Integration of ECQFD and Weighted Decision Matrix for Selection of Eco-design Alternatives

Mohd Fahrul Hassan[1], Muhammad Zekri Safiee[1], Nik Hisyamudin Muhd Nor[1], Mohd Nasrull Abdol Rahman[2], Ibrahim Masood[2]
[1]Department of Material and Design Engineering,
[2]Department of Manufacturing and Industrial Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia
Email: fahrul@uthm.edu.my; nhisyam@uthm.edu.my; mnasrull@uthm.edu.my; ibrahim@uthm.edu.my

***Abstract*— This study proposes an integration of Environmentally Conscious Quality Function Deployment (ECQFD) and Weighted Decision Matrix in Conceptual design stage, so that selection of the final design among the alternatives with regard to environmental concerns can be done. Once several possible design alternatives are generated, ECQFD methodology which consists of four phases is used to identify the most relevant criteria that collected from customer needs focused on environmental aspects. Then, Weighted Decision Matrix is applied to evaluate the design alternatives based on criteria in the phase III of ECQFD. An example of designing an office chair using this approach is illustrated.**

***Index Term*— Eco-product, ECQFD, product design, Weighted Decision Matrix**

I. Introduction

An evolution of product design is depending on design paradigms that changes with time and based on market forces. Currently, environmentally conscious design or well-known as eco-design has taken the latest paradigm shift in design focus. When applying the eco-design in product design, such examples of the future product will be are a product that can be recycled, reducing the materials used, improving efficiency in energy use, and more concerns to the environmental conservation. According to Lockrey [1], eco-product is a product created without causing environmental destruction or harmful to the earth and lead to a green living. Modifying the design and material composition of a product is one of the successively approaches to achieve the eco-products, so they generate less pollution and waste throughout their life cycle [2].

Evaluation of product performances during conceptual design stage has become an imperative apprehension for most product-based industries. Hassan et al. [2] have stated that conceptual design is essential for product design to generate new variants for design elements of products, structuring them into a complete configuration and evaluating the alternate concepts. This phase is very important since the future product as much as 85% of the life-cycle cost is determined at this stage [3]. Hence, conceptual design stage is the right place to implement eco-design improvement of a product lifecycle towards sustainable development.

Life cycle assessment (LCA) is an environmentally fundamental methodology which is used to comprehensively and quantitatively evaluate the significance of potential environmental impacts and to systematically identify hot spots incurring heavy environmental impacts [4]. Bevilacqua *et al.* [5], Maruschke and Rosemann [6], Schneider *et al.* [7], and Gehin *et al.* [8] used a commercial software tool that based on the LCA approach to evaluate the environmental aspects and potential impacts associated with a product and related services over its entire life [9]. According to Russo [10], the LCA approach is too complex and not a user-friendly tool, and it is not useful in the design process. Regarding to this matter, many approaches that intentionally to overcome the limitations have been proposed extensively [11]. Chan et al. [12] presented a model that integrates fuzzy logic and Analytic Hierarchy Process (AHP) for the selection of green product designs. Meanwhile, Ng and Chuah [13] integrated a fuzzy AHP and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) methodology to prioritize design options. Another recent study, Ng and Chuah [14] used AHP with evidential reasoning (ER) in the environmental performances evaluation and prioritization of different design options. However, all proposed approach were integrated with an LCA methodology where the LCA is often cumbersome, expensive to perform and designed to measure primarily resource use and environmental impact with no allowance for qualitative analysis [15].

Quality Function Deployment (QFD) is a method to transform user needs into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into subsystems and components, and ultimately to specific elements of the manufacturing process [16]. Many researches have extending the traditional QFD to consider environmental aspects focus on the initial product planning phase [17]. Vinodh and Rathod [18] have collected and summarized an application of QFD for enabling eco-design from several researchers all over the world. From the summarization, four phases of ECQFD have been constructed where phases I and II are concerned with the identification of components for product design that considers both customer needs and environmental requirements. Meanwhile, ECQFD phases III and IV are focused on examination of the possibility of design improvements for components and to determine the improvement rate and effect of design changes. Then, ECQFD has been extended by integrating with LCA in a single methodology for sustainable product design [19].

In this study, the developed ECQFD methodology is integrated with Weighted Decision Matrix to assist in selection of eco-design alternatives. The most interesting part in this integration is the use of design criteria that have been decided by Phase III of ECQFD in the Weighted Decision Matrix method for evaluation purpose. The proposed approach is outlined in the next section.

II. Methodology

A. Environmentally Conscious Quality Function Deployment (ECQFD)

Vinodh and Rathod [9] have constructed the ECQFD methodology based on the literature review on QFD, and its application on environmentally friendly aspects, as shown in Fig. 1. The ECQFD consists of four phases. Phase I is concerned with the application of ECQFD for product design considering Voice of Customer (VOC) from an environmental perspectives. Phase II is concerned with the deployment of Engineering Metrics (EM) items to product components. In phase III, the options of a set of design changes on EM items are discussed. The goal of phase IV is to translate the effect of design changes on EM into environmental quality requirements.

B. Weighted Decision Matrix

Weighted decision matrix is one of the design tools that are widely used in evaluating competing concepts based on the weighting factors of design criteria and giving a score to the concept pertaining to the design criteria [20].

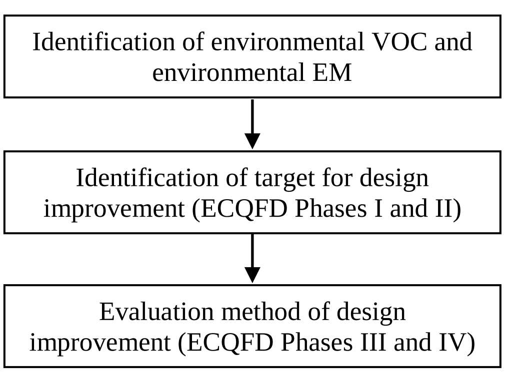

Fig. 1. ECQFD methodology

C. Integrated ECQFD and Weighted Decision Matrix

The proposed approach for selection of eco-design alternatives is outlined in Fig. 2. There have two major activities during Conceptual design stage; concept generation, and concept evaluation and selection. ECQFD methodology is performed at the beginning of conceptual design activities. Decisions from the ECQFD phase IV are discussed and finalize the possible design improvement of a target product. Once several possible design alternatives have been generated, all the design alternatives will be evaluated in terms of product performance that based on design criteria using Weighted Decision Matrix. It is very important to decide the design criteria focused on environmental aspects. Thus, selected EM items in ECQFD phase III will be used as the design criteria. In this stage, a decision for the final design among the design alternatives with regard to environmental concerns is made. Finally, the selected eco-design concept is achieved.

III. Case Study

In this section, a case study is conducted to illustrate the proposed approach. An office chair was identified as the product. All calculations by ECQFD approach are not fully presented in this study, yet it is only shows the results. The detail calculations of ECQFD can be referred in Vinodh and Rathod (2010).

A. Identification of environmental VOC and environmental EM

To begin the ECQFD, customers’ need is collected to identify the importance requirements from the customer feedback. Besides, in this study, the VOC must be considered from the environmental perspective over the product life cycle, and translates into a set of feasible EM. The list of identified environmental VOC and EM are shown in Table I.

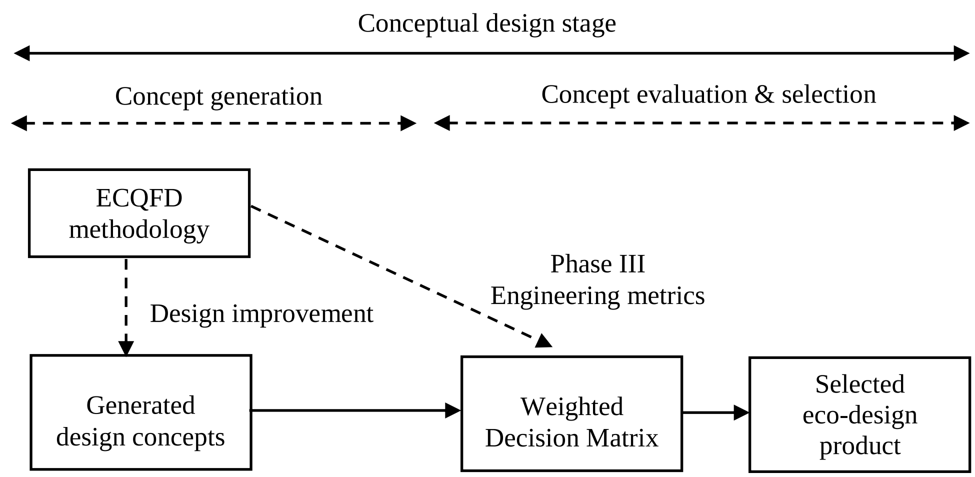

Fig. 2. Integrated ECQFD and Weighted Decision Matrix in Conceptual design stage

TABLE I
ECQFD Phase I of office chair design

Engineering Metric / Voice of customers	Customer weights	Price (RM)	Number of part	Weight (kg)	Size / Dimension (mxmxm)	Seat height Range (m)	Maximum supported weight (kg)	Backrest angle range (°)	Seat depth (m)	Physical lifetime	Type of material	Compression of gas spring	Rate of recycle material
Low cost	9	9	9								9		
Easy to use	3		3		3								
Easy to stored	3		3		9								
Durable	9			3						9	3	3	1
Good fabrics material	3	9									9		3
Ergonomic features	9					9	9	9	9				
Safe to use	3		3				1						
Lighter	9		9	9							9		
Save space	9				9								
Recyclable material	9									1	9		9
More Comfort	9											9	
Raw score		108	189	108	117	81	84	81	81	90	297	108	99
Relative weight		0.075	0.131	0.075	0.081	0.056	0.058	0.056	0.056	0.062	0.206	0.075	0.069

B. Identifying the target for design improvement

Identification of the target for design improvement through ECQFD consists of 4 phases.

ECQFD Phase I

Phase 1 is the first stage of ECQFD application to the design of office chair to deploy VOC against EM as shown in Table I. There are 11 criteria of VOC that have been collected from a market survey. All identified VOC are associated with the 12 items of EM. Each criteria from the VOC are weighted based on the market survey. EM consist of characteristics of office chair that may be associated with conditions by the consumer.

The important relation of VOC and EM has been indicated and determined by the designer using a scale, “9” indicates strong, “3” indicates moderate, and “1” indicates low. It can be interpreted as an attribute that must be met from the findings of consumer need, such as performance, availability and diversity of office chair that will be designed.

ECQFD Phase II

Phase II is the second stage of ECQFD where 12 items of EM in this study are correlated to components of office chair. Each item of EM used the weights that are obtained from Phase I. The important relation between EM and components of office chair is performed in the same way as Phase I. As shown in Table 2, components of office chair are consists of Backrest, Armrest, Mechanism, Caster/wheel, Seat, Base and Gas spring.

ECQFD Phase III

Phase III in ECQFD discussed the effect of design improvement of components of office chair on EM items, as shown in Table 3. There are two options have been discussed, the first option relates to the requirement by the customer that based on VOC. Another option is based on the most important components identified in Phase II. In this study, environmental aspects are playing an important role in the design improvement for components of office chair. The two proposed options as follows:

Option I

- Reduce the size of armrest.
- Reduce the weight of base.
- The type of material used in seat cushion should be from a recycle material

Option II

- The material used for backrest should be minimized as much as can.
- The type of material used in seat cushion should be from a recycle material.
- The size or dimension of armrest should be reduced

TABLE II
ECQFD Phase II of office chair design

Components of office chair / Engineering metrics (EM)	Phase I relative weighted	Backrest	Armrest	Mechanism	Caster / Wheel	Seat	Base	Gas spring
Price (RM)	0.075				3			3
Number of part	0.131		1		3			
Weight (kg)	0.075					1	3	3
Size / Dimension (mxmxm)	0.081	9	9			3	3	
Seat height Range (m)	0.056		3			3		
Maximum supported weight (kg)	0.058				9	3	3	
Backrest angle range (°)	0.056	9						
Seat depth (m)	0.056			3		3		
Physical lifetime	0.062			9				3
Type of material	0.206	9	3		3	9		
Compression of gas spring	0.075							3
Rate of recycle material	0.069	3	3		1	3		
Raw score		3.29	1.85	0.73	1.83	2.89	0.64	0.86
Relative weight		0.272	0.153	0.060	0.151	0.239	0.053	0.071

ECQFD Phase IV

In the Phase IV, the implication of changes in design on engineering matrices was translated into environment quality requirement. Phase IV for office chair as shown in Table 4 is to convert the effect of design improvement on EM into environmental considerations. Based on the calculation, it is found that the amount of (improvement effect of customer requirement) option II of Phase IV is higher than option I, where option II is 4.464. Meanwhile, option I is 3.450. Therefore, the office chair design is focus on the target set from the option II. The design alternatives for critical component in the office chair are generated. There are three critical components have been identified from the result of ECQFD Phase II, but the environmental improvement will be made only for one critical component with the highest score.

Thus, the design improvement is focused on the backrest of office chair.

TABLE III
ECQFD Phase III of office chair design

Component of office chair / Engineering metrics (EM)	Phase I relative weighted	Backrest	Armrest	Mechanism	Caster / Wheel	Seat	Base	Gas spring	Score	Improvement rate of EM
Price (RM)	0.075									
Number of part	0.131		(1)						(1)	(0.25)
Weight (kg)	0.075					1	3		4	0.57
Size / Dimension (mxmxm)	0.081		9 (9)			3 (3)			12 (12)	0.8 (0.8)
Seat height Range (m)	0.056									
Maximum supported weight (kg)	0.058									
Backrest angle range (°)	0.056									
Seat depth (m)	0.056									
Physical lifetime	0.062									
Type of material	0.206	(9)	3 (3)			9 (9)			12 (21)	0.88 (0.88)
Compression of gas spring	0.075									
Rate of recycle material	0.069	(3)	(3)			(3)			(9)	(0.9)

* the number in brackets is the score for option II

Weighted Decision Matrix

Weighted Decision Matrix is used to make a selection between the generated alternatives of design concept that have been listed for narrowing elections to get the concepts selected according to several design criteria. The design criteria are based on EM in ECQFD Phase III for option II where the highest improvement rate of EM are selected. Those selected design criteria for the evaluation on the backrest alternatives are material consumption, rate of recyclable material, dimension and number of part. Table-5 shows the application of Weighted Decision Matrix on the generated backrest alternatives of office chair using selected EM. Calculations are made to select the best alternative with respect to environmental considerations. This selection process is based on evaluation using rating. The highest value means the best concept, meanwhile the lowest value means poor concept.

From the Weighted Decision Matrix analysis, the design alternative which meets the EM items is the winner. Hence, Table V concluded that design A is selected as an eco-design product for the final design. The detail design of office chair with the consideration of eco-design concept is illustrated in Fig. 3.

Fig. 3. Selected eco-design concept of office chair

IV. Conclusions

In this paper, an integration of ECQFD and Weighted Decision Matrix for evaluation of eco-design alternatives is presented with a simple case study of an office chair. ECQFD methodology which consists of four phases is used at the beginning of Conceptual design stage for design improvement. Then, results from ECQFD Phase III are noted as the design criteria in Weighted Decision Matrix for evaluation of the generated design alternatives. The result has demonstrated that the final design based on environmental considerations has been successfully selected. This methodology provides a new and much more meaningful basis for developing eco-products in the design platform.

TABLE IV
ECQFD Phase IV of office chair design

Engineering Metrics / Voice of customers	Customer weights	Price (RM)	Number of part	Weight (kg)	Size / Dimension (mxmxm)	Seat height Range (m)	Maximum supported weight (kg)	Backrest angle range (°)	Seat depth (m)	Physical lifetime	Type of material	Compression of gas spring	Rate of recycle material	Improvement rate of customer requirements	Improvement effect of customer requirements
Low cost	9	9 (9)	9 (9)								9 (9)			0.0326 (0.0419)	0.293 (0.377)
Easy to use	3		3 (3)		3 (3)									0.1333 (0.1750)	0.340 (0.525)
Easy to stored	3		3 (3)		9 (9)									0.2000 (0.2208)	0.600 (0.662)
Durable	9			3 (3)						9 (9)	3 (3)	3 (3)	1 (1)	0.0254 (0.0207)	0.229 (0.186)
Good fabrics material	3	9 (9)									9 (9)		3 (3)	0.1257 (0.1686)	0.377 (0.506)
Ergonomic features	9					9 (9)	9 (9)	9 (9)	9 (9)					0.0000 (0.000)	0.000 (0.000)
Safe to use	3		3 (3)				1 (1)							0.0000 (0.0625)	0.000 (0.188)
Lighter	9		9 (9)	9 (9)							9 (9)			0.0537 (0.0419)	0.483 (0.377)
Save space	9				9 (9)									0.0889 (0.0889)	0.801 (0.800)
Recyclable material	9									1	9 (9)		9 (9)	0.0463 (0.0937)	0.417 (0.843)
More Comfort	9											9 (9)		0.0000 (0.000)	0.000 (0.000)
Improvement rate of engineering metrics		0.00	0.00 (0.25)	0.57	0.80 (0.8)	0.00	0.00	0.00	0.00	0.00	0.88	0.00	0.00		
Total														0.7059 (0.9140)	3.540 (4.464)

* the number in brackets is the score for option II

ACKNOWLEDGMENT

This research is funded by Universiti Tun Hussein Onn Malaysia (UTHM) under Incentive Grant Scheme for Publication (IGSP) with Vot no. U411.

REFERENCES

[1] Lockrey, S., "The ecocraze, a case study: negotiating a greener product design landscape", *Design Principles and Practices: An International Journal*, vol. 5, pp. 41-62, 2011.

[2] Hassan, M.F., Saman, M.Z.M., Sharif, S., Omar, B., Zhang, X., Badurdeen, F. and Jawahir, I.S. 2013. Selection of Product Design Configuration for Improved sustainability using the Product Sustainability Index (ProdSI) Scoring Method. *Applied Mechanics and Materials*. 315: 51-56.

[3] Hassan, M.F., Saman, M.Z.M., Sharif, S. and Omar, B. (2012). Integration of morphological analysis theory and artificial neural network approach for sustainable product design: a case study of portable vacuum cleaner. *Int. J. Sustainable Manufacturing*, Vol.2(4), pp.293-316.

[4] Lim, S. R., and Park, J. M., 2009, "Environmental Indicators for Communication of Life Cycle Impact Assessment Result and Their Application," Journal of Environmental Management 90, pp. 3305-3312.

[5] Bevilacqua, M., Ciarapica, F. E., Giacchetta, G. 2007. Development of a Sustainable Product Lifecycle in Manufacturing Firms: a Case Study. *International Journal of Production Research*. 45(18-19): 4073-4098.

[6] Maruschke, J., Rosemann, B. 2005. Measuring Environmental Performance in the Early Phases of Product Design using Life Cycle Assessment. *Environmentally Conscious Design and Inverse Manufacturing, Fourth International Symposium*. Tokyo. 12-14 December 2005. 248-249.

[7] Schneider, F., Salhofer, S., Schiffleitner, A., Stachura, M. (2008). The Development of an Ecodesign Product – the Ecomouse Case Study. *Progress in Industrial Ecology – An International Journal*. 5(1/2): 102-123.

[8] Gehin, A., Zwolinski, P., Brissaud, D. 2009. Integrated Design of Product Lifecycles – The Fridge Case Study. *CIRP Journal of Manufacturing Science and Technology*. 4: 214-220.

[9] Krishnan, S. S., Sunder, P. S., Vunnam, V., Balasubramaniam, N. 2013. *Integrating Low Carbon and Energy Efficiency Constraints in Sustainable Product Design*. CIRP Design. London: Springer.

[10] Russo, D. 2011. A Computer Aided Strategy for More Sustainable Products. *Proceedings of the 4th IFIP WG 5.4 Working Conference, CAI 2011*. Strasbourg, France. 30 June–1July 1 2011.149-162.

[11] Chiu, M. C., and Chu, C. H. (2012). Review of Sustainable Product Design from Life Cycle Perspectives. *International Journal of Precision Engineering and Manufacturing*. Vol. 13, No. 7, 1259-1272.

[12] Chan, H. K., Wang, X., and Chung, S. H. (2013). A Fuzzy-AHP framework for evaluation of eco-design alternative. *International Journal of Innovation, Management and Technology*. Vol. 4, No. 1, pp. 147-151.

[13] Ng, C. Y., and Chuah, K. B. (2012). Evaluation of eco design alternatives by integrating AHP and TOPSIS methodology under a

fuzzy environment. *International Journal of Management Science and Engineering Management*. Vol. 7, Issue 1, pp. 43-52.

[14] Ng, C. Y., and Chuah, K. B. (2014). Evaluation of design alternatives' environmental performance using AHP and ER approaches. *IEEE System Journal*. Vol. 8, No. 4, pp. 1182-1189.

[15] Cunningham, B., Battersby, N., Wehrmeyer, W., and Fothergill, C., 2004, "A Sustainability Assessment of a Biolubricant," *Journal of Industrial Ecology*, vol. 7, no. 3-4, 179-192.

[16] Wang, J., Yu, S., Qi, B. and Rao, J. (2010). ECQFD & LCA based methodology for sustainable product design. *2012 IEEE 11th International Conference on Computer-Aided Industrial Design & Conceptual Design (CAIDCD)*, pp.1563-1567.

[17] Romli, A., Prickett, P., Setchi, R. and Soe, S. (2015) Integrated eco-design decision-making for sustainable product development. *International Journal of Production Research*, Vol. 53, No. 2, pp. 549-571.

[18] Vinodh, S. and Rathod, G. (2010). Application of ECQFD for enabling environmentally conscious design and sustainable development in an electric vehicle. Clean Techn Environ Policy. Vol.13(2), pp.381-396.

[19] Vinodh, S., and Rathod, G., 2010, "Integration of ECQFD and LCA for Sustainable Product Design," *Journal of Cleaner Production 18*, 833-842.

[20] Hassan, M. F., Saman, M. Z. M., Sharif, S., Omar, B., "Sustainability evaluation of alternative part configurations in product design: weighted decision matrix and artificial neural network approach," *Clean Techn Environ Policy*, vol. 18, no. 1, pp. 63-79, 2016.

TABLE V
Weighted decision matrix of office chair design alternatives

			Design A			Design B			Design C		
Phase III option II engineering metrics	**Phase I relative weights**	**Units**									
			Mag.	**Score**	**Rating**	**Mag.**	**Score**	**Rating**	**Mag.**	**Score**	**Rating**
Material consumption	0.09	Experience	High	8	0.72	High	8	0.72	High	8	0.72
Rate of recyclable material	0.09	Experience	Good	7	0.63	High	8	0.72	Good	7	0.63
Dimension of backrest	0.06	m x m x m	0.4 x 0.27 x 0.038	8	0.48	0.37 x 0.3 x 0.04	7	0.48	0.32 x 0.29 x 0.025	9	0.54
Number of part	0.07	Experience	High	8	0.56	Good	7	0.49	Good	7	0.49
	Total				2.39			2.35			2.38