



A THESIS ON THE TOPICS OF
EVALUATION IN PRODUCT DEVELOPMENT FOR DESIGN

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A thesis submitted in
fulfilment of requirement for the award of the
Doctor of Philosophy.

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DECEMBER 2013

ABSTRACT

In order to remain competitive in today's technologically driven world, the faster and more efficient development of innovative products has become the focus for manufacturing companies. In tandem with this, design evaluation plays a critical role in the early phases of product development, because it has significant impact on the downstream development processes as well as on the success of the product being developed. Owing to the pressure of primary factors, such as customer expectations, technical specifications and cost and time constraints, designers have to adopt various techniques for evaluating design alternatives in order to make the right decisions as early as possible. In this work, a novel three-stage methodology for design evaluation 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 finalising their choice. Case examples from industry are presented to demonstrate the efficacy of the proposed methodology. The result of the examples shows that the integration of Fuzzy-AHP with HoQ and Rough-Grey Analysis provides a novel alternative to existing methods of design evaluation.

ABSTRAK

Untuk kekal kompetitif dalam dunia yang dipacu teknologi pada hari ini, membangunkan produk inovatif dengan lebih cepat dan cekap telah menjadi fokus utama bagi syarikat pembuatan. Selaras dengan itu, penilaian rekabentuk memainkan peranan yang sangat penting di awal peringkat pembangunan produk kerana ianya memberikan kesan yang signifikan terhadap pembangunan produk berikutnya dan juga kejayaan produk yang dibangunkan. Disebabkan tekanan daripada faktor utama seperti permintaan pelanggan, spesifikasi teknikal, kos dan kekangan masa telah menyebabkan jurutera menggunakan pelbagai teknik di dalam penilaian rekabentuk bertujuan untuk membuat keputusan yang tepat seawal mungkin. Kaedah baru yang mempunyai tiga peringkat telah dibangunkan di dalam penyelidikan ini. Peringkat awal ialah menyaring semua kriteria dari sudut pandangan yang berbeza menggunakan 'House of Quality (HoQ)'. Peringkat kedua menggunakan 'Fuzzy-Analytical Hierarchy Process (Fuzzy-AHP)' untuk mendapatkan pemberat bagi setiap alternatif, dan peringkat terakhir ialah mengesahkan kedudukan setiap alternatif menggunakan 'Rough-Grey Analysis'. Kaedah ini akan memberikan jurutera rekabentuk kemudahan membuat keputusan yang lebih bijak dan bermakna sebelum membuat pilihan muktamad. Kes-kes kajian daripada industri telah dijalankan bagi menunjukkan keberkesanan metodologi yang dicadangkan. Hasil contoh kes menunjukkan bahawa integrasi 'Fuzzy-AHP' dengan "HoQ" dan 'Rough-Grey Analysis' merupakan alternatif baru kepada kaedah yang sedia ada di dalam melaksanakan penilaian rekabentuk.

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LIST OF SYMBOLS AND ABBREVIATIONS

<i>MCDM</i>	-	Multi-Criteria Decision Making
<i>AHP</i>	-	Analytical Hierarchy Process
<i>HoQ</i>	-	House of Quality
$\otimes v$	-	Attribute ratings value / Grey number value
<i>EDR</i>	-	Engineering Design Research
<i>DM</i>	-	Decision Maker
<i>MADM</i>	-	Multi-Attribute Decision Making
<i>PIS</i>	-	Positive Ideal Solution
<i>NIS</i>	-	Negative Ideal Solution
<i>TOPSIS</i>	-	Technique for Order Preference by Similarity to Ideal Solution
<i>TRIZ</i>	-	The Russian acronym for the “Theory of Inventive Problem Solving”
<i>QFD</i>	-	Quality Function Deployment
<i>CA</i>	-	Customer Attributes
<i>TR</i>	-	Technical Requirement
<i>V</i>	-	Correlation value
<i>F</i>	-	Fuzzy set
<i>x</i>	-	Values on the real time
<i>U</i>	-	Universe of discourse / General criterion
$\mu(x)$	-	Membership function
λ	-	Eigen value
<i>A</i>	-	$n \times n$ fuzzy matrix
<i>RM</i>	-	Ringgit Malaysia
Wt_i	-	Relative weight value of HoQ
V_i	-	Rating value of evaluation criteria
WV_i	-	Weighted value of evaluation criteria
<i>DC</i>	-	Difference Coefficient
<i>DI</i>	-	Difference Index

<i>PCM</i>	-	Pair-wise Comparison Matrice
<i>w</i>	-	Prioritization weight (relative importance)
<i>J</i>	-	Index number of columns
<i>I</i>	-	Index number of rows
<i>a</i>	-	Value of pair-wise comparison
<i>CI</i>	-	Consistency Index
<i>CR</i>	-	Consistency Ratio
<i>RI</i>	-	Random consistency index
<i>TW</i>	-	Total prioritization weight
<i>VP</i>	-	Very Poor
<i>P</i>	-	Poor
<i>MP</i>	-	Medium Poor
<i>F</i>	-	Fair
<i>MG</i>	-	Medium Good
<i>G</i>	-	Good
<i>VG</i>	-	Very Good
<i>K</i>	-	Number of persons in a decision group
<i>d</i>	-	Decision value
<i>S*</i>	-	Suitable alternatives
\underline{RS}^*	-	Lower approximation of suitable alternatives
S^{\max}	-	Ideal alternative
$\otimes x$	-	
<i>GRC</i>	-	Grey Relational Coefficient
ρ	-	Distinguishing coefficient
<i>GRG</i>	-	Grey Relational Grade
Γ	-	Degree of relation
<i>ABS</i>	-	Acrylonitrile Butadiene Styrene
<i>PS</i>	-	Polystyrene
<i>PP</i>	-	Polypropylene
<i>PE</i>	-	Polyethylene
<i>OEM</i>	-	Original Equipment Manufacturer
<i>PCB</i>	-	Printed Circuit Board
<i>UDE</i>	-	Undesired Effect

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CHAPTER 1

INTRODUCTION

1.1 Background

The product development process is one of transformation from customer requirements to a physical structure with consideration of the various design constraints (Li *et al.*, 2010). For a long time, new product development has been considered an essential element for organisational competitiveness and success (Edwards *et al.*, 2005). Product development also plays a critical role in the survival and success of manufacturing enterprises and many researchers have improved their understanding of the need for its strategic management (Brown & Eisenhardt, 1995; Griffin & Hauser, 1996; Krishnan & Ulrich, 2001; Chesbrough & Teece, 2002; Ayag & Odzimir, 2008). However, truly effective product development remains difficult (Lee & Santiago, 2008). A study by Minderhoud & Fraser (2005) indicates that product development practices have evolved over recent years as product cost; quality and time-to-market have each become progressively important. In parallel, the rapid pace of technological development has led to shorter product life cycles for many product categories, most notably in consumer electronics.

Following the identification of a market (user need), a total design system, as espoused by Pugh (1996), 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 *et al.* (1996) 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 *et al.* (2007) classify the activities of designers into conceptualising, embodying, detailing and computing, drawing and collecting information. Wallace (1989) points out that “the engineering

design process cannot be carried out efficiently if it is left entirely to chance...” (p.35). Furthermore, Finger & Dixon (1989b) 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 *et al.*, (2013) 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 become more refined only as the design process moves towards its goal.

In today’s industries, product design has become the main focus in a highly competitive environment and fast-growing global market (Turan & Omar, 2012; 2013). 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 (Hsu & Woon, 1998; Subrahmanian *et al.*, 2005; Shai *et al.*, 2007). Today’s product designer is being asked to develop high-quality products at an ever increasing pace (Ye *et al.*, 2008). 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 (2009) 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. Tools, techniques and methods are being developed that can support engineering design with an emphasis on the customer, the designer and the community (Chandrasegaran *et al.*, 2013). 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 (Turan & Omar, 2012; 2013).

One important step in designing new products is generating conceptual designs (Turan & Omar, 2013). The conceptual design process includes a set of technical activities, which are the refinement of customer requirements into design functions, new concept development and the embodiment engineering of a new product (Li *et al.*, 2010). A study by Lotter (1986) indicates that as much as 75% of the cost of a product is being committed during the design phase. In the same context, Nevins & Whitney (1989) surmise that up to 70% of the overall product development

cost is committed during the early design phases. Furthermore, Ullman (2009) points out that 75% of the manufacturing cost is committed early in the design process. Under such circumstances, the design concept evaluation in the early phase of product development plays a critical role because it has a significant impact on downstream processes (Zhai *et al.*, 2009). Similarly, Geng *et al.* (2010) point out that design concept evaluation, which is at the end of the conceptual design process, is one of the most critical decision points during product development. It relates to the ultimate success of product development, because a poor design concept can rarely be compensated in the latter stages.

Design concept evaluation is a complex multi-criteria decision-making (MCDM) process, which involves many factors ranging from initial customer needs to the resources and constraints of the manufacturing company. Concept design selection is the process of evaluation and selection from a range of competing design options with respect to customer needs and other criteria, comparing the relative strengths and weaknesses of the concept design and selecting one or more concept designs for further investigation, testing, or development (Green, 2000). However, how to evaluate effectively and objectively design concepts at the early stage of product development has not been well addressed, because the information available is usually incomplete, imprecise, and subjective or even inconsistent (Rosenman, 1993). As such, the quest for more effective and objective approaches to evaluate systematically design concepts in the early stage of the design process has invoked much research interest.

The success of the completed design depends on the selection of the appropriate concept design alternative (Green, 1997; Ulrich & Eppinger, 2005; Zhai *et al.*, 2009). A mismatch between the customer's need and the product and manufacturing process causes loss of quality, delay to market and increased costs (Millson *et al.*, 2004). Changes made early in the design process are less costly than those made during detailed design and later stages (Childs, 2004). Any design defect in the conceptual design is very difficult to correct in the detailed design stage and will incur further costs in the future (Francis *et al.*, 2002). The process of choosing the concept design is frequently iterative and may not produce immediately a dominant concept design (Liu *et al.*, 2003). An initially large set of concept design alternatives should be screened down to a smaller set, because some would clearly not be feasible for reasons, such as infeasibility of manufacturing or the cost of

production (Lovatt & Shercliff, 1998). Failing to choose the most appropriate concept design alternative might lead to reworking or redesigning and waste of resources. To choose a concept design, a company should pay attention to its manufacturing process but also consider the criteria of potential customers. Figure 1.1 represents the aforementioned explanation of product design requirement.

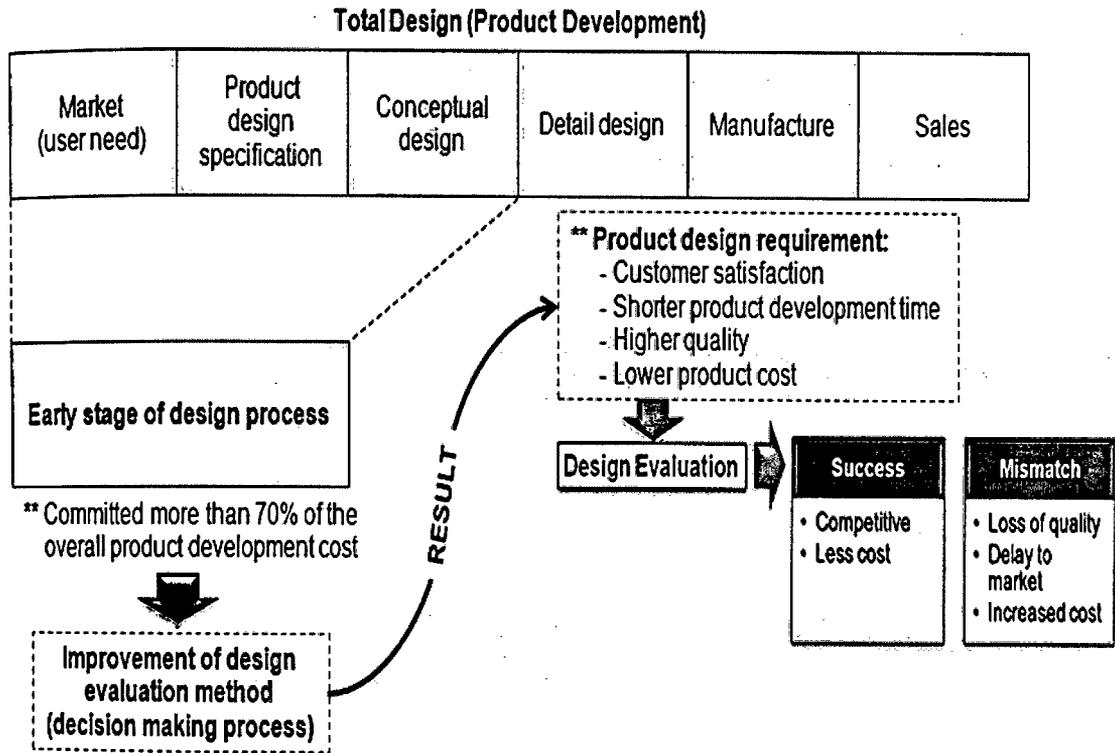


Figure 1.1: The product design requirement

1.2 Problem statement

In order to help designers become better-informed than conventional method prior to making a judgement, a systematic design evaluation method is needed. Amongst the various tools developed for design concept evaluation, fuzzy set theory and the Analytical Hierarchy Process (Fuzzy-AHP) methods have received the most attention owing to their abilities in handling uncertainty and MCDM (Scott, 2002; Turan & Omar, 2013). Scott (2002) and Ayag & Odzemir (2007b) state that AHP is one of the best methods for deciding among a complex criteria structure of different levels, whereas Fuzzy-AHP is a synthetic extension of the classical AHP method in which the fuzziness of the decision makers is considered. The nature of vagueness in

design concept evaluation has made this method a topic of considerable interest to many researchers (Scott, 2002; Ayag & Odzemir, 2007b). In accordance with this, an ideal design evaluation method, as espoused by Ayag & Odzemir (2007b), Zhai *et al.* (2009) and Turan & Omar (2013), needs to use fewer numbers of design criteria, fewer numbers of pair-wise comparisons and have a support tool to verify and validate the ranking of the alternatives obtained.

The conventional Fuzzy-AHP method aims to use an optimum number of pair-wise comparisons. In AHP, pair-wise comparisons are often preferred by the decision makers, because they facilitate the weighting of criteria and scores of alternatives from comparison matrices, rather than quantifying the weights or scores directly (Javanbarg *et al.*, 2012). 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 judgements. Although the use of the discrete scale for performing pair-wise comparative analysis has the advantage of simplicity, a decision maker might find it extremely difficult to express the strength of his preferences and to provide exact pair-wise comparison judgements in relation to the design criteria (Triantaphyllou & Lin, 1996; Duran & Aguilo, 2007). Consequently, the decision makers will need a process of reconsideration of design alternatives in relation to the design criteria, which might not help them reduce the number of design criteria. In addition, the final weight of design alternatives might not produce significant differences, which will affect the designers or decision makers when making a judgement. Thus, a sole conventional Fuzzy-AHP is insufficient when applied to ambiguous problems.

With the Fuzzy-AHP method, designers also face the same issues in design evaluation for new product development. A study by Zhai *et al.* (2009) indicates that although the Fuzzy-AHP method offers many advantages for design concept evaluation, it can be a time-consuming process due to the increase in the number of design criteria and design concepts. This might result in a huge evaluation matrix and the need to conduct a large number of pair-wise comparisons, which might lead to low consistency (Ayag & Ozdemir, 2007b). Figure 1.2 shows the relationship between the number of design criteria and pair-wise comparisons of conventional Fuzzy-AHP.

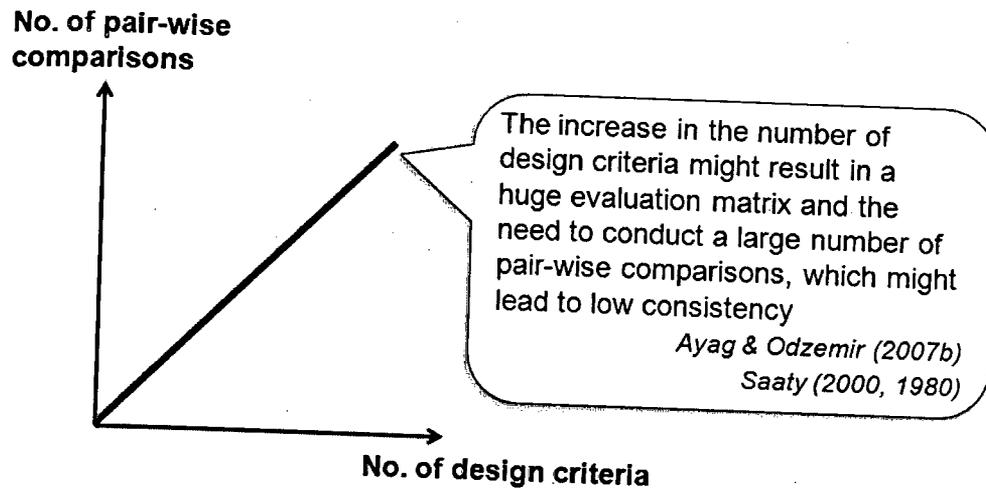


Figure 1.2: The relationship between number of design criteria and pair-wise comparisons of conventional Fuzzy-AHP

The proposed design evaluation method will integrate Fuzzy-AHP with another effective method 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 implementation of the proposed novel method will be divided into three stages: screening, evaluating and verifying, which use fewer numbers of design criteria, fewer numbers of pair-wise comparisons and have a support tool to verify and validate the ranking of the alternatives obtained. Thus, it can fulfil the aforementioned requirement of ideal design evaluation as well as contribute towards the body of knowledge.

1.3 Objective

The following defines in more detail what this work intends to achieve. Thus, it will be possible to evaluate later on, whether the steps chosen in the proposed methodology have led to successful results.

The overall aim of the research is formulated as follows:

To develop a novel methodology for design evaluation that enables designers to make better-informed decisions than conventional method when finalising their choice.

This research proposes a novel three-stage method of design evaluation using the integration of Fuzzy-AHP with House of Quality (HoQ) and the Rough-Grey Analysis approach.

As the overall aim is broad, it has been divided into single objective in order to support its achievement. The objective of this research, as depicted in Figures 1.3 and 1.4 is to develop a method of interfacing Fuzzy-AHP with HoQ and Rough-Grey Analysis as the following steps:

- (i) Introduce the scale of “Weighting criteria” for survey process prior to the first stage of design evaluation, which is a screening process using the HoQ method. HoQ will reduce the number of design criteria.
- (ii) Introduce the method of computing the priority of element for constructing the pair-wise comparison matrix to execute the second stage of design evaluation, which is Fuzzy-AHP method with fewer numbers of pair-wise comparisons using the results from the first stage.
- (iii) Introduce the method of quantifying the attribute ratings $\otimes v$ to carry out the third stage of design evaluation, which is verification and validation stage using the Rough-Grey Analysis method. This stage will reduce the unnecessary iteration process.

The final target of the proposed approach is to help the design community become better-informed than conventional method before making final judgements and consequently, reduce development time and cost.

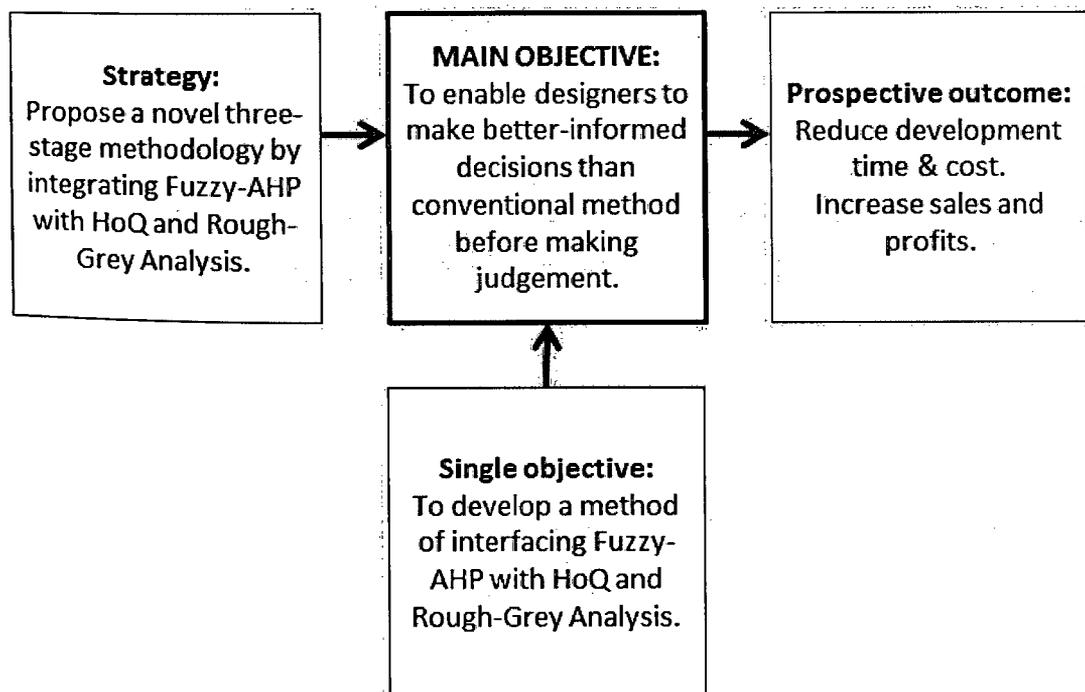


Figure 1.3: The overall aim of research

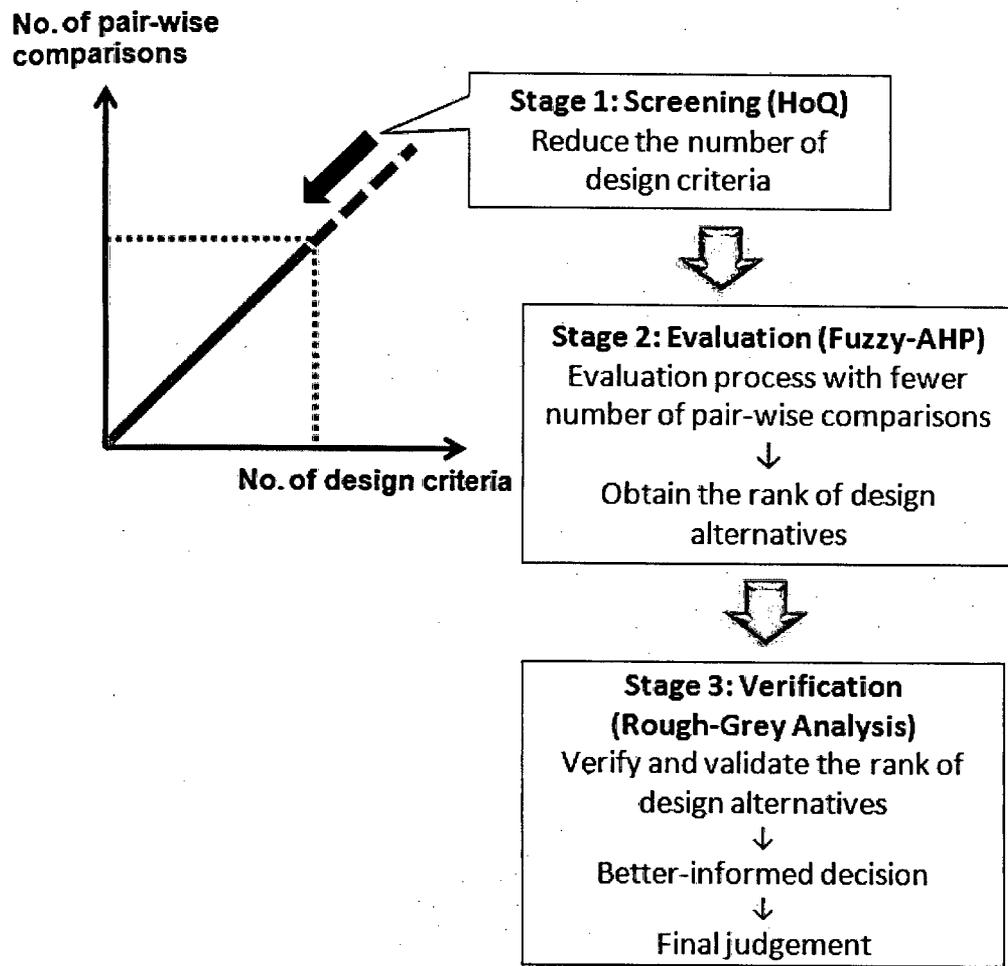


Figure 1.4: The aim of proposed approach

1.4 Scope

A Venn diagram or set of diagrams in Figure 1.5 shows all the hypothetically possible logical relations between product development and the proposed model of design evaluation. Mathematical equations of the aforementioned statement can be denoted by the following equation:

$$x = \{(A \cap B) \cap C\} \cap D \quad (1.1)$$

where,

- x : Proposed model of design evaluation
- A : Product development
- B : Engineering design