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Multi-Attribute Utility Theory Modelling for Product Design Evaluation

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Abstract: At the core of every manufacturing supply chain that contributes to national economic development, are the products the supply chain produces and delivers. The design engineers of these products handle the process of generating ideas, solving complex problems, as well as overseeing the development and refinement of the products, to meet the needs of the consumer. Oftentimes, design engineers have to evaluate multiple product designs to select the best alternative. Therefore, this study utilized the Multi-attribute Utility Theory (MAUT) for selecting the best filing cabinet design among a set of five (5) alternatives. The designs were evaluated based on criteria such as profitability, aesthetics, feasibility and maintainability. From the results, Filing Cabinet 4 (FC4) was the best alternative, ranking first according to the global utility scoring. Therefore, FC4 had a score of 0.608, followed by FC5 which had a score of 0.550, followed by FC3 which had a score of 0.525, followed by FC1 which had a score of 0.517 and finally, FC2 which had a score of 0.250. The product design evaluation problem was modelled in the RightChoice software, and the results from the analytical calculations were confirmed. Sensitivity analyses of the global utility scores of the filing cabinet designs when the weights of various criteria are varied was also conducted in the RightChoice software, and they indicated that the results are robust. This study provides a procedure for implementing the MAUT method of decision-making for product design evaluation by design engineers.

Keywords: *Decision-making, multi-attribute utility theory, product design, ranking, rightChoice.*

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I. INTRODUCTION

The importance of manufacturing supply chains for national economic development of countries cannot be overemphasized [1]; [2]; [3]. Countries like the United States, China, Germany etc. which are known for their manufacturing prowess, are experiencing national economic development in leaps and bounds [4]. Product design is at the core of every manufacturing supply chain that positively contributes to national economic development and environmental sustainability. Design engineers are constantly faced with the problem of providing the most profitable product designs, that are of high quality, meet consumer demand and are environmentally sustainable. Therefore, more than one criterion is simultaneously considered when making product design decisions. A mix of those product design criteria makes the product design evaluation process complex for the design engineer, necessitating the need for appropriate decision-making methods. The ancient Greek philosopher Aristotle has pointed out that excellence is never an accident. It is always the result of high intention, sincere effort, and intelligent execution; it represents the wise choice of many alternatives choice, not chance, determines your destiny. Therefore, multi-criteria decision methods and their hy-

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brids constitute a group of methods that are useful for aiding design engineers in making wise choices, no matter the complexity of the decision problem [5]; [6]; [7]; [8]. This aspect of operations research is very vast, with several methods and method combinations for solving peculiar problems in decision-making.

The multi-criteria decision methods can be applied to manufacturing supply chain optimization in many ways, including supplier selection, materials selection, production scheduling, routing, inventory management, pricing strategies as well as evaluation of various product designs, to name a few [9]; [10]. The end goal is the improvement and optimization of the manufacturing supply chain, in order to obtain predictable supply chain performance. [11]; [12].

Metals have been used to make indispensable products, tools, and machinery since time immemorial [13]; [14]; [15] . Products of metalworking processes are important and evident in our daily lives [16]. This is why the optimization of metalworking supply chains, especially with respect to product design evaluation, is vital.

The aim of this work is to develop and utilize the Multi-attribute Utility Theory (MAUT) model for product design evaluation in a metalworks manufacturing supply chain. The objectives of the work include carrying out a step-by-step process of the MAUT method on filing cabinet design alternatives, as well as conducting sensitivity analyses to determine the robustness of the results. Therefore, this study provides a procedure for implementing the MAUT method of decision-making for product design evaluation by design engineers.

II. METHODOLOGY

This study evaluates five (5) alternative product designs of a filing cabinet in a metalworking supply chain, in order to select the best alternative based on certain criteria. The calculations were conducted in Microsoft Excel and the MAUT model for sensitivity analysis was built using the RightChoice software. The filing cabinet designs were evaluated based on design goals, user needs and business objectives. The criteria include: profitability (to be maximized), aesthetics (to be maximized), feasibility (to be maximized), functionality (to be maximized), maintainability (to be maximized). Each criterion was scored on a scale of 1 to 5.

A. Preference and Indifference Relations

Consider a set of alternatives, A. Each alternative of set A is evaluated on the basis of function U and receives a utility score U(a) as shown in Figure 1. This utility score allows the ranking of all alternatives from best to worst.

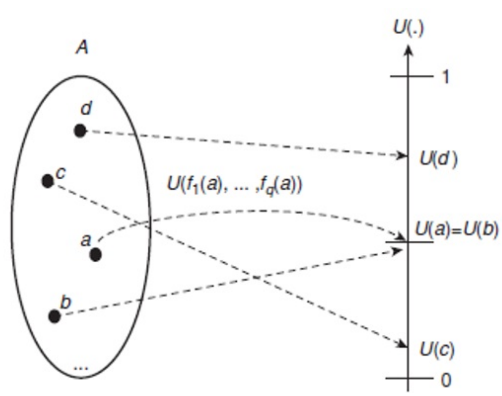

Fig. 1. Representation of the ranking of the set A using the MAUT model [17].

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

$\forall a, b \in A : aPb \Leftrightarrow U(a) > U(b)$: a is preferred to b.....(1)

$\forall a, b \in A : aIb \Leftrightarrow U(a) = U(b)$: a and b are indifferent ....(2)

B. Normalization of Raw Data

Normalization or rescaling is usually based on the minimum and maximum performance of the alternatives on each criterion. Denoting by f the set of q criteria fj (j = 1, , q). According to Ishizaka and Nemery [17] for maximizing the criterion,

$$f'_j(a_i) = \frac{f_j(a_i) - \min(f_j)}{\max(f_j) - \min(f_j)} \Big| .....(3)$$

where, $f'_j(a_i)$ is the normalization of $f_j(a_i) \cdot f_j(a_i)$ is the evaluation of the alternative, ai, 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 [17] for minimizing the criterion,

$f'_j(a_i) = 1 + \left(\frac{\min(f_j) - f_j(a_j)}{\max(f_j) - \min(f_j)}\right)$.....(4)

C. The MAUT Additive Model

Denoting by f the set of q criteria fj (j = 1, , q). To avoid scale problems, the evaluations of the alternatives fj(ai) are first transformed into marginal utility contributions, denoted by Uj. The marginal utility scores are aggregated with a weighted sum or addition to obtain the global utility scores. According to Ishizaka and Nemery [17] the general additive utility function can be written as follows:

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

where $U_j(f_j) \geq 0$ is usually a non-decreasing function, and wj represents the weight of criterion fj. 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 [17]:

$\sum_{j=1}^{q} w_j = 1$....(6)

D. Sensitivity Analysis

The RightChoice software was used for conducting the sensitivity analysis, to determine the impact of changing certain data on the final ranking of the alternatives. RightChoice can be used in calculating marginal utility scores, global utility scores and the ranking of the alternatives. RightChoice can also perform a sensitivity analysis to illustrate when the ranking will be modified after changing a specific weight value.

III. RESULTS AND DISCUSSION

This section presents the results of applying the equations of the Materials and Methods section to the product design evaluation problem. The criteria against which the filing cabinets (FC1, FC2, FC3, FC4 and FC5) were assessed are profitability (P), aesthetics (A), feasibility (F), maintainability (M). The profitability criterion is the degree to which the design yields profit. The aesthetics criterion is the degree to which the design is visually appealing. The feasibility criterion is the degree to which the design can be easily constructed. While the maintainability criterion is the degree to which the product can be restored to a working condition after damage. The performance of the five (5) filing cabinet designs on these criteria is shown in Table 1.

TABLE 1
PERFORMANCE TABLE.

Raw Data	P	A	F	M
FC1	3	3	4	2
FC2	2	5	2	3
FC3	4	2	3	5
FC4	5	4	3	2
FC5	3	2	4	4

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	P	A	F	M
FC1	0.333	0.333	1	0
FC2	0	1	0	0.333
FC3	0.667	0	0.5	1
FC4	1	0.667	0.5	0
FC5	0.333	0	1	0.667

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

TABLE 3
MARGINAL UTILITY SCORES TABLE

Marginal Utility Scores	P	A	F	M
FC1	0.333	0.333	1	0
FC2	0	1	0	0.333
FC3	0.667	0	0.5	1
FC4	1	0.667	0.5	0
FC5	0.333	0	1	0.667

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

TABLE 4
WEIGHTS FOR CRITERIA

	P	A	F	M
Weights	0.3	0.2	0.35	0.15

From Table 4, the profitability criterion has a weight of 0.3, the aesthetics criterion has a weight of 0.2, the feasibility criterion has a weight of 0.35, while the maintainability criterion has a weight of 0.15. 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
FC1	0.517	4
FC2	0.25	5
FC3	0.525	3
FC4	0.608	1
FC5	0.55	2

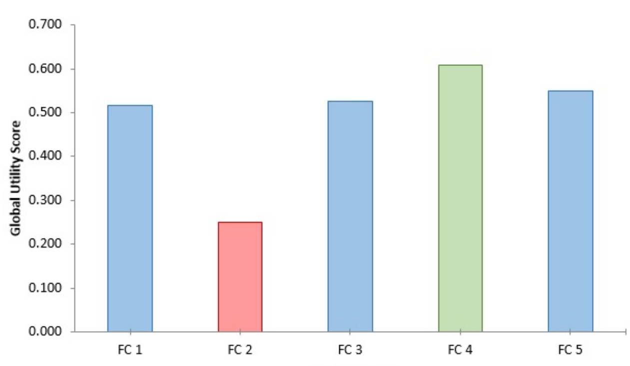

Fig. 2. Final Global Utility Score

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

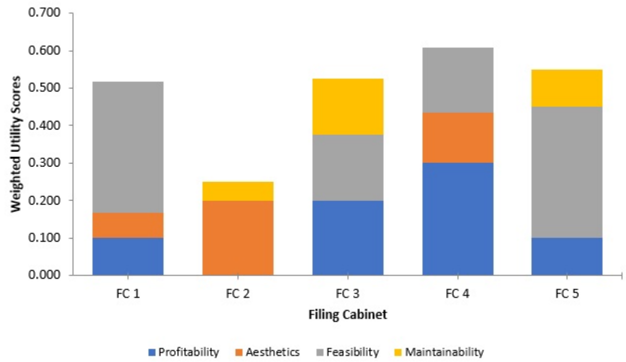

Fig. 3. Chart Showing Global Utility Scores and Criteria.

From Figure 2 and Figure 3, Filing Cabinet 4 (FC4) is the best alternative considering profitability, aesthetics, feasibility and maintainability. Moreover, FC4 had a global utility score of 0.608, followed by FC5 which had a score of 0.550, followed by FC3 which had a score of 0.525, followed by FC1 which had a score of 0.517 and finally, FC2 which had a score of 0.250. The product design evaluation problem was modelled in the RightChoice software in order to confirm the results of the analytical calculations. Figure 4 shows the model developed in the RightChoice software.

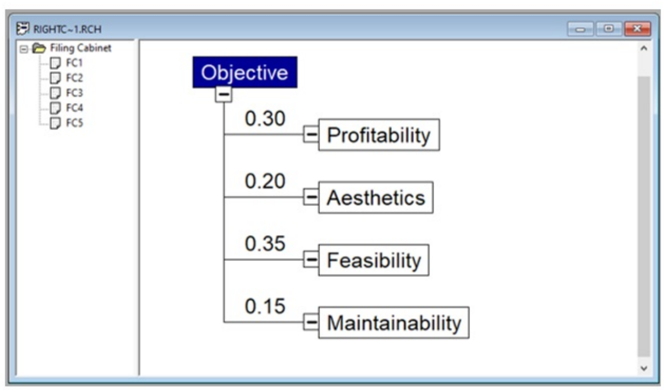

Fig. 4. RightChoice Model.

From Figure 4, the profitability criterion has a weight of 0.30, aesthetics criterion has a weight of 0.20, feasibility criterion has a weight of 0.35, and the maintainability criterion has a weight of 0.15. Figure 5 shows the results of running the RightChoice model.

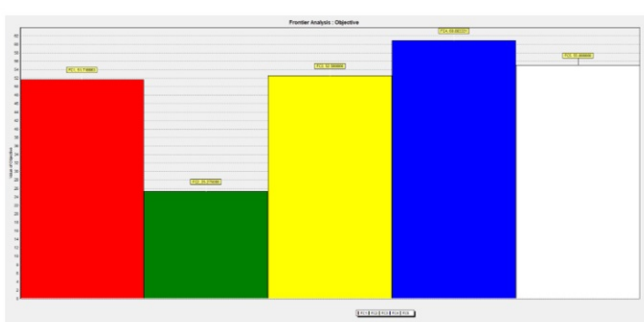

Fig. 5. RightChoice model results

From Figure 5, based on the various criteria, FC4 is the best filing cabinet design, followed by FC5, and then FC3, before FC1 and finally, FC2. This confirms the result from the analytical calculations. Figure 6 shows the sensitivity analysis of the global utility scores of the five filing cabinet designs when changing the profitability criterion.

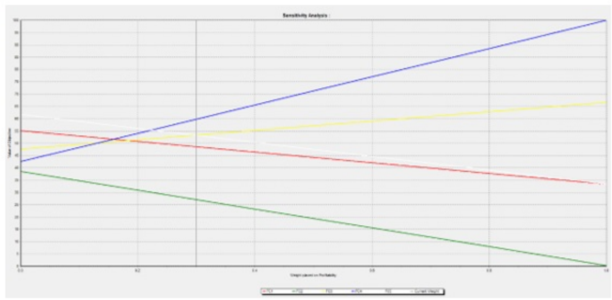

Fig. 6. Sensitivity analysis when changing the Profitability criterion.

From Figure 6, if the weight of the profitability criterion is lower than 0.225, FC5 will have the highest score and be the best alternative, otherwise, it is FC5. Figure 7 shows the sensitivity analysis of the global utility scores of the five filing cabinet designs when changing the aesthetics criterion.

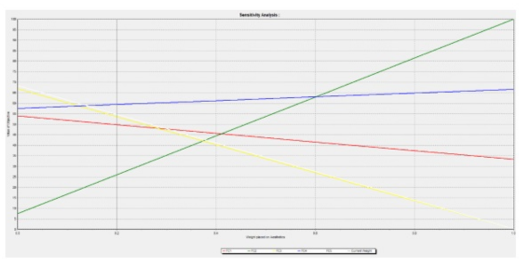

Fig. 7. Sensitivity analysis when changing the Aesthetics criterion.

From Figure 7, if the weight of the aesthetics criterion is higher than 0.6, FC2 is the best alternative. If the weight is lower than 0.6, FC4 is the best alternative. If the weight is lower than 0.15, FC5 is the best alternative. Figure 8 shows the sensitivity analysis of the global utility scores of the five filing cabinet designs when changing the feasibility criterion.

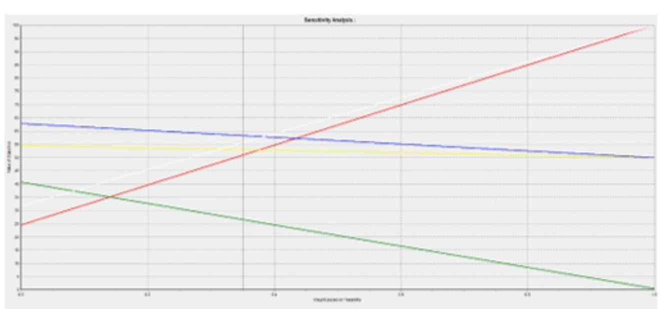

Fig. 8. Sensitivity analysis when changing the Feasibility criterion.

From Figure 8, if the weight of the feasibility criterion is greater than 0.375, FC5 is the best alternative. Otherwise, FC4 is the best alternative. Figure 9 shows the sensitivity analysis of the global utility scores of the five filing cabinet designs when changing the maintainability criterion.

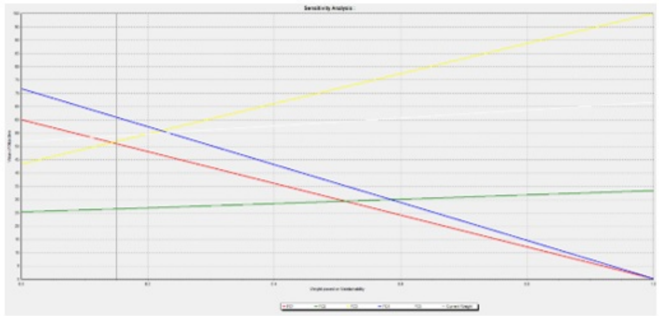

Fig. 9. Sensitivity analysis when changing the Maintainability criterion.

From Figure 9, if the weight of the maintainability criterion is less than 0.23 FC4 is the best alternative. Otherwise, FC3 is the best alternative.

IV. CONCLUSION

Decision-making is a vital aspect of operations research which, in turn, is an aspect of the industrial and production engineering practice. Design engineers are constantly faced with problems of evaluating product designs in order to find the best alternative among them. This study utilised the Multi-attribute Utility Theory (MAUT) for selecting the best filing cabinet design among a set of five (5) alternatives. The designs were evaluated based on criteria such as profitability, aesthetics, feasibility and maintainability. From the results, Filing Cabinet 4 (FC4) was the best alternative, ranking first according to the global utility scoring. Therefore, FC4 had a score of 0.608, followed by FC5 which had a score of 0.550, followed by FC3 which had a score of 0.525, followed by FC1 which had a score of 0.517 and finally, FC2 which had a score of 0.250. The product design evaluation problem was modelled in the RightChoice software and the results from the analytical calculations were confirmed. Sensitivity analyses of the global utility scores of the filing cabinet designs when the weights of various criteria are varied was also conducted in the RightChoice software, and they indicated that the results are robust. This study provides a procedure for implementing the MAUT method of decision-making for product design evaluation by design engineers. Further research can involve the utilisation of other multi-criteria decision-making methods for product design evaluation.

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