A THREE-STAGE METHODOLOGY FOR DESIGN EVALUATION IN PRODUCT DEVELOPMENT

FAIZ BIN MOHD TURAN

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Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

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Bismillahirrahmanirrahim.

Specially dedicated to my beloved family and friends for their continuous love, motivation, support and encouragement

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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 menggunapakai 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

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

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

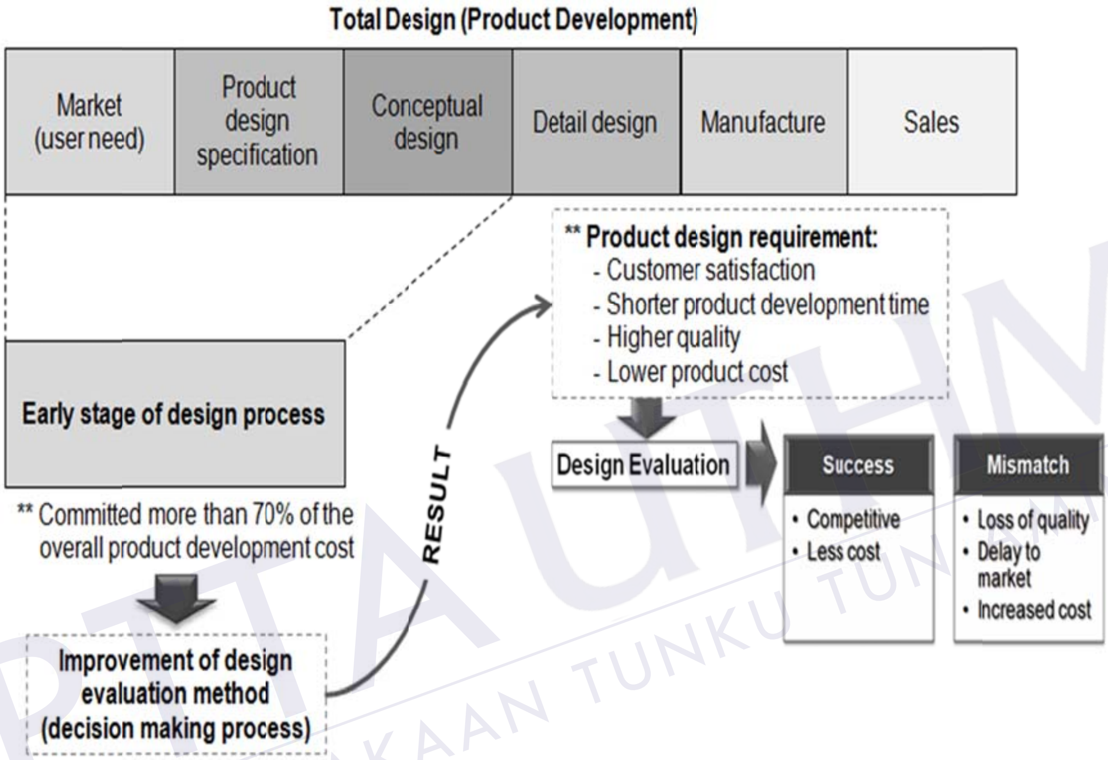

Figure 1.1: The product design requirement

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.

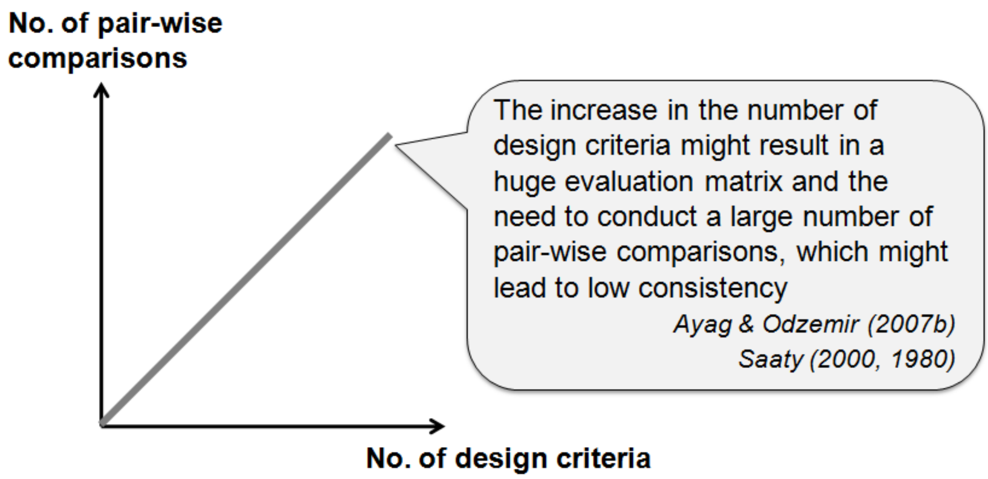

Figure 1.2: The relationship between number of design criteria and pair-wise comparisons of conventional Fuzzy-AHP

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.

REFERENCES

Altshuller, G. (1999). *The innovation algorithm*. USA: Technical Innovation Centre Inc.

Askin, O., Guzin, O. (2007). Comparison of AHP and Fuzzy-AHP for multicriteria decision making process with linguistic evaluations *Ýstanbul Ticaret Üniversitesi Fen Bilimleri Dergisi* (Vol. 6, pp. 65-85).

Ayag, Z., Odzemir, R. G. (2007a). An Analytic Network Process-Based Approach to Concept Evaluation in a New Product Development Environment. *Journal of Engineering Design, 18(3)*, 209-226.

Ayag, Z., Odzemir, R. G. (2007b). A combined fuzzy AHP-goal programming approach to assembly-line selection. *Journal of Intelligent and Fuzzy Systems, 18*(4), 345-362.

Ayag, Z., Odzemir, R. G. (2008). A hybrid approach to concept selection through fuzzy analytic network process. *Computers & Industrial Engineering, 56*(1), 368-379.

Bai, C., Sarkis, J. (2010). Integrating sustainability into supplier selection with grey system and rough set methodologies. *Int. J.ProductionEconomics, 124*, 252-264.

Bai, C., Sarkis, J. (2011). Evaluating supplier development programs with a grey based rough set methodology. *Expert Systems with Applications, 38*, 13505-13517.

Bounds, G., Yorks, L., Adams, M., Rannsey, G. (1994). *Beyond total quality management: Toward the emerging paradigm*. New York: McGraw-Hill.

Brown, P. G. (1991). QFD: Echoing the voice of the customer. *AT&T Technical Journal, March-April*, 18-32.

Brown, S., Eisenhardt, K. (1995). Product development: Past research, present findings, and future directions. *Academy of Management Review*, 343-378.

Burns, N., Grove, S. K. (1993). *The practice of nursing research: Conduct, critique & utilization 2nd edition*. Philadelphia: Sanders.

Carnahan, J. V., Thurston, D. L., Liu, T. (1994). Fuzzing ratings for multi-attribute design decision-making. *Journal of Mechanical Design, 116*, 511-521.

Chandrasegaran, S. K., Ramani, K., Sriram, R. D., Horváth, I., Bernard, A., Harik, R. F., Gao, W. (2013). The evolution, challenges, and future of knowledge representation in product design systems. *Computer-Aided Design, 45*, 204-228.

Chatterjee, D., Mukherjee, B. (2010). Study of Fuzzy-AHP model to search the criterion in the evaluation of the best technical institutions: A case study. *International Journal of Engineering Science and Technology, 2*(7), 2499-2510.

Chen, C. T. (2000). Extensions of the TOPSIS for group decision making under fuzzy environment. *Fuzzy Sets Systems, 114*, 1-9.

Chen, L. C., Lin, L. (2002). Optimisation of product configuration design using functional requirements and constraints. *Research in engineering design, 13*, 167-182.

Chesbrough, H., Teece, D. (2002). Organizing for innovation: When is virtual virtuous? *Harvard Business Review, 80*(8), 127-134.

Childs, P. R. (2004). *Mechanical design*. Oxford: Elsevier Butterworth-Heinemann.

Cook, T. D., Campbell, D. T. (1979). *Quasi-experimentation: design & analysis issues for field settings*. Chicago: Rand McNally College Pub.

Cross, N. (2000). *Engineering Design Methods: Strategies for Product Design* (3rd ed.). Chichester, West Sussex, England: John Wiley & Sons Ltd.

Dang, Y. G., Liu, S. Y., Liu, B. (2005). *On the multiple-attribute incidence decision model for interval numbers.* Paper presented at the Proceedings on Networking, Sensing and Control IEEE.

Darlington, M. J., Culley, S. J. (2002). Current Research in the Engineering Design Requirement. *Proceedings of the Institution of Mechanical Engineers Part B - Journal of Engineering Manufacture, 216*, 375-388.

Domb, E. (1997). 40 inventive principles with examples. *TRIZ Journal of 1997*(July).

Duran, O., Aguilo, J. (2007). Computer-aided machine-tool selection based on a fuzzy-AHP approach. *Expert Systems with Applications, 34*(3), 1787-1794.

Edwards, T., Battisti, G., W. P. McClendon Jr., Denyer, D., Neely, A. (2005). *Pathways to Value How UK Firms Create More Value Using Innovation Strategically* (1 ed.). London: Advanced Institure of Management Research (AIM).

Eisenhardt, K. M. (1989). Building the theories from case study research. *Academy of Management Review, 14*(4), 532-550.

Evans, J. R., Lindsay, W.M. (1996). *The Management and Control of Quality*. Saint Paul, MN: West Publishing.

F. O. Ebuomwan, N., Sivaloganathan, S., Jebb, A. (1996). A Survey of Design Philosophies, Models, Methods and Systems. *Proceedings of the Institution of Mechanical Engineers Part B - Journal of Engineering Manufacture, 210*, 301-320.

Finger, S., Dixon, J. R. (1989a). A Review of Research in Mechanical Engineering Design. Part I: Descriptive, Prescriptive, and Computer-Based Models of Design Process. *Research in Engineering Design, 1*, 51-67.

Finger, S., Dixon, J. R. (1989b). A Review of Research in Mechanical Engineering Design. Part II: Representations, Analysis, and Design for the Life Cycle. *Research in Engineering Design, 1*, 121-137.

Francis, E., Tay, H., Gu, J. (2002). Product Modeling for Conceptual Design Support. *Computer in Industry, 48*(2), 143-155.

Frenklach, G. (1998). Classifying the technical effects. *TRIZ Journal of 1998*(March).

Geng, X., Chu, X., Zhang, Z. (2010). A new integrated design concept evaluation approach based on vague sets. *Expert Systems with Applications, 37*, 6629-6638.

Green, G. (1997). Modeling concept design evaluation. *Artificial intelligence for engineering design, analysis and manufacturing, 11*, 211-217.

Green, G. (2000). Towards integrated evaluation: validation of models. *Journal of engineering design, 11*(2), 121-132.

Griffin, A., Hauser, J. (1992). The voice of the customer: Technical Report, Working paper 92-106, Marketing Science Institute, Cambridge, MA.

Griffin, A., Hauser, J. (1996). Integrating R&D and marketing: A review and analysis of the literature. *Journal of Product Innovation Management, 13*(3), 191-215.

Hakim, C. (2000). *Research Design: Succesful Designs for Social Economics Research 2nd edition*. New York: Routledge.

Hartley, J. (2004). Case study research . In Catherine Cassell & Gillian Symon (Eds.) *Essential guide to qualitative methods in organizational research* (pp. 323-333). London: Sage Publications.

Hauser, J. R. (1993). How Puritan-Bennett used the house of quality. *Sloan Management Review, 34*(3), 61-70.

Hauser, J. R., Clausing, D. (1988). The house of quality. *Harvard Business Review, 32*(5), 63-73.

Hayes, J. (1996). A new framework for understanding cognition and effect in writing. In Levy, Michael; Ransdell, Sarah (eds.) *The science of writing: Theories, methods, individual differences, and applications* (pp. 1-27). Mahwah, NJ: Lawrence Erlbaum.

Hayes, J., Flower, L. (1980). Identifying the organization of writing processes. In Gregg, Lee; Steinberg, Erwin (eds.) *Cognitive processes in writing: An interdisciplinary approach* (pp. 3-30). Hillsdale, NJ: Lawrence Erlbaum.

Herrera, F., Herrera-Viedma, E. (2000). Linguistic decision analysis: Steps for solving decision problems under linguistic information. *Fuzzy Sets and Systems,, 115*, 67-82.

Herrera, F., Herrera-Viedma, E., Verdegay, J. L. (1996). A model of consensus in group decision making under linguistic assessments. *Fuzzy Sets and Systems,, 78*, 73-87.

Hongre, L. (2006). *Identifying the Most Promising Business Model by using the Analytic Hierarchy Process Approach.* Paper presented at the 23rd World Gas Conference, Amsterdam, Netherlands.

Hsu, W., M. Y. Woon, I. (1998). Current Research in the Conceptual Design of Mechanical Products. *Computer-Aided Design, 30*(No. 5), 377-389.

Huang, H. Z., Bo, R. F., Chen, W. (2006). An integrated computational intelligence approach to product concept generation and evaluation. *Mechanism and Machine Theory, 41*, 567-583.

Hwang, C. L., Yoon, K. (1981). *Multiple Attribute Decision Making: Methods and Applications*. Berlin: Springer-Verlag.

Javanbarg, M. B., Scawthorn, C., Kiyono, J., Shahbodaghkhan, B. (2012). Fuzzy AHP-based multicriteria decision making systems using particle swarm optimization. *Expert Systems with Applications, 39*, 960–966.

Johnson, M. D., Herrmann, A., Bauer, H. H. (1999). The effects of price bundling on consumer evaluations of product offerings. *International Journal of Research in Marketing, 16*(2), 129-142.

Khoo, L. P., Ho, N. C. (1996). Framework of a fuzzy quality function deployment system. *International Journal of Production Research, 34*(2), 299-311.

Khoo, L. P., Tor, S. B., Zhai, L. Y. (1999). A rough-set based approach for classification and rule induction. *International Journal of Advanced Manufacturing Technology, 15*, 438-444.

Krishnan, V., Ulrich, K. (2001). Product development decisions: A review of the literature. *Management Science,* 1-21.

Krohling, R. A., Campanharo, V. C. (2011). Fuzzy TOPSIS for group decision making: A case study for accidents with oil spill in the sea. *Expert Systems with Applications, 38*, 4190-4197.

Lee, F., Santiago, M. (2008). *Creativity in New Product Development : An Evolutionary Integration* (1 ed.). USA: Butterworth-Heinemann.

Li, G. D., Yamaguchi, D., Nagai, M. (2008). A grey-based rough decision-making approach to supplier selection. *International Journal of Advanced Manufacturing Technology, 36*, 1032-1040.

Li, T. S., Huang, H. H. (2009). Applying TRIZ and Fuzzy AHP to develop innovative design for automated manufacturing systems. *Expert Systems with Applications, 36*, 8302-8312.

Li, W., Li, Y., Wang, J., Liu, X. (2010). The Process Model to Aid Innovation of Products Conceptual Design. *Expert Systems with Applications, 37*, 3574-3587.

Liu, S., Boyle, I. M. (2009). Engineering design: perspectives, challenges, and recent advances. *Journal of Engineering Design, 20*(1), 7-19.

Liu, Y. C., Bligh, T., Chakrabarti, A. (2003). Towards an ‘ideal’ approach for concept generation. *Journal of design studies, 24*, 341-355.

Lo, C., Wang, P., Chao, K. (2006). A fuzzy group-preferences analysis method for new-product development. *Expert Systems with Applications, 31*(4), 826-834.

Lotter, B. (1986). *Manufacturing Assembly Handbook*. Boston, USA: Butterworth-Heinemann.

Lovatt, A. M., Shercliff, H.R. . (1998). Manufacturing process selection in engineering design. Part 2: an approach for creating task-based process selection procedures. *Journal of material and design, 19*, 217-230.

Miles, M. B., Huberman, A. M. (1994). *Qualitative data analysis 2nd edition*. California: Sage Publications.

Millson, M., Miles, B., Tennant. C. (2004). *Effective new product introduction in SMEs.* Paper presented at the Paper presented at the Proceeding of 2nd International Conference on Manufacturing Technology, Sheffield Hallam University, United Kingdom.

Minderhoud, S., Fraser, P. (2005). Shifting paradigms of product development in fast and dynamic markets. *Reliability Engineering and System Safety, 88*, 127-135.

Mintzberg, H. (1979). *The structuring of organizations: A systhesis of the research*. Englewood Cliffs, N.J.: Prentice-Hall.

Nepal, B., Yadav, O. P., Murat, A. (2010). A fuzzy-AHP approach to prioritization of CS attributes in target planning for automotive product development. *Expert Systems with Applications, 37*, 6775-6786.

Nevins, J. L., Whitney, D. (1989). *Concurrent design of products and processes - A strategy for the next generation in manufacturing*. New York: McGraw-Hill.

Ordoobadi, S. M., Mulvaney, N. J. (2001). Development of a justification tool for advanced manufacturing technologies: system-wide benefits value analysis. *Journal of engineering and technology management, 18*, 157-184.

Pahl, G., Beitz, W., Feldhuson, J., Grote, K. H. (2007). *Engineering Design: A Systematic Approach* (3rd ed.). London: Springer-Verlag London Ltd.

Pawlak, Z. (1991). *Rough sets: Theoretical aspects of reasoning about data*. Dordrecht: Kluwer Academic Publishing.

Petrov, V. (2002). The laws of system evolution. *TRIZ Journal of 2002*(March).

Polit, D. F., Hungler, B. P. (1993). *Essentials of nursing research*. Philadelphia: Lippincott.

Polit, D. F., Hungler, B. P. (1995). *Nursing research: principles and methods 5th edition*. Philadelphia: Lippincott.

Pugh, S. (1996). *Total Design: Integrated Methods for Successful Product Engineering*. Wolkingham, England: Addition-Wesley Publishing Company.

Rosenman, M. A. (1993). Qualitative evaluation for topological specification in conceptual design. *Applications and Techniques of Artificial Intelligence in Engineering, 2*, 311-326.

Saaty, T. L. (1977). A Scaling Method for Priorities in Hierarchical Structures. *Journal of Mathematical Psychology, 15*, 234-281.

Saaty, T. L. (1980). *The Analytic Hierarchy Process: Planning, Priority Setting and Resources Allocation*. New York: McGraw-Hill.

Saaty, T. L. (1990). *The Analytic Hierarchy Process (2nd ed.)*. Pittsburgh, PA: RWS Publication.

Saaty, T. L. (2000). *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process*. Pittsburg: RWS Publications.

Saaty, T. L., Ozdemir, M. S. (2003). Why the magic number seven plus or minus two. *Mathematical and Computer Modelling, 38*, 233-244.

Scott, M. J. (2002). *Quantifying Certainty in Design Decisions: Examining AHP*. Paper presented at the ASME Design Engineering Technical Conferences (DETC2002).

Shai, O., Reich, Y., Rubin, D. (2007). Creative conceptual design: extending the scope by infused design. *Computer-Aided Design, 41*(3), 117-135.

Shaw, A., Aitchison, D. R., Raine, J. K., Whybrew, K. (2001). Rapid product development for world class manufacturing. *Technical Report* (Vol. 58). New Zealand: University of Canterbury.

Shih, H. S., Shyur, H. J., Lee, E. S. (2007). An Extension of TOPSIS for Group Decision Making. *Mathematical and Computer Modeling, 45*, 801-813.

Stake, R. E. (2003). Case Studies in Denzin, N.K. &Lincoln, Y. (eds.) *Strategies of Qualitative Inquiry 2nd edition* (pp. 134-164). London: Sage Publications.

Streubert, H. J., Carpenter, D. R. (1999). *Qualitative research in nursing: Advancing the humanistic imperative 2nd edition*. Philadelphia: Lippincott.

Subrahmanian, E., Rachuri, S., Fenves, S. J., Foufou, S., Sriram, R. D. (2005). Product lifecycle management support: A challenge in supporting product design and manufacturing in a networked economy. *International Journal of Product Lifecycle Management, 1*(1), 4-25.

Sun, J., Kalenchuk, D. K., Xue, D., Gu, P. (2000). Design candidate identification using neural network based fuzzy reasoning. *Robotics and Computer Integrated Manufacturing, 16*, 383-396.

Suskie, L. A. (2009). *Assessing student learning: A common sense guide 2nd edition*. San Francisco, CA: John Wiley & Sons.

Temponi, C., Yen, J., Tiao, W. J. (1999). House of quality: A fuzzy logic-based requirements analysis. *European Journal of Operational Research, 117*, 340-354.

Terninko, J. (2000). Su-field analysis. *TRIZ Journal of 2000*(February).

Triantaphyllou, E., Lin, C. T. (1996). Development and evaluation of five fuzzy multiattribute decision-making methods. *International Journal of Approximate Reasoning, 14*, 281-310.

Tsai, H. C., Hsiao, S. W. (2004). Evaluation of alternatives for product customization using fuzzy logic. *Information Sciences, 158*(1), 233-262.

Turan, F. M., Omar, B. (2011). *In situ design evaluation for product life cycle management.* Paper presented at the 2nd International Conference on Mechanical and Manufacturing Engineering (ICME 2011), Putrajaya, Malaysia.

Turan, F. M., Omar, B. (2012). *In situ design evaluation for product life cycle management using Fuzzy-AHP approach.* Paper presented at the International Conference on Applications and Design in Mechanical Engineering (ICADME 2012), Penang, Malaysia.

Turan, F. M., Omar, B. (2013). The Integration of HOQ and Fuzzy-AHP for Design Concept Evaluation. *Applied Mechanics and Materials, 315*(2013), 25-29.

Udo, G. G. (2000). Using Analytic Hierarchy Process to Analyze the Information Technology Outsourcing Decision. *Industrial Management & Data Systems, 100(9)*, 421-429.

Ullman, D. G. (2009). *The Mechanical Design Process* (4 ed.). New York: McGraw-Hill.

Ulrich, K., Eppinger, S. (2005). *Product design and development, 5th edition*. New York: McGraw-Hill Inc.

Ulrich, K., Seering, W. (1987a). *A Computational Approach to Conceptual Design.* Paper presented at the International Conference on Engineering Design, Cambridge, UK.

Ulrich, K., Seering, W. (1987b). Conceptual Design as Novel Combinations of Existing Device Features. *Advances in Device Automation, American Society of Mechanical Engineers, Boston MA*, 27-30.

Ulrich, K., Seering, W. (1987c). Conceptual Design: Synthesis of Systems Components. *Intelligent and Integrated Manufacturing Analysis and Synthesis, American Society of Mechanical Engineers, New York*, 57-66.

Vairaktarakis, G. L. (1999). Optimization tools for design and marketing of new / improved products using the house of quality. *Journal of Operations Management, 17*, 645-663.

Wallace, K. M. (1989). Better by Design. *Manufacturing Engineer*, 35-36.

Wang, J. (2001). Ranking engineering design concepts using a fuzzy outranking preference model. *Fuzzy Sets and Systems,, 119*, 161-170.

Ye, X., Liu, H., Chen, L., Chen, Z., Pan, X., Zhang, S. (2008). Reverse innovative design - an integrated product design methodology. *Computer-Aided Design, 40*, 812-827.

Yin, R. K. (1984). *Case study research*. Beverly Hills, CA: Sage Publications.

Yin, R. K. (2003). *Applications of case study research 2nd edition* (Vol. 34). California: Sage Publications.

Zhai, L. Y., Khoo, L. P., Zhong, Z. W. (2007). A rough set enhanced fuzzy approach to quality function deployment. *International Journal of Advanced Manufacturing Technology, 37*(5-6), 613-624.

Zhai, L. Y., Khoo, L. P., Zhong, Z. W. (2009). Design Concept Evaluation in Product Development using Rough Sets and Grey Relation Analysis. *Expert Systems with Applications, 36*, 7072-7079.

Zhang, Z., Chu, X. (2009). A new integrated decision-making approach for design alternative selection for supporting complex product development. *International Journal of Computer Integrated Manufacturing, 22*(3), 179-198.

Zoyzen, Z. (1997). Solving contradictions in development of new generation products using TRIZ. *TRIZ Journal of 1997*(February).