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Research Article

Biodegradable Cutting Fluids Evaluation for Sustainable Machining Processes

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Abstract: Sustainably selecting the best cutting fluid among alternatives, considering various weighted criteria or factors, is a complex problem encountered by machine operators in engineering workshops worldwide. The aim of this work is to utilize the Multi-Attribute Utility Theory (MAUT) decision-making model for biodegradable cutting fluids selection in a machine shop. The objectives of the work include carrying out a step-by-step process of the MAUT method on biodegradable cutting fluid alternatives. Therefore, this study utilizes the MAUT decision-making method for selecting the best biodegradable cutting fluid among a set of five (5) alternatives namely soybean oil, palm oil, polyalphaolefin, trimethylpropane trioleate and polyethylene glycol. The cutting fluids were evaluated based on criteria such as heat dissipation, stability, lubrication and cost-effectiveness. From the results, Polyalphaolefin is the best alternative, ranking first according to the global utility scoring. Therefore, Polyalphaolefin had a global utility score of 0.688, followed by Polyethylene Glycol which had a score of 0.600, followed by Trimethylpropane Trioleate which had a score of 0.588, followed by Soybean Oil which had a score of 0.363 and finally, Palm Oil which had a score of 0.263. This study provides a procedure for implementing the MAUT method of decision-making for cutting fluids selection within engineering workshops for sustainable machining practices.

Keywords**:** decision-making; multi-attribute utility theory; biodegradable; cutting fluid; ranking

1. Introduction

Products of metal working supply chains are very common in our daily lives [1–4]. These products are indispensable due to their unique properties and versatility such as strength and durability, versatility, conductivity, corrosion resistance, recyclability, good weight-to-strength ratio as well as aesthetic appeal [5,6]. As a result of these properties, these products have a high demand and are produced regularly in engineering workshops with the aid of cutting fluids [7]. Cutting fluids are important for cooling the workpiece and tool edge as well as flushing away swarf generated during the machining process. Without these fluids, the workpiece will possess rough surface finish, tool wear will be increased and subsequent premature damage of the tool will occur leading to waste in various forms [8,9]. Therefore, the fluids serve to make the machining process easier by providing lubrication, cooling and corrosion protection as well as improving surface finish and prolonging the life of the cutting edge of the tool.

When selecting cutting fluids several factors need to be considered including material compatibility, cutting operation, environmental impact, health and safety, machining conditions, tool life and surface finish, cost-effectiveness, as well as

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maintenance requirements. The material compatibility factor demands that the machine operator should ensure the fluid is compatible with the materials being machined to prevent corrosion and other adverse effects. The cutting operation factor demands that the machine operator be knowledgeable about the various cutting operations which include milling, drilling and turning, and how these operations require a viscous, lubricating and cooling cutting fluid during the machining process. The environmental impact factor takes the environmental impact of the cutting fluid into consideration, based on biodegradability, toxicity and regulatory compliance. The health and safety factor considers the potential health hazards associated with the cutting fluid, including exposure to operators and environmental impacts. The machining conditions factor demands that the machine operator properly assesses the operating conditions such as feed rate, tool material and cutting speed to ensure the selected fluid can effectively lubricate and cool the cutting process. The tool life and surface finish factor demands that cutting fluids should be chosen based on their ability to promote longer tool life and the desired surface finish on the machined parts. The cost-effectiveness factor demands that the overall cost of using the cutting fluid, including purchase price, disposal costs and potential savings from increased productivity or tool life, should be evaluated. The maintenance requirement factor demands that the maintenance of the cutting fluid should be considered including filtration, concentration control and replenishment frequency.

For maintaining sustainability while meeting these demands, the world is moving towards the use of green cutting fluids that are environmentally friendly, and still provide the required lubrication and cooling during machining processes [10]. Biodegradable cutting fluids are an eco-friendly alternative to the traditional cutting fluids. Therefore, they reduce environmental impact and promote sustainability. The biodegradability property of the cutting fluid means that the fluid can break down into natural compounds through biological processes, thereby reducing its environmental footprint. The common types of biodegradable cutting fluids are vegetable oil-based cutting fluids, esters-based fluids, and polyglycols-based fluids. The useful properties of these cutting fluids can be further improved by particle additives and chemical modification of the carboxyl group or fatty acid chain, through transesterification or epoxidation [11]. Transesterification is a versatile chemical reaction having significant industrial importance and involves the exchange of ester group from one molecule to another [13]. On the other hand, epoxidation is a valuable chemical transformation that introduces an epoxide functional group into a molecule, thereby allowing for the efficient synthesis of the epoxide [14,15].

Several researchers have applied multi-criteria decision-making methods for choosing the optimum alternative when faced with a group of similar alternatives, based on multiple criteria or factors [16,17]. This process can be described as multi-criteria decision analysis. Therefore, multi-criteria decision-making is a process used in making decisions when there are numerous criteria or factors to consider, each with its own importance or weight. The process usually involves identification of criteria, definition of alternatives, evaluation of alternatives, weighting of criteria, aggregation of criteria and finally, selection of the best alternative. Multi-criteria decision analysis has been used widely in various fields, especially engineering, management, economics, and environmental science, to aid complex decision-making processes involving multiple conflicting criteria and objectives [18–21]. Apart from MAUT, several multicriteria decision analysis methods exist for ranking and making choices between alternatives. They include Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), MACBETH, PROMETHEE, ELECTRE, TOPSIS etc. Using MAUT is advantageous because the method considers multiple criteria simultaneously, allowing for a more comprehensive evaluation of alternatives. This holistic approach can lead to more informed decisions that take into account various aspects of a problem. Moreover, MAUT allows decision-makers to incorporate qualitative as well as quantitative criteria, making it suitable for a wide range of decision contexts. It can accommodate diverse perspectives and preferences, promoting inclusivity in decision-making.

The aim of this work is to utilize the Multi-attribute Utility Theory (MAUT) decision-making model for biodegradable cutting fluids selection in a machine shop. The objectives of the work include carrying out a step-by-step process of the MAUT method on biodegradable cutting fluid alternatives. Therefore, this study provides a procedure for implementing the MAUT method of decision-making for cutting fluids selection within engineering workshops for sustainable machining practices.

2. Methodology

This study evaluates five (5) alternative cutting fluids, in order to select the best alternative based on certain criteria. The cutting fluids that were evaluated are soybean oil, palm oil, polyalphaolefin, trimethylpropane trioleate and polyethylene glycol. The cutting fluids were evaluated based on certain criteria which reflect specific goals, user needs and business objectives. The criteria include: heat dissipation (to be maximized), stability (to be maximized), lubrication (to be maximized), cost-effectiveness (to be maximized). Each criterion was scored on a scale of 1 to 5 for each of the alternative cutting fluids.

Heat dissipation was measured by the degree to which the cutting tool forms built up edges or wears with and without the use of the cutting fluids. Lubrication was measured by assessing the degree of surface roughness or smoothness of the surface of workpiece after cutting with the various cutting fluids. The stability of the cutting fluids was assessed based on their tendency to foam during machining operations. Excessive foaming indicates fluid degradation or contamination, affecting its stability and performance. Cost of cutting fluid was assessed based on the price of purchasing the cutting fluids and the frequency of repurchase in cases of cutting fluid deterioration. The choices of weights for each criterion were subjective, based on the relative importance of each criterion as judged by the author.

2.1 *Preference and Indifference Relations*

Consider a set of alternatives, A. An alternative of set A is evaluated based on function U and obtains a utility score U(a) as shown in Figure 1. The utility score is used for ranking all the alternatives from the most optimal to the worst, in terms of optimality.

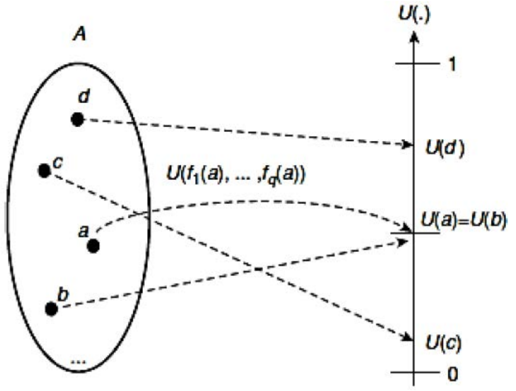

Figure 1. Representation of the ranking of the set A using the MAUT model[22].

The indifference and preference relations among the substitutes or alternatives of the set A, are defined as follows:

$$\forall \mathrm{a}, \mathrm{b} \in \mathrm{A} : \mathrm{aPb} \Leftrightarrow \mathrm{U}(\mathrm{a}) > \mathrm{U}(\mathrm{b}) : \text{a is preferred to b} \tag{1}$$

$$\forall \mathrm{a}, \mathrm{b} \in \mathrm{A} : \mathrm{aIb} \Leftrightarrow \mathrm{U}(\mathrm{a}) = \mathrm{U}(\mathrm{b}) : \text{a and b are indifferent} \tag{2}$$

2.2 *Normalization of Raw Data*

Normalization or rescaling is usually based on the maximum and minimum performance of the substitutes or alternatives on a particular criterion. Denoting by f the set of q criteria f_j ($j = 1, \ldots, q$).

According to Ishizaka and Nemery 22 for maximizing the criterion,

$$f_j^{'}(a_i) = \frac{f_j(a_i) - min(f_j)}{\max(f_j) - min(f_j)} \tag{3}$$

where, $f_j^{'}(a_i)$ is the normalization of $f_j(a_i)$. $f_j(a_i)$ is the evaluation of the alternative, a_i, based on criteria, f, $min(f_j)$ is the minimum performance of the alternatives on each criterion, $max(f_j)$ is the maximum performance of the alternatives on each criterion.

According to Ishizaka and Nemery[22] for minimizing the criterion,

$$f_j^{'}(a_i) = 1 + \left(\frac{min(f_j) - f_j(a_i)}{\max(f_j) - min(f_j)} \right) \tag{4}$$

2.3 *The MAUT Additive Model*

Denoting by f the set of q criteria f_j (j = 1, …, q). To avoid scale problems, the evaluations of the alternatives $f_j(a_i)$ are first transformed into marginal utility contributions, denoted by U_j. The marginal utility scores are aggregated with a weighted sum or addition to obtain the global utility scores.

According to Ishizaka and Nemery[22] the general additive utility function can be written as follows:

$$\forall a_i \in A : U(a_i) = U(f_1(a_i), \cdots, f_q(a_i)) = \sum_{j=1}^{q} U_j(f_j(a_i)) \cdot w_j \tag{5}$$

where $U_j(f_j) \geq 0$ is usually a non-decreasing function, and w_j represents the weight of criterion f_j. The weights represent the amount a decision maker is ready to give up on one criterion so as to gain one unit on another criterion. They satisfy the normalization constraint[22]:

$$\sum_{j=1}^{q} w_j = 1 \tag{6}$$

2.4 *Composition and Properties of Ranked Cutting Fluids*

The cutting fluids that were ranked include soybean oil, palm oil, polyalphaolefin, trimethylpropane trioleate and polyethylene glycol. The soybean oil ranked consists of about 51% linoleic acid, about 23% oleic acid, about 10% palmitic acid, about 3% stearic acid and about 4.5% alpha-linoleic acid. It has a melting point of −16 °C. At room temperature, the density of soybean oil is about 0.922 g/cm^3 and its viscosity is about 65 cP. The palm oil ranked consists of about 44% palmitic acid, 39% oleic acid, 10% linoleic acid, 4% stearic acid. It has a melting point of about 33 °C. At room temperature, the density of palm oil is about 0.89 g/cm^3 and its viscosity is about 50 cP. The polyalphaolefin ranked has a pour point of about −50 °C, density of about 0.8 g/cm^3, and viscosity of 16 cP. The trimethylpropane trioleates has a pour point of about −40 °C, density of about 0.95 g/cm^3 and viscosity of about 47.5 cP. The polyethylene glycol ranked has a melting point of about 17 °C, density of about 1.12g/cm^3 and viscosity of about 1.79 cP.

3. Results and Discussion

This section presents the results of applying the equations of the Methodology section to the cutting fluid selection problem. The cutting fluids that were evaluated are soybean oil, palm oil, polyalphaolefin, trimethylpropane trioleate and polyethylene glycol. The criteria against which the cutting fluids were assessed are heat dissipation (H), stability (S), lubrication (L), cost-effectiveness (C). The heat dissipation criterion is the degree to which the cutting fluid cools the workpiece and cutting tool during the machining operation. The stability criterion is the degree to which the cutting fluid resists oxidation, microbial growth and degradation. The lubrication criterion refers to the degree to which the cutting fluid is viscous, forms films, and resists breakdown under heat and pressure. While the cost-effectiveness criterion is the degree to which the cutting fluid can be easily purchased, including its performance over time which determines if the cutting fluid will be repurchased. The objective is to maximize all the criteria. The performance of the five (5) cutting fluids on these criteria is shown in Table 1.

Table 1. Performance Table.

Raw Data	H	S	L	C
Objective	MAX	MAX	MAX	MAX
Soybean Oil	2	2	1	5
Palm Oil	1	1	2	4
Polyalphaolefin	5	4	3	3
Trimethylpropane Trioleate	3	5	4	2
Polyethylene Glycol	4	3	5	1

The normalized performance table calculated using Equation (3) is shown in Table 2. Table 2 represents the rescaled performances in Table 1, in order to ensure utility scores of between 0 and 1.

Table 2. Normalized Scores Table.

Normalized Scores	H	S	L	C
Soybean Oil	0.250	0.250	0.000	1.000
Palm Oil	0.000	0.000	0.250	0.750
Polyalphaolefin	1.000	0.750	0.500	0.500
Trimethylpropane Trioleate	0.500	1.000	0.750	0.250
Polyethylene Glycol	0.750	0.500	1.000	0.000

Assuming that the marginal utility functions of all criteria are linear. The marginal utility scores for each cutting fluid, considering the various criteria are shown in Table 3.

Table 3. Marginal Utility Scores Table.

Marginal Utility Scores	H	S	L	C
Soybean Oil	0.250	0.250	0.000	1.000
Palm Oil	0.000	0.000	0.250	0.750
Polyalphaolefin	1.000	0.750	0.500	0.500
Trimethylpropane Trioleate	0.500	1.000	0.750	0.250
Polyethylene Glycol	0.750	0.500	1.000	0.000

The weights attached to each criterion are shown in Table 4. The weights represent the decision maker's preference for a particular criterion.

Table 4. Weights for Criteria.

	H	S	L	C
Weights	0.3	0.15	0.3	0.25

From Table 4, the heat dissipation criterion has a weight of 0.3, the stability criterion has a weight of 0.15, the lubrication criterion has a weight of 0.3, while the cost-effectiveness criterion has a weight of 0.25. The final global utility scores and ranking of the alternatives are shown in Table 5, considering the weights attached to each criterion.

Table 5. Global Utility Scores and Ranking.

Final Utility Scores	Scores	Rank
Soybean Oil	0.363	4
Palm Oil	0.263	5
Polyalphaolefin	0.688	1
Trimethylpropane Trioleate	0.588	3
Polyethylene Glycol	0.600	2

Figure 2 is a bar chart that shows the final global utility scores for each of the alternative cutting fluids.

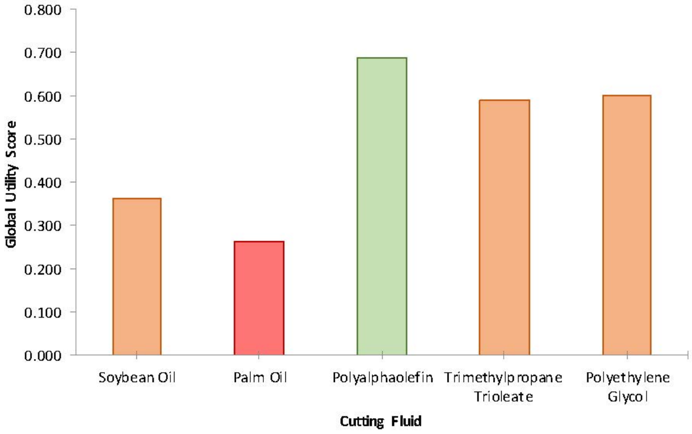

Figure 2. Final Global Utility Score.

Figure 3 is a stacked bar chart that shows the final global utility scores, as well as how each of the alternative cutting fluids performed with respect to the criteria and criteria weights.

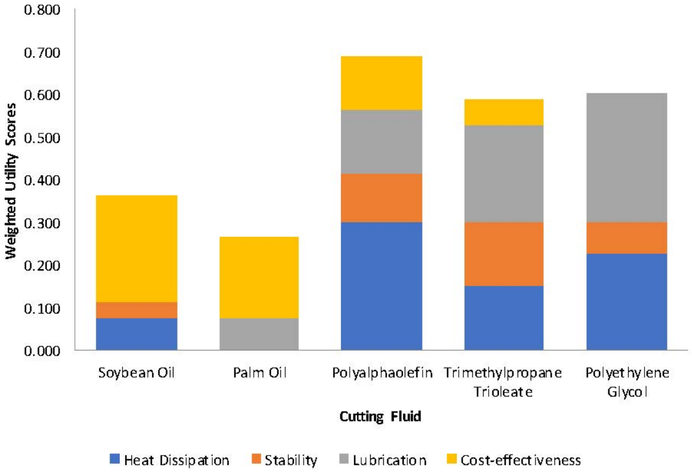

Figure 3. Chart Showing Global Utility Scores and Criteria.

From Figures 2 and 3, Polyalphaolefin is the best biodegradable cutting fluid alternative considering heat dissipation, stability, lubrication and cost-effectiveness. Moreover, Polyalphaolefin had a global utility score of 0.688, followed by Polyethylene Glycol which had a score of 0.600, followed by Trimethylpropane Trioleate which had a score of 0.588, followed by Soybean Oil which had a score of 0.363 and finally, Palm Oil which had a score of 0.263. Therefore, the Polyalphaolefin had the best combination of heat dissipation, stability, lubrication and cost-effectiveness, in terms of its properties.

Polyalphaolefins offer superior cutting fluid performance for several reasons 14, 15. Their excellent thermal stability allows them to perform effectively at high temperatures without deterioration. They have high oxidation resistance which prolongs the lifespan of the cutting fluid, reducing the need for frequent fluid changes, thereby lowering maintenance cost and downtime. Polyalphaolefins are also less volatile than other cutting fluids, thereby reducing the loss of fluid due to evaporation and improving cutting efficiency and cost-effectiveness. Moreover, their excellent lubricity reduces friction between the cutting tool and workpiece resulting in smoother cuts, improved surface finish and reduced tool wear.

4. Conclusions

Machining processes can generate a lot of heat, and impart rough surface finish to the workpiece, if the proper cutting fluids are not used. Traditional mineral-based cutting fluids are toxic to machine operators, as well as the environment. For sustainability, researchers are considering the use of biodegradable cutting fluids which are more operator friendly and have no negative impact on the environment. Therefore, in selecting biodegradable cutting fluids, several factors of varying weights need to be considered. This study utilized the Multi-attribute Utility Theory (MAUT) decision-making method for selecting the best biodegradable cutting fluid among a set of five (5) alternatives namely soybean oil, palm oil, polyalphaolefin, trimethylpropane trioleate and polyethylene glycol. The cutting fluids were evaluated based on criteria such as heat dissipation, stability, lubrication and cost-effectiveness. From the results, Polyalphaolefin is the best alternative, ranking first according to the global utility scoring. Therefore, Polyalphaolefin had a global utility score of 0.688, followed by Polyethylene Glycol which had a score of 0.600, followed by Trimethylpropane Trioleate which had a score of 0.588, followed by Soybean Oil which had a score of 0.363 and finally, Palm Oil which had a score of 0.263. This study provides a procedure for implementing the MAUT method of decision-making for biodegradable cutting fluid selection by engineers. Further research can involve the utilization of other multi-criteria decision-making methods for cutting fluid alternatives evaluation.

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Confilict of Interest

There is no conflict of interest for this study.

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