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APPLICATION OF HOUSE OF QUALITY, FUZZY-ANALYTICAL HIERARCHY PROCESS AND ROUGH-GREY ANALYSIS IN DESIGN CONCEPT EVALUATION – A CASE STUDY

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ABSTRACT

Design concept evaluation plays a critical role in the early phases of product development as it has a significant impact on the downstream development processes, as well as on the success of the product developed. In this work, a novel three-stage methodology has been developed. The preliminary stage screens all the criteria from different viewpoints using House of Quality (HoQ). The second stage uses a Fuzzy-Analytical Hierarchy Process (Fuzzy-AHP) to obtain the alternatives weighting, and the final stage verifies the ranking of the alternatives by a Rough-Grey Analysis. This method will enable designers to make better informed decisions before finalizing their choice. A case example from industry is presented to demonstrate the efficacy of the proposed methodology. The prospective benefit of this new method is that it can help designers to reduce the risk of late design changes or corrections. The result of the example shows that the HoQ, Fuzzy-AHP and Rough-Grey Analysis approach provided a novel alternative to existing methods of performing design concept evaluation. The proposed framework has successfully helped the designers to reduce the product development time.

Keywords**:** design concept evaluation; decision making; HoQ; Fuzzy-AHP; Rough-Grey Analysis.

INTRODUCTION

In today's industries, product design has become the main focus of competition in a highly competitive environment and fast-growing global market. Benchmarks used to determine the competitive advantage of a manufacturing company are customer satisfaction, shorter product development time, higher quality and lower product cost(Hsu & Woon, 1998; Shai, Reich, & Rubin, 2009; Subrahmanian, Rachuri, Fenves, & Foufou, 2005). Today's product designer is being asked to develop high quality products at an ever-increasing pace(Ye et al., 2008). To meet this new 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 and Boyle (2009)describe how the current challenges 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. Thus, a good design process should take into account the aforementioned criteria as early as possible in order to ensure the success of a product.

The product development process is a transformation process from customer requirements to a physical structure while considering the various design constraints(Qian, Bismarck, Greenhalgh, Kalinka, & Shaffer, 2008). For a long time, new product development has been considered as an essential element for organizational competitiveness and success. Product development also plays a critical role in the survival and success of manufacturing enterprises, and many researchers have improved their cognition of the need to manage it strategically (Ayağ & Özdemir, 2009; Brown & Eisenhardt, 1995; Chesbrough & Teece, 2002; Griffin & Hauser, 1996; Krishnan & Ulrich, 2001; Motlagh, Ramli, Motlagh, Tang, & Ismail, 2010). However, truly effective product development remains difficult(Lee & Santiago, 2008). The rapid pace of technology development has led to shorter product life cycles for many product categories, most notably in consumer electronics. The need to stay competitive has shrunk product development time through the use of simultaneous and collaborative design processes. One important step in designing new products is generating conceptual designs. Design concept evaluation is a complex multi-criteria decision-making (MCDM) process which includes a set of technical activities, which are the refinement of customer requirements into design functions, new concept development, and embodiment engineering of a new product(Nguyen, Lee, Lee, & Lim, 2010). (Lotter, 1989)and (Ullman, 2009)point out that 75% of the manufacturing cost is committed early in the design process. In such circumstances, design concept evaluation in the early phase of product development plays a critical role as it has a significant impact on downstream processes(Geng, Chu, & Zhang, 2010; Zhai, Khoo, & Zhong, 2009).

In order to help the designers to make a better informed decision before making a judgment, a systematic design evaluation method is needed. Amongst the various tools developed for design concept evaluation, the fuzzy set theory and Analytical Hierarchy Process (Fuzzy-AHP) methods have received the most attention due to their ability to handle uncertainty and MCDM. An ideal design evaluation method needs to use fewer design criteria, use an optimum number of pair-wise comparisons, and have a supportive tool to verify and validate the ranking of the alternatives obtained. However, in many practical situations, the human preference model is uncertain and decision-makers might be reluctant or unable to assign exact numerical values to the comparison judgments. Consequently, the decision-makers will need a process for reconsideration of design alternatives in relation to design criteria, and it may not help them to reduce the number of design criteria. In addition, the final weight of the design alternatives may not give a significant difference that will have an impact on the designers or decision-makers in making a judgment. A sole conventional Fuzzy-AHP is thus insufficient when applied to ambiguous problems. The proposed design evaluation method will integrate Fuzzy-AHP with another effective method in order to provide another alternative to the designers. The literature search indicates that no work has been done with the above proposed methodology in design evaluation for new product development. The implementation of the proposed novel method will be divided into three stages, which are screening, evaluating and verifying, which refers to using fewer design criteria, the optimum number of pair-wise comparisons, and having a supportive tool to verify and validate the rank of alternatives obtained. Following the methodology as outlined above can perhaps fulfil the aforementioned requirement for ideal design evaluation.

PROPOSED METHODOLOGY

The general framework of the approach is depicted in Figure 1. Based on the prescriptive design process model of Pahl and Beitz, the proposed design concept evaluation will focus on the conceptual design and embodiment design stage. The designer or decision-maker will initially set up the design structure according to the recommended procedure, from specification to definitive layout process. Then, they can create a general hierarchy and then identify the relevant criteria or sub-criteria, which can then be put into a hierarchy. The output can be produced using a screening process, followed by an evaluation and verification method from each hierarchy with its relevant criteria.

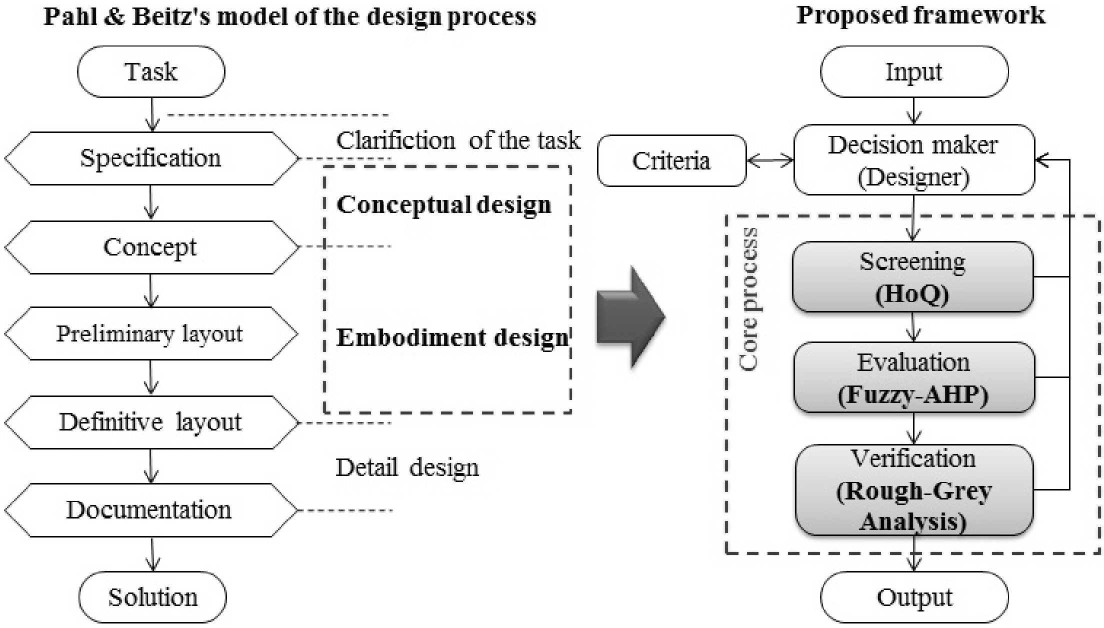

Figure 1. General framework of proposed approach.

In this research, the HoQ method has been used for screening or pre-evaluating the alternatives suggested by the designer. Then the Fuzzy-AHP method will be used to obtain the weights of alternatives from the point of view of each decision-maker. Finally, the rank of alternatives will be verified and validated using the Rough-Grey Analysis method.

Screening using HoQ

First of all, the customer needs and the engineering characteristics have to be identified.

(i) Identification of customer needs.
The first step is to compose a list of customer needs that underlie in particular the design requirement. The second step is to complete the list of customer needs and to establish the most important of these from a systematic survey.

(ii) Establishing engineering characteristics.
The engineering characteristics that are related to the customer needs were drawn up by a design team consisting of industrial engineers who had experience in using the House of Quality for different kinds of products.

(iii) Estimating WHATs/HOWs correlations by design team.

After the customer needs and engineering characteristics were identified, the design team estimated the strength of the relation between each customer need and each engineering characteristic individually. After that, the strengths of the correlations were entered into the House of Quality.

(iv) WHATs/HOWs correlations derived from customers' evaluations.
In order to derive the WHATs/HOWs correlations from customers' evaluations, each of the engineering characteristics from the House of Quality was represented in a single design alternative.

Figure 2 depicts the House of Quality matrix. The outcome from this process is the rank of criteria, and the higher rank of these criteria will be considered for evaluation in the next process.

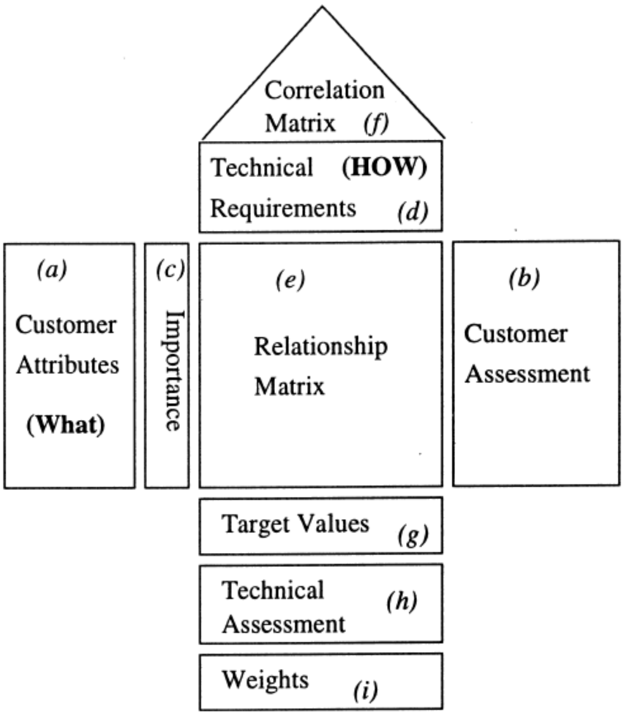

Figure 2. House of Quality matrix(Temponi, Yen, & Amos Tiao, 1999).

Evaluation Using Fuzzy-AHP

The proposed Fuzzy-AHP based methodology provides a framework for the prioritization of alternatives at early stages of the design process. The methodology can be divided into four steps as described in the following paragraphs.

(i) Benchmarking and building of model hierarchical structure.
The proposed Fuzzy-AHP based methodology provides a framework for prioritization.

(ii) Construction of pair-wise comparison matrices (PCM).
The pair-wise comparison process requires inputs from multiple layers of decision-makers. Therefore, in order to get good and reliable data, the subject matter experts should be chosen carefully.

(iii) Calculation of eigenvectors of elements by solving fuzzy PCM.

The objective of this step is to compute the relative importance (or principal eigenvector) of all the elements with respect to their next higher level element in the hierarchy.

(iv) Calculation of overall prioritization weights for each alternative.

The overall or total prioritization weight (TW) of an alternative was calculated by considering the individual weights of all the relevant criteria. Mathematically, this can be represented as follows(Nepal, Yadav, & Murat, 2010):

$$TW_{Ak} = \sum_{k} W_{\substack{Ui \\ i \in Uij}} \times W_{\substack{Uij \\ Uij \in Ak^*}} W_{Ak} \quad \forall k \qquad (.1)$$

where $W_{\substack{Ui \\ i \in Uij}}$ is the relative importance of general criterion U_i that is relevant to the secondary criteria U_{ij}. $W_{\substack{Uij \\ Uij \in Ak}}$ is the relative importance of secondary criteria U_{ij} that are relevant to the alternatives A_k. W_{Ak} is the relative importance of an alternative A_k with regard to its next higher level secondary criterion. A_K is the alternatives, k = 1, 2, 3.

Verification Using Rough–Grey Analysis

The Rough-Grey Analysis approach is very suitable for solving the group decision-making problem in an uncertainty environment. The selection procedures are summarized as follows (Bai & Sarkis, 2010, 2011; Qian et al., 2008):

(i) Establishment of grey decision table.

Form a committee of decision-makers (DMs) and determine attribute values of alternatives.

(ii) Normalization of grey decision table.

The normalization method mentioned above is to preserve the attribute that the ranges of normalized grey numbers belong to [0, 1].

(iii) Determination of suitable alternatives.

In order to reduce unnecessary information and keep the determining rules, we determine suitable alternatives by a grey-based rough set with lower approximation.

(iv) Making the ideal alternative for reference.

(v) Selection of the most suitable alternative.

The grey relational grade (GRG) between each comparative sequence $\otimes x_i$ and the reference sequence $\otimes x_0$ can be derived from the average of the grey relational coefficients (GRC), which is denoted as

$$\Gamma_{0i} = \sum_{k-1}^{n} \frac{1}{n} \gamma\left(\otimes x_0(k), \otimes x_i(k)\right) \qquad (2)$$

where Γ_{0i} represents the degree of relation between each comparative sequence and the reference sequence. The alternative corresponding to the maximum value of GRG can be considered as the most suitable alternative.

Case Example

This paper presents an example from industry to demonstrate the efficacy of the proposed methodology. The application is to select the best mold design for a video camera top cover among three developed concepts which have been designed by design engineers. From the point of view of the design engineers, all three alternatives can potentially be implemented. There are five decision-makers whose views are deemed important and they should be taken into account when making the decision. They are from the production, maintenance, engineering, quality control, and production control departments.

RESULTS AND DISCUSSION

Screening Process Using HoQ Method

In utilizing the HoQ for the screening process in this case example, the process explained in the previous section was followed. Then, experts in the multidisciplinary team identified the relationships between each pair of customer attributes (CAs) and technical requirements (TRs). Table 1 presents a summary of the HoQ, including the relative weight or relative importance of each quality characteristic.

Table 1. HoQ summary

Row Number	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")	Requirement Weight	Relative Weight (Relative Importance)
1	Cavity design - Number of cavities	297.83	16.30%
2	Mold structure - Operation mode (manual, semi-auto, auto)	279.35	15.29%
3	Feeding - Runner (conventional, insulated runner, hot runner)	267.39	14.63%
4	Feeding - Gating (side gate, submarine gate, pin point gate, disc gate)	255.43	13.98%
5	Cavity design - Cavity layout (equal runner, symmetrical, diaphragm)	247.83	13.56%
6	Undercut release mechanism - Split mold	240.22	13.15%
7	Mold structure - 3 plate	239.13	13.09%

Evaluating Process Using Fuzzy-AHP Method

Figure 3 depicts the hierarchical structure of the alternatives and criteria to prioritize alternatives for selecting the best mold design in order to optimize the cost and performance. The criteria (U_i) represent a combination of the strategic index and key factors in design selection based on screening results obtained from the previous process. At the next level, three alternatives that significantly influence the criteria were considered.

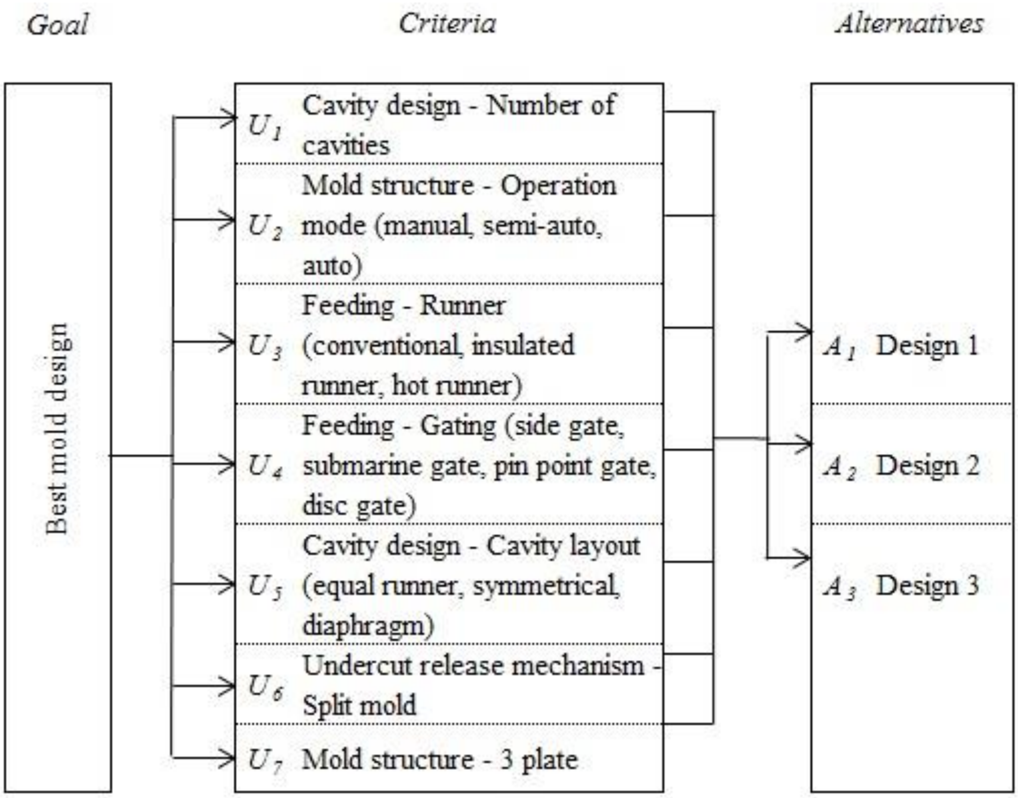

Figure 3. Hierarchy tree

Table 2 presents the results of the prioritization weights calculations for the alternatives with respect to the criteria. In this study, the consistency ratio (CR) values for all of the pair-wise comparison matrices have been found to be less than 0.1, which is consistent and acceptable. It also shows the largest eigenvalue, consistency index (CI) and CR validating the pair-wise comparison. The final results of the overall prioritization weight for each alternative are presented below in Table 3.

Table 2. Summary of relative importance

	Criteria	λ_{max}	C.I.	C.R.
U_1	Cavity design - Number of cavities	3.213	0.106	0.085
U_2	Mold structure - Operation mode (manual, semi-auto, auto)	3.045	0.022	0.018
U_3	Feeding - Runner (conventional, insulated runner, hot runner)	3.000	0.000	0.000
U_4	Feeding - Gating (side gate, submarine gate, pin point gate, disc gate)	3.000	0.000	0.000
U_5	Cavity design - Cavity layout (equal runner, symmetrical, diaphragm)	3.045	0.022	0.018
U_6	Undercut release mechanism - Split mold	3.000	0.000	0.000
U_7	Mold structure - 3 plate	3.000	0.000	0.000

Table 3. Overall prioritization weight

Total alternative weight TW_{Ak}		Ranking
A_1=	0.3455	1
A_2=	0.3365	2
A_3=	0.3179	3

Verifying Process Using Rough-Grey Analysis Method

There is a grey information system $T=(U,A,V,f_{\otimes})$ for the selection of alternatives. The grey decision table is expressed by $T=(U,A\cup D,f_{\otimes})$. $U=\{S_i, i=1,2,3\}$ are three potential alternatives for seven attributes $A=\{a_j, j=1,2,...,7\}$. The seven attributes include qualitative attributes and quantitative attributes.

Survey results from five groups of decision-makers express their preferences on attributes and the decision. Then a grey decision table is formed as shown in Table 4.

Table 4. Grey decision table

Alternatives	S_1	S_2	S_3
a_1	[5.7,6.7]	[5.7,6.7]	[3.7,4.7]
a_2	[4.3,5.3]	[3.5,4.5]	[4.3,5.3]
a_3	[3.7,4.7]	[3.7,4.7]	[3.7,4.7]
a_4	[2.9,3.9]	[2.9,3.9]	[2.9,3.9]
a_5	[4.3,5.3]	[4.3,5.3]	[3.5,4.5]
a_6	[4.3,5.3]	[4.3,5.3]	[4.3,5.3]
a_7	[6.3,7.3]	[6.3,7.3]	[6.3,7.3]
Decision	2	2	1

The next step is to normalize the grey decision table. The resulting grey normalized decision table is shown in Table 5. The grey relational analysis (GRA) is a numerical measure of the relationship between comparative values and objective values, and the numeric values are between 0 and 1. According to the rule that the design corresponding to the maximum value of GRG is the most suitable design, the grade is $S_1 > S_2 > S_3$ as shown in Table 6.

The Fuzzy-AHP analysis suggests that Design 1 with a weight of 0.3455 should be given the highest priority. Among the three alternatives selected in this study, the second most important alternative is Design 2 with a weight of 0.3365, followed by Design 3 (0.3179). The result can be verified using the Rough-Grey analysis method. Similarly, from the GRG results, Design 1 is the most suitable design $(\Gamma_{01}=1.000)$, followed by Design 2 $(\Gamma_{02}=0.667)$, and Design 3 $(\Gamma_{03}=0.333)$. All of this ranking is consistent with the Fuzzy-AHP ranking. Even though this is a simple case example, the results obtained from this analysis provide an in-depth insight on the real problem being faced by the industry. The distribution of weights assigned to various criteria, and alternatives provide hands-on information to formulate an order-winning strategy for design engineers.

Table 5. Grey normalized

Alternatives	S_1	S_2	S_3
a_1^*	[0.867,1]	[0.813,0.947]	[0.467,0.6]
a_2^*	[0.867,1]	[0.867,1]	[0.493,0.627]
a_3^*	[0.789,0.965]	[0.789,0.965]	[0.789,0.965]
a_4^*	[0.804,1]	[0.804,1]	[0.804,1]
a_5^*	[0.804,1]	[0.804,1]	[0.804,1]
a_6^*	[0.787,1]	[0.787,1]	[0.787,1]
a_7^*	[0.787,1]	[0.787,1]	[0.787,1]
Decision	2	2	1

Table 6. Grey relational grade

GRG	Total	Ranking
$\square_{01}$	1.000	1
$\square_{02}$	0.667	2
$\square_{03}$	0.333	3

CONCLUSION

The result of the example presented in this work shows that the proposed HoQ, Fuzzy-AHP and Rough-Grey Analysis provided another alternative to enable the designers to perform design concept evaluations in the early stages of product development, with the capability of accommodating uncertainties and vagueness and using the optimum number of pair-wise comparisons. Prospective applications of the proposed method may facilitate the establishment of expert systems for systematic evaluation of design concepts during the product development process. Overall, the proposed framework will provide design engineers with a structured decision-making tool to reduce product development time by reducing the number of criteria with the optimum number of pair-wise comparisons.

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