. The results for certain applications of this technique have shown promise but the scope of application is limited, especially for hard to machine materials like titanium where thermal management itself is an issue. Minimum Quantity Lubrication (MQL) and High Pressure Jet Assisted Machining (HPJAM) are techniques that seek to optimize the application of CLF in the cutting zone by minimal application and high pressure application respectively. Cryogenic machining on the other hand is a technique that replaces the conventional CLF’s and uses cryogenic fluids that are more efficient and environment friendly. All of the above alternative machining techniques have their own set of pro’s and con’s. The need is to evaluate these techniques on basic sustainability criteria’s and identify the most sustainable technique amongst them. Hence a decision making technique to evaluate alternatives is required for the analysis [8-15].

Multi-Criteria Decision Making (MCDM) methods have been used in the past by researchers for analyzing complex real world problems, due to the functionality and ease of these techniques in judging different alternatives on the basis of several criteria’s [16-19]. Duckstein et al. [17] formulated basic steps in the MCDM methodology such as; defining the problem and criteria’s; data collection; identifying feasible/efficient alternatives; developing a payoff matrix; selecting the appropriate solving method; incorporating the decision makers preference; choosing the best alternative. Under the classification of MCDM methods, the distance based method known as Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was chosen for the present study.

2. Methodology

2.1. Fuzzy TOPSIS

The present study proposes to use the methodology given by the authors Deng & Yong (2006) in their research on plant location selection. The various sustainable machining techniques were evaluated on certain criteria’s to identify the most appropriate technique of them all. On analysing the research done in the field of sustainable machining, the present study identified the following criteria’s as those that have been adopted by authors to evaluate sustainability. These are environmental impact, energy consumption, safety, personal health, waste management and cost. These parameters were further adopted in the MCDM methodology as criteria’s (Table 2) to evaluate the alternatives (Table 1).

| Table 1. Alternatives evaluated in the analysis. |
|-------------------------------------------------
| Alternatives | Description                      |
| A1           | Dry Machining                   |
| A2           | High Pressure Jet Assisted Machining (HPJAM) |
| A3           | Cryogenic Machining             |
| A4           | MQL Machining                   |

| Table 2. Criteria used to evaluate alternatives in the analysis. |
|---------------------------------------------------------------|
| Criteria | Description               | Benefit / Cost |
|---------|---------------------------|----------------|
| C1      | Environment friendliness  | Benefit        |
| C2      | Low Energy Consumption    | Benefit        |
| C3      | Safety & Personnel Health | Benefit        |
| C4      | Low Cost                  | Benefit        |
| C5      | Product Quality           | Benefit        |
A panel of three experts (shown as E1, E2, E3) was constituted for the analysis and select the most suitable alternative. The experts were asked to rate the criteria using linguistic variable having five values as shown in table 3. This table also shows the importance weight in fuzzy terms and crisp values based on graded mean integration representation. Also the experts were asked to rate the alternatives using linguistic variables having five values as shown in Table 3. This table also shows the importance weight in fuzzy terms and crisp values based on graded mean integration representation Eq(1)

\[ P(\bar{A}) = \frac{1}{6}(a_1 + 4 \times a_2 + a_3) \]  

(1)

**Table 3.** Linguistic variables for the importance weight and for rating of each criterion and their crisp values.

| Linguistic Variables | Importance weight for criteria | Crisp values | Linguistic Variables | Preference for alternative | Crisp values |
|----------------------|--------------------------------|--------------|----------------------|---------------------------|--------------|
| Very low (VL)        | (0, 0.1, 0.3)                  | 0.1167       | Very poor (VP)       | (0, 0, 3)                 | 0.5000       |
| Low (L)              | (0.1, 0.3, 0.5)                | 0.3000       | Poor (P)             | (0, 3, 5)                 | 2.8333       |
| Medium (M)           | (0.3, 0.5, 0.7)                | 0.5000       | Fair (F)             | (2, 5, 8)                 | 5.0000       |
| High (H)             | (0.5, 0.7, 0.9)                | 0.7000       | Good (G)             | (5, 7, 10)                | 7.1667       |
| Very high (VH)       | (0.7, 0.9, 1.0)                | 0.8833       | Very good (VG)       | (7, 10, 10)               | 9.5000       |

Table 4. The importance weight of the criteria.

|         | E1 | E2 | E3 | Weight (W_j) |
|---------|----|----|----|--------------|
| C1      | VH | H  | VH | 0.82220      |
| C2      | M  | M  | H  | 0.56667      |
| C3      | H  | H  | H  | 0.70000      |
| C4      | M  | M  | L  | 0.43333      |
| C5      | VH | H  | VH | 0.82220      |
| C6      | H  | H  | M  | 0.63333      |

**Step 1:** The experts used the linguistic weighting variables for shown in table 3 to assess the importance of the criteria. Further the aggregated weights were calculated. The aggregated importance weight \( W_j \) for criterion \( C_j \) assessed by the committee of \( k \) experts can be evaluated as:

\[ W_j = \frac{\sum_{t=1}^{k} W_{jt}}{k} \]  

(2)

**Step 2:** Further the experts used the linguistic weighting variables shown in table 4 to rate the alternatives under each criteria based on preference. Next the aggregated rating \( R_{ij} = (o_{ij}, p_{ij}, q_{ij}) \), of an alternative \( A_i \) with respect to the criteria \( C_j \) was obtained using the below formula.

\[ R_{ij} = \frac{\sum_{t=1}^{k} r_{ijt}}{k} \]  

(3)

**Step 3:** The weighted decision matrix and its normalized form was constructed. The decision matrix was formulated using the below equation, the weights \( W_j \) are incorporated from the previous steps to obtain the decision matrix.
Values in decision matrix were then normalized using the below equation

\[ V = \left[ v_{ij} \right]_{m \times n} \]

\[ v_{ij} = \frac{s_{ij}}{\sum_{i=1}^{m} (s_{ij})^2} \]

**Step 4:** The ideal positive and negative solutions were evaluated. The positive ideal solution and negative ideal solution can be defined as

\[ \tilde{v}_j^+ = \max_{i=1,2,...,m} (v_{ij}) \] and \[ \tilde{v}_j^- = \min_{i=1,2,...,m} (v_{ij}) \]

**Step 5:** The distance of each alternative from \( A^+ \) and \( A^- \) was calculated using the relations given below along with the closeness coefficient

\[ d^+ = \sqrt{\sum_{j=1}^{n} (\tilde{v}_j - \tilde{v}_j^+)^2} \]

\[ d^- = \sqrt{\sum_{j=1}^{n} (\tilde{v}_j - \tilde{v}_j^-)^2} \]

\[ C_i = \frac{d^-}{d^+ + d^-}, I = 1,2, ..., m \]

3. Results and discussion

Using the importance weights and preference ratings defined in Table 3 and Table 4, the criteria’s determined from the literature review were assessed in Table 5 and the aggregated importance weight for each criteria was evaluated and shown in the last column of Table 5. This associates a numeric value with each criteria. Similarly, the experts evaluated each alternative on each criteria and aggregated ratings were established. Finally the weighted decision matrix and its normalized form were tabulated in Table 6. Eventually the method proceeded to determine the ideal positive and ideal negative solutions as well as the distance of each alternative from these solutions (Table 7). This helped the authors in evaluating the closeness of each alternative to the ideal solution, which is the fundamental behind the TOPSIS approach. In the end, calculation of the closeness coefficients revealed that alternative 3, cryogenic machining has the highest closeness coefficient and is the most favourable alternative.

**Table 5.** Experts rating of alternatives under different criteria.

| Criteria | Alternatives | E1 | E2 | E3 | Aggregate Rating |
|----------|--------------|----|----|----|------------------|
| C1       | A1           | VG | G  | VG | 8.7222           |
|          | A2           | G  | M  | G  | 6.4445           |
|          | A3           | VG | G  | G  | 7.9445           |
|          | A4           | G  | G  | G  | 7.1667           |
| C2       | A1           | VG | G  | G  | 7.9445           |
|          | A2           | G  | G  | G  | 7.1667           |
|          | A3           | VG | VG | G  | 8.7222           |
|          | A4           | F  | F  | F  | 5.0000           |
| C3       | A1           | G  | VG | G  | 7.9445           |
|          | A2           | F  | F  | G  | 5.7222           |
|          | A3           | VG | G  | VG | 8.7222           |
Criteria | Alternatives | Experts | | | E1 | E2 | E3 | Aggregate Rating |
--- | --- | --- | --- | --- | --- | --- | --- | --- |
C4 | A4 | G | G | G | 7.1667 |
C5 | A1 | VG | G | G | 7.9445 |
C6 | A1 | VG | G | G | 7.9445 |

Table 6. Normalized decision matrix.

| Alternatives | C1 | C2 | C3 | C4 | C5 | C6 |
| --- | --- | --- | --- | --- | --- | --- |
| A1 | 0.57254 | 0.54111 | 0.53165 | 0.40539 | 0.63670 | 0.57377 |
| A2 | 0.42302 | 0.48814 | 0.38293 | 0.34684 | 0.45860 | 0.41327 |
| A3 | 0.52148 | 0.59409 | 0.58369 | 0.70719 | 0.34284 | 0.57377 |
| A4 | 0.47043 | 0.34056 | 0.47960 | 0.46395 | 0.51649 | 0.41327 |

Table 7. Distance measurement and closeness coefficient.

| Alternatives | d⁺ | d⁻ | cc |
| --- | --- | --- | --- |
| A1 | 0.31080 | 0.40351 | 0.56490 |
| A2 | 0.51109 | 0.11577 | 0.18468 |
| A3 | 0.29827 | 0.46566 | 0.60956 |
| A4 | 0.43001 | 0.27792 | 0.39258 |

4. Conclusion
On the basis of the existing research on sustainable manufacturing techniques and methods, the metrics on which the sustainability of a technique is evaluated were identified after reviewing the literature. Modern day sustainable manufacturing techniques in the area of metal cutting such as cryogenic machining, dry machining, HPJAM and MQL machining were identified and analyzed. A fuzzy TOPSIS methodology was then adopted which evaluated these alternative manufacturing techniques on the basis of sustainability criteria’s identified through literature and discussion with practitioners. Crisp numbers were adopted using the canonical representation of fuzzy numbers that themselves represented linguistic terms. This enables avoidance of complex arithmetic operations on triangular fuzzy numbers, which saves time. Hence on the basis of computing the positive ideal solution, negative ideal solution and closeness coefficient elucidated in the TOPSIS approach, the study identified cryogenic machining as the most suitable and sustainable manufacturing technique amongst the alternatives. The present study expanded the applicability of Fuzzy TOPSIS and provided a framework to industrial professionals and practitioners on how to evaluate machining techniques on the basis of fundamental sustainability parameters. The findings and methodology of the study can be utilized in future for process selection on the basis of sustainability.
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