Criteria Assessment Model for Sustainable Product Development

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Criteria Assessment Model for Sustainable Product Development

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Abstract. The instability in today's market and the ever increasing and emerging demands for mass customized and hybrid products by customers, are driving companies and decision makers to seek for cost effective and time efficient improvements in their product development process. Design concept evaluation which is the end of conceptual design is one of the most critical decision points in product development. It relates to the final success of product development, because poor criteria assessment in design concept evaluation can rarely compensated at the later stages. This has led to real pressure for the adaptation of new developmental architecture and operational parameters to remain competitive in the market. In this paper, a new integrated design concept evaluation based on fuzzy-technique for order preference by similarity to ideal solution (Fuzzy-TOPSIS) is presented, and it also attempts to incorporate sustainability practices in assessing the criteria. Prior to Fuzzy-TOPSIS, a new scale of "Weighting criteria" for survey process is developed to quantify the evaluation criteria. This method will help engineers to improve the effectiveness and objectivity of the sustainable product development. Case example from industry is presented to demonstrate the efficacy of the proposed methodology. The result of the example shows that the new integrated method provides an alternative to existing methods of design concept evaluation.

1. Introduction

In today's industries, product design has become the main focus in a highly competitive environment and fast-growing global market [1]. The benchmarks used to determine the competitive advantage of a manufacturing company are customer satisfaction, shorter product development time, higher quality and lower product cost [2]. To meet this challenge, new and novel design methodologies that facilitate the acquisition of design knowledge and creative ideas for later reuse are much sought after. In the same context, Liu & Boyle [3] highlighted that the challenges currently faced by the engineering design industry are the need to attract and retain customers, the need to maintain and increase market share and profitability and the need to meet the requirements of diverse communities.

In the early phases of product development, it is important to both reduce costs and improve a product's sustainability performance [4]. Developing products with improved environmental performance is regarded as a crucial component of companies' commitment towards sustainable development. The potential benefits derived from ecodesign are constantly highlighted in the literature, and go beyond the pure environmental dimension. However, the primary focus has been positioned on evaluating those benefits in terms of product-related environmental performance, which leaves an open potential for capturing performance from a broader managerial perspective [5].

Following the identification of a market (user need), a total design system, as espoused by Pugh [6], is a systematic activity that is necessary to produce and sell a successful product to satisfy that need; the activity encompasses product, process, people and organisation. In accordance with this, Ebuomwan [7] proposed that the total design activity model consists principally of a central design core, which in turn comprises a market (user need), product design specification, conceptual design, detailed design, manufacture and sales. Pahl [8] classify the activities of designers into conceptualising, embodying, detailing and computing, drawing and collecting information. Furthermore, Finger & Dixon [9] mentioned that the mapping between the requirements of a design and the attributes of the artefact is not fully understood. Because the goal of design is to create artefacts that meet functional requirements, further fundamental research is needed on relating the attributes of designs to those functional requirements, that is, on prescribing the artefact. In addition, Chandrasegaran [10] stated that product design is a highly involved, often ill-defined, complex and iterative process and that the needs and specifications of the required artefact be-come more refined only as the design process moves to-wards its goal.

During product development, especially in the early phases, one must be aware of an environmentally conscious design process [11]. While environmental and social product characteristics can be altered at this stage to the greatest extent, knowledge about these characteristics is limited [12]. For example, the choice of product material largely determines the recycling options available or emissions produced during the use phase. The designers and engineers do not always have enough data to assess recycling options or emission impacts. This is especially relevant during the development of new materials and technologies, where no generic data is available, as compared to well-studied materials and technologies. On one hand, the high degree of uncertainty and lack of information can hinder the application of quantitative sustainability assessment tools such as Life Cycle Assessment (LCA), which is solely used to assess environmental impacts [13, 14]. On the other hand, this puts a focus on designers and engineers. They ideally have the most updated knowledge and can significantly influence the sustainability performance of the technologies they are developing, but they need instruments and tools that can be effectively used to assess the impacts of their design decisions on sustainability. Hence, the main objective of this paper is to provide automotive designers and engineers with a tool that they can use to consider sustainability when making decisions in situations that are characterized by uncertainty and a lack of information and experience

The proposed design evaluation method will integrate Fuzzy-TOPSIS with the new contribution in this research which is the scale of “Weighting criteria” and incorporating sustainability practices in order to provide the designers with an alternative. A literature search indicates that no work has been done previously on the proposed methodology in design evaluation for new product development.

The aim of the research is to develop a methodology for sustainable design evaluation that enables designers to make better-informed decisions when finalising their choice, and consequently, reduce development time and cost. This research introduces the scale of “Weighting criteria” for survey process prior to the stage of incorporating design practices and design evaluation using Fuzzy-TOPSIS.

2. Methodology

The general framework of proposed approach is as depicted in Figure 1.

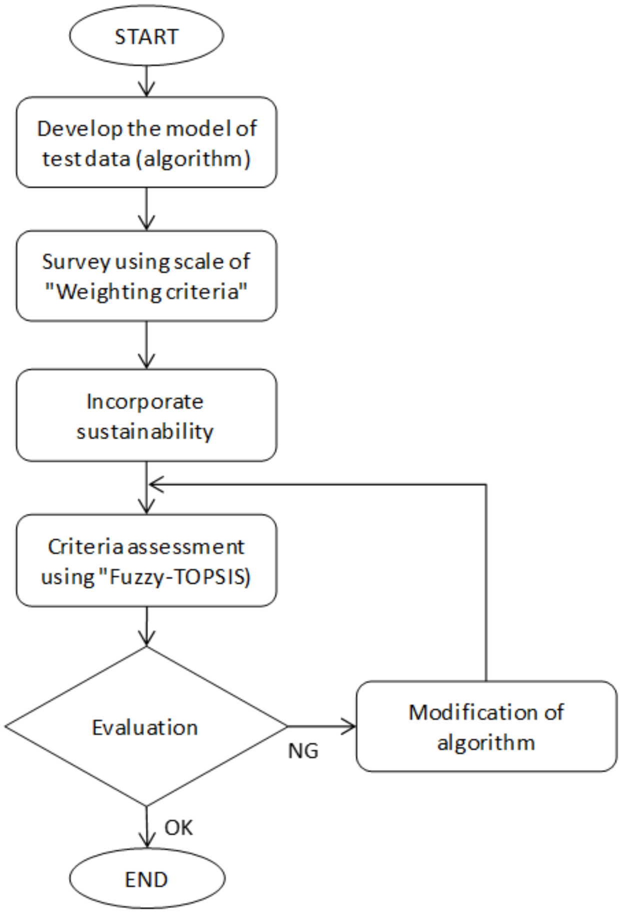

Figure 1. General framework of proposed approach

2.1. Scale of "Weighting criteria"

The scale between 0 – 10 was developed to ease the respondents' group for rating the evaluation criteria, which initially selected by the design engineers based on technical documents and the results of a prior survey. The rating value obtained from the survey then will be used to calculate the aggregate fuzzy importance weights. Table 1 describes the scale of "Weighting criteria" in more detail.

Table 1. Scale of "Weighting criteria" [15]

Numerical rating	Description
0	Absolutely useless
1	Very inadequate
2	Weak
3	Tolerable
4	Adequate
5	Satisfactory
6	Good with few drawbacks
7	Good
8	Very good
9	Exceeding the requirement
10	Ideal

2.2. Incorporating sustainability

The steps for incorporating sustainability are as follows:

- Translate customer requirements into design criteria.
- Map each design criteria to the triple bottom line of sustainability (People, Planet, Profit).
- Normalise the quantification value obtained from scale of "Weighting criteria".
- Calculate the normalised value to determine level of sustainability practices of each criteria.

2.3. Fuzzy-TOPSIS

The technique for order preference by similarity to ideal solution (TOPSIS) is a useful technique in dealing with multi attribute or multi criteria problems of decision making (MADM/MCDM) in the real world [16]. The positive ideal solution (PIS) is a solution that maximises the bene-fit criteria/attributes and minimises the cost criteria/attributes. The negative ideal solution (NIS) maximises the cost criteria/attributes and minimises the benefit criteria/attributes [17]. The best alternative is the one that is closest to the PIS and furthest from the NIS [18].

Prior to the process of rank the alternatives, relative close-ness shall be calculated. The step is described as follows.

Step 1: Identify the positive ideal solution A^+ (benefits) and negative ideal solution A^- (costs) as follows:

$$A^+ = \left(\tilde{p}_1^+, \tilde{p}_2^+, \ldots, \tilde{p}_m^+\right) \tag{1}$$

$$A^- = \left(\tilde{p}_1^-, \tilde{p}_2^-, \ldots, \tilde{p}_m^-\right) \tag{2}$$

where $\tilde{p}_{ij}$ is weighted fuzzy normalised value.

Step 2: Calculate the Euclidean distances the positive from ideal solution A^+ and the negative from ideal solution A^- for each alternative A_i, respectively as follows:

$$d_i^+ = \sum_{j=1}^{n} d\left(\tilde{p}_{ij}, \tilde{p}_{ij}^+\right) \tag{3}$$

$$d_i^- = \sum_{j=1}^{n} d\left(\tilde{p}_{ij}, \tilde{p}_{ij}^-\right) \tag{4}$$

where i = 1, …, m and $d\left(\tilde{p}_{ij}, \tilde{p}_{ij}^+\right)$ is the distance between two fuzzy numbers.

Step 3: Calculate the relative closeness ζ_i for each alternative A_i with respect to positive ideal solution:

$$\zeta_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{5}$$

The general steps of the Fuzzy-TOPSIS approach can be summarised as in Figure 2.

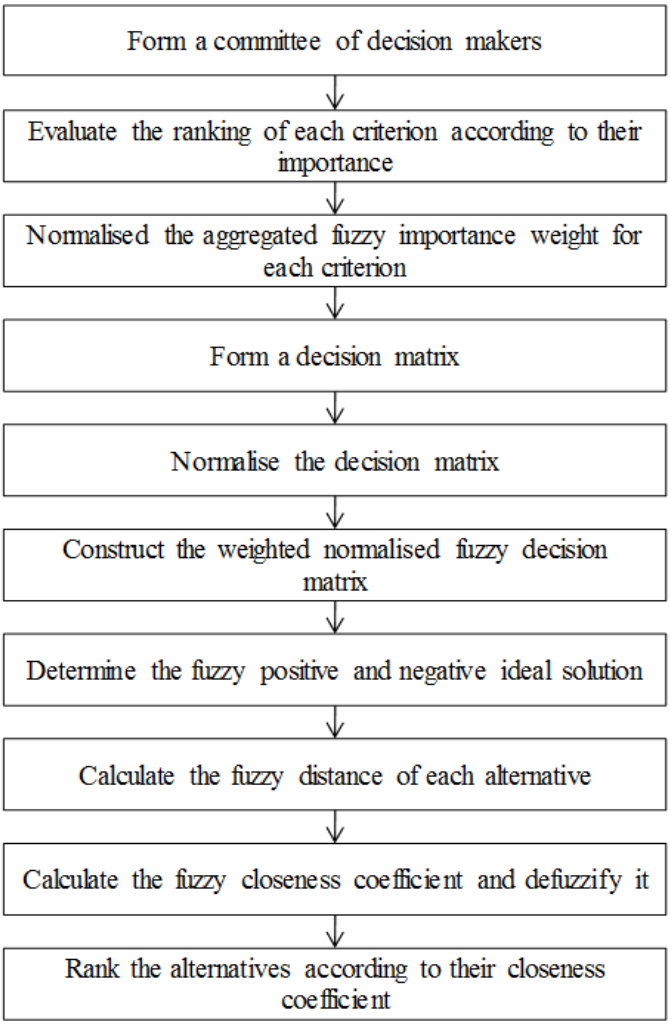

Figure 2. The steps of the Fuzzy-TOPSIS method

3. Case Study

This research presents an example from industry to demonstrate the efficacy of the proposed methodology. The application is to select the best knob design for universal clamp from among six developed concept designs, which have been designed by the design engineers, as depicted in Figure 3. There are five decision makers whose views are deemed important and they should be taken into account for making a decision. They are selected customers, selected distributors, sales department, top management and the manufacturing department.

Figure 3. Design alternatives for the case study

Based on data from the survey results of the respondents' group for rating the evaluation criteria using the new scale of "Weighting criteria", the aggregate fuzzy importance weights were calculated, their normalised aggregate fuzzy weights computed and the values are shown in Table 2. The next step is to measure the performance of the alter-natives with respect to each criterion.

Table 2. Normalised aggregated fuzzy importance weight

Criteria	Customer	Distributor	Sales	Top management	Manufacturing
	w_{j1}	w_{j2}	w_{j3}	w_{j4}	w_{j5}
Aesthetic ($\hat{w}_1$)	0.088	0.099	0.091	0.099	0.097
Market standard ($\hat{w}_2$)	0.085	0.083	0.088	0.084	0.082
Price ($\hat{w}_3$)	0.075	0.078	0.077	0.063	0.077
Production errors ($\hat{w}_4$)	0.048	0.047	0.049	0.060	0.059
Spec control ($\hat{w}_5$)	0.048	0.047	0.049	0.047	0.043
Safety standard ($\hat{w}_6$)	0.080	0.078	0.082	0.078	0.077
Patent ($\hat{w}_7$)	0.080	0.078	0.099	0.078	0.077
Manufacturing cost ($\hat{w}_8$)	0.059	0.060	0.060	0.060	0.056
Recyclable ($\hat{w}_9$)	0.048	0.047	0.049	0.047	0.046
Assembling process ($\hat{w}_{10}$)	0.061	0.060	0.063	0.060	0.072
Handling ($\hat{w}_{11}$)	0.048	0.047	0.049	0.047	0.046
Maintenance ($\hat{w}_{12}$)	0.048	0.047	0.049	0.047	0.046
Performance ($\hat{w}_{13}$)	0.077	0.078	0.080	0.078	0.074
Reliability ($\hat{w}_{14}$)	0.075	0.073	0.047	0.073	0.072
Environment standard ($\hat{w}_{15}$)	0.080	0.078	0.066	0.078	0.077
Total	1.000	1.000	1.000	1.000	1.000

Table 3 shows the normalised decision matrix, which is obtained depending on whether the objective of the selection criterion is that of minimisation or maximisation.

Table 3. Normalised decision matrix

Criteria	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6
Aesthetic ($\hat{w}_1$)	0.18	0.18	0.18	0.08	0.18	0.18
Market standard ($\hat{w}_2$)	0.22	0.16	0.16	0.09	0.16	0.22
Price ($\hat{w}_3$)	0.22	0.17	0.11	0.11	0.17	0.22
Production errors ($\hat{w}_4$)	0.17	0.17	0.17	0.15	0.17	0.17
Spec control ($\hat{w}_5$)	0.17	0.17	0.17	0.16	0.17	0.17
Safety standard ($\hat{w}_6$)	0.17	0.17	0.17	0.17	0.17	0.17
Patent ($\hat{w}_7$)	0.17	0.17	0.17	0.17	0.17	0.17
Manufacturing cost ($\hat{w}_8$)	0.22	0.18	0.09	0.09	0.13	0.29
Recyclable ($\hat{w}_9$)	0.17	0.17	0.17	0.17	0.17	0.17
Assembling process ($\hat{w}_{10}$)	0.18	0.18	0.18	0.13	0.18	0.18
Handling ($\hat{w}_{11}$)	0.17	0.17	0.17	0.17	0.17	0.17
Maintenance ($\hat{w}_{12}$)	0.17	0.17	0.17	0.17	0.17	0.17
Performance ($\hat{w}_{13}$)	0.17	0.17	0.17	0.10	0.22	0.17
Reliability ($\hat{w}_{14}$)	0.18	0.18	0.18	0.11	0.18	0.18
Environment standard ($\hat{w}_{15}$)	0.17	0.17	0.17	0.17	0.17	0.17

The fuzzy closeness coefficient and defuzzified closeness coefficient is then determined. The values of both the fuzzified and defuzzified closeness coefficients are shown in Table 4. As initial average weights were used in the TOPSIS calculations, the values of CCi5 in Table 3 are considered as crisp TOPSIS results. Fuzzy TOPSIS results, however, are shown in Table 5 (CCi). When the Fuzzy-TOPSIS approach was employed, it was identified that Design 6 with a weight of 0.87717 should be given the highest priority. The second most important alternative is Design 1 with a weight of 0.82385, followed by Design 2 (0.66117), Design 5 (0.64836), Design 3 (0.52357) and Design 4 (0.0000)

Table 4. Computations

	CC_{i1}	CC_{i2}	CC_{i3}	CC_{i4}	CC_{i5}
Design 1	0.79193	0.79419	0.78821	0.78839	0.80004
Design 2	0.60385	0.61238	0.59420	0.61503	0.61814
Design 3	0.45408	0.46084	0.44105	0.47582	0.46904
Design 4	0.00000	0.00000	0.00000	0.00000	0.00000
Design 5	0.59074	0.59729	0.58226	0.59891	0.60375
Design 6	0.85377	0.85597	0.85139	0.85228	0.85901

Table 5. Evaluation results

	CC_i	Ranking	Sustainability practices
Design 1	0.82385	2	0.661
Design 2	0.66117	3	0.639
Design 3	0.52357	5	0.476
Design 4	0.00000	6	0.250
Design 5	0.64836	4	0.594
Design 6	0.87717	1	0.677

The normalised value of sustainability practices for each design is shown in the last column of Table 5. It was determined that the highest rank of design concept also has the highest ratio of sustainability compliance.

4. Conclusion

The results of the example presented in this research show that the idea of using the integration of scale of "Weighting criteria" and Fuzzy-TOPSIS, provides designers with another alternative to the existing methods, for the performance of design concept evaluation in the early stages of sustainable product development. The proposed framework has successfully helped the designers to perform design concept evaluation and assess the level of sustainability practices.

Although the analysis and methodologies provided are quite good and constitute a set of powerful tools by which to guarantee the requirements of the design evaluation, some improvements could still be made. In this research, the weight or ranking of alternatives using Fuzzy-TOPSIS will be accepted. However, the difference from the view-point of each stakeholder was not considered. Thus, the proposed method could be enhanced by including the aggregation process of stakeholder viewpoints by using the appropriate method. In addition, the process of map design criteria to sustainability element still can be improved.

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