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Eco-design methods for developing new products based on QFD: a literature analysis

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Abstract: With the increasing pollution and consumption of natural resources due to the growing demand for manufactured goods, a number of eco-design methods aimed at achieving environmental suitability of products have been proposed since the 1990's. This study aimed at examining QFD applications that ensure the development of more environmentally suitable products. To this end, a systematic literature review of eco-design requirements was performed. This allowed for the identification of characteristics that the methods must meet from the environmental point of view and application. For this review on the eco-design requirements, 17 publications based on QFD were analyzed. One of the main results from the eco-design QFD analysis was the absence of the traditional QFD characteristics such as quality plan, design quality, and deployment of technical requirements into components, processes, etc. Another result determined through the analysis was that many authors consider only the house of quality as the whole QFD when they are developing environmental methods. In conclusion, most of these methods cannot be considered QFD, and often do not really promote environmental benefits as well.

Keywords: eco-design, environmental issues, QFD.

1. Introduction

Environmental issues have been introduced in new product development especially from the 90's. The terms usually referred to those are eco-design or design for environment. Eco-design can be defined as product development that incorporates environmental concern considering environmental requirements that allow reducing environmental impacts in product life cycle (BAKKER, 1995). To improve environmental aspects of products a number of practices have been considered such as simple methods, tools, and guidelines to more complex techniques such as life-cycle management (BOVEA; WANG, 2007).

Among the eco-design practices, some of them are adapted from methods and tools already available in new product development body of knowledge. One of methods and tools that have emerged in the literature is QFD (quality function deployment). There have been a large number of publications on 'environmental QFD' in the past ten years when compared to other methods and tools. One of the main advantages of using QFD in eco-design is the possibility to consider environmental requirements when developing a new product by translating those requirements into design specifications (MASUI; SAKAO; INABA, 2001).

Although the benefits of eco-design methods some authors argue that not always new products are environmentally better (RITZEN; LINDAHL, 2001) as well as eco-design practices are not necessarily applied in the product development (KNIGHT; JENKINS, 2009). In this sense, this paper aims at analyzing a number of publications that propose eco-design methods based on QFD. To do so, a systematic literature review was conducted. Twelve research strings related to the terms 'QFD and 'ecodesign', 'design of environmental', and others were used to search 7 data bases. As a result, 17 methods based on QFD published between 1993 and 2009 were identified.

The paper is organized as follows: the next section presents the research design followed by the description of eco-design methods based on QFD. The third section analyzes the literature and the final one establishes some concluding remarks and future work.

2. Research design

This work has adopted a systematic literature review that involves specific objectives that allow a critical analysis of data collected from the literature, solve possible conflicts of published works as well as identify research questions for further work (BIOLCHINI et al., 2005). Firstly, research strings were identified (Table 1). The main objective was

Table 1. Research strings for eco-design methods based on QFD.

QFD ecodesign	Quality function deployment ecodesign
QFD eco-design	Quality function deployment eco-design
QFD DfE	Quality function deployment design for environment
QFD design for environment	Environmental QFD
Quality function deployment DfE	Environmental quality function deployment
QFD ambiental	Quality function deployment environmental

Table 2. Accessed data bases.

Data base	URL
Compendex	http://www.engineeringvillage2.org
IEEE	http://ieeexplore.ieee.org
Science Direct	http://www.sciencedirect.com
Emerald	http://www.emeraldinsight.com
Web of Science	http://isiknowledge.com
Google Scholar	http://scholar.google.com.br
Scielo (Brazilian)	http://www.scielo.org

to identify eco-design methods available in the literature related to QFD.

Secondly, using the strings, a literature search was conducted whose main targets were publications in various data bases, such as Compendex, Science Direct, and Web of Science (Table 2).

Finally, the main criterion used to select the articles on QFD was based on only those methods related to new product/service development that considered environmental issues. All selected articles were then recorded in a spreadsheet for further analysis. The analysis considered some basic QFD characteristics based on the literature (AKAO, 1990; CAUCHICK MIGUEL, 2008; CHENG; MELO FILHO, 2007). This allows checking if those eco-design methods may be considered as QFD in the sense of its concepts and characteristics.

3. Synthesis of eco-design methods based on QFD

As mentioned in the introduction, after conducting a systematic literature review, 17 eco-design methods based on QFD were identified, from 1993 to 2009. Table 3 presents a general profile of the publications and Table 4 shows important aspects of eco-design methods proposed by the literature. Each of them is outlined next in a chronological order.

The first method identified in the literature was proposed by Hochman and O'Connell (1993). The authors claim that the method aims at improving quality, speed, and costs of implementation of eco-design initiatives, i.e. reduction of environmental impacts in the product life-cycle. This proposal presents very few differences to traditional QFD matrix; the environmental requirements are present in the matrix together with product specifications.

Green QFD-II was developed by Zhang, Wang and Zhang (1999) with the objective of integrating environmental and cost issues to QFD matrices. It uses life-cycle cost (LCC) and life-cycle assessment (LCA). Green QFD-II also proposes a concept selection matrix that relates conventional product specifications, environmental issues, and costs as well as analyses those requirements together and individually.

QFDE by Masui, Sakao and Inaba (2001) is one of the most cited methods in the subject of environmental QFD. It is basis of other publications such as '3D-QFDE', 'Eco-VOC', integration 'QFDE/LCA' and 'QFDE/LCA/TRIZ'. Its objective is to identify which functions and components must be prioritized to satisfy a customer concerned with environmental issues in addition to help engineers who are not familiar with environmental sciences. As a fundamental difference, QFDE presents a set of 15 environmental requirements and 15 engineering measures that must be incorporated to demanded quality and quality characteristics.

Wong and Juniper (2002) developed the Green Quality Function Deployment (GQFD). It relates environmental requirements and demanded quality to product specifications. This proposal points out the importance of considering all stakeholders in the process of obtaining VoC (Voice of Customer). However, it does not present significant differences with traditional QFD.

Rahimi and Weidner (2002) propose the QFD-DfE. It aims at relate customer requirements, cost reduction, and environmental impacts with design characteristics, considering the product life-cycle. Its application involves three distinct phases of design: to define product as a whole, its components, and product attributes. Although the QFD-DfE considers environmental issues and costs, similarly to Green-QFD II, it differentiates because do not use LCC and LCA as in ref. (ZHANG; WANG; ZHANG, 1999).

Kato and Kimura (2003) developed the Environmental QFD to systematize environmental and technological issues. Quality demanded is divided into 3 types of requirements: user, social, and company's. The last one is related to environmental requirements. Quality characteristics are also divided into groups and related to the phase of product life-cycle: definition of raw material, design, manufacturing, sales, usage, recycling, and reverse logistics.

Table 3. Demographics of the publications.

Year	Author(s)	Source	Origin
1993	Hochman and O'Connell	IEEE	USA
1999	Zhang, Wang and Zhang	International Journal Production Research	USA
2001	Masui, Sakao and Inaba	IEEE	Japan
2002	Wong and Juniper	8th International Interdisciplinary Conference on the Environment	Australia
2002	Rahimi and Weidner	The Journal of Sustainable Product Design	USA
2003	Kato and Kimura	Proceedings of EcoDesign Conference	Japan
2003	Yim and Hermann	Proceedings of EcoDesign Conference	Germany
2003	Ernzer, Matthei, and Birkhofer	Proceedings of EcoDesign Conference	Germany
2003	Sakao, Watanabe and Shimomura	Proceedings of EcoDesign Conference	Japan
2003	Ernzer and Birkhofer	The 1st international workshop on sustainable consumption	Germany
2005	Shih and Liu	IEEE	Taiwan
2005	Sakao et al.	3rd Int. Symposium Environmentally Conscious Design and Inverse Manufacturing	Japan
2007	Cagno and Trucco	Int. J. Product Life-cycle Man	Italy
2007	Sakao	Int. J. Production Research	Germany
2008	Wolniak and Sędek	Quality and Quantity (research note)	Poland
2009	Kuo, Wu and Shieh	Expert Systems Application	Taiwan
2009	Utne	Journal of Cleaner Production	Norway

Table 4. Eco-design methods based on QFD.

Year	Author(s)	Highlights
1993	Hochman and O'Connell	Adaptation of traditional QFD by considering some environmental requirements
1999	Zhang, Wang and Zhang	Green QFD-II based on life-cycle cost and life-cycle assessment
2001	Masui, Sakao and Inaba	QFDEnvironment identifies functions and components to be prioritized
2002	Wong and Juniper	Green QFD relates environmental requirements, demanded quality and specifications
2002	Rahimi and Weidner	QFD-DfE relates customer satisfaction, cost reduction and environmental impacts
2003	Kato and Kimura	Environmental QFD systematizes environmental with technological requirements
2003	Yim and Hermann	Eco-VOC tries to identify the 'voice of environmental customer' ('eco-voice')
2003	Ernzer, Matthei and Birkhofer	EI2QFD obtains the 'voice of the environment' through 'eco-Indicator 99
2003	Sakao, Watanabe and Shimomura	QFD is based on a 'receive state parameter' to design environmental conscious services
2003	Ernzer and Birkhofer	Eco-QFD deploys market demands into product environmental requirements that
2005	Shih and Liu	3D QFDE analyses *n* product design under the perspective of the environment
2005	Sakao et al.	QFD/LCA proposes to integrate life-cycle assessment into QFDE
2007	Cagno and Trucco	IGQFD simplifies Green-QFD II by excluding cost analysis
2007	Sakao	QFDE/LCA/TRIZ applies life-cycle assessment and TRIZ to QFDE
2008	Wolniak and Sędek	QFD Environmental identifies critical environmental parameters
2009	Kuo, Wu and Shieh	Eco-QFD applies fuzzy logic to value environmental customer requirements and others
2009	Utne	Eco-QFD aims at improving environmental performance of fishing fleet

A new contribution presented by authors is the use of 'quantification theory type IV' that allows to analyze matrix results in a bi-dimensional diagram. Figure 1 illustrates some aspects of that research.

Eco-VoC was developed from QFDE by Yim and Hermann (2003). Its objective is to present an alternative that facilitates the identification of 'environmental voice of customer', called 'eco-voice'. The stage of extracting the eco-voice is based on 3 steps. After defining the environmental voice of customer, the authors (YIM; HERRMANN, 2003) propose the use of a simplified version of QFDE from Masui, Sakao and Inaba (2001).

EI2QFD is presented by Ernzer, Matthei and Birkhofer (2003) and aims at obtaining the 'voice of environment'. It is obtained from a method called 'eco-indicator 99' commonly used in life-cycle assessment. The voice of environment represents environmental issues need for a product. To do so, the proposal uses a QFD structure that consists of two 'environmental matrices'. Both of matrices establish as demanded quality the results from eco-indicator 99; the first group comprises requirements related to the stage of usage (first matrix) and production requirements as well as end of life for second matrix.

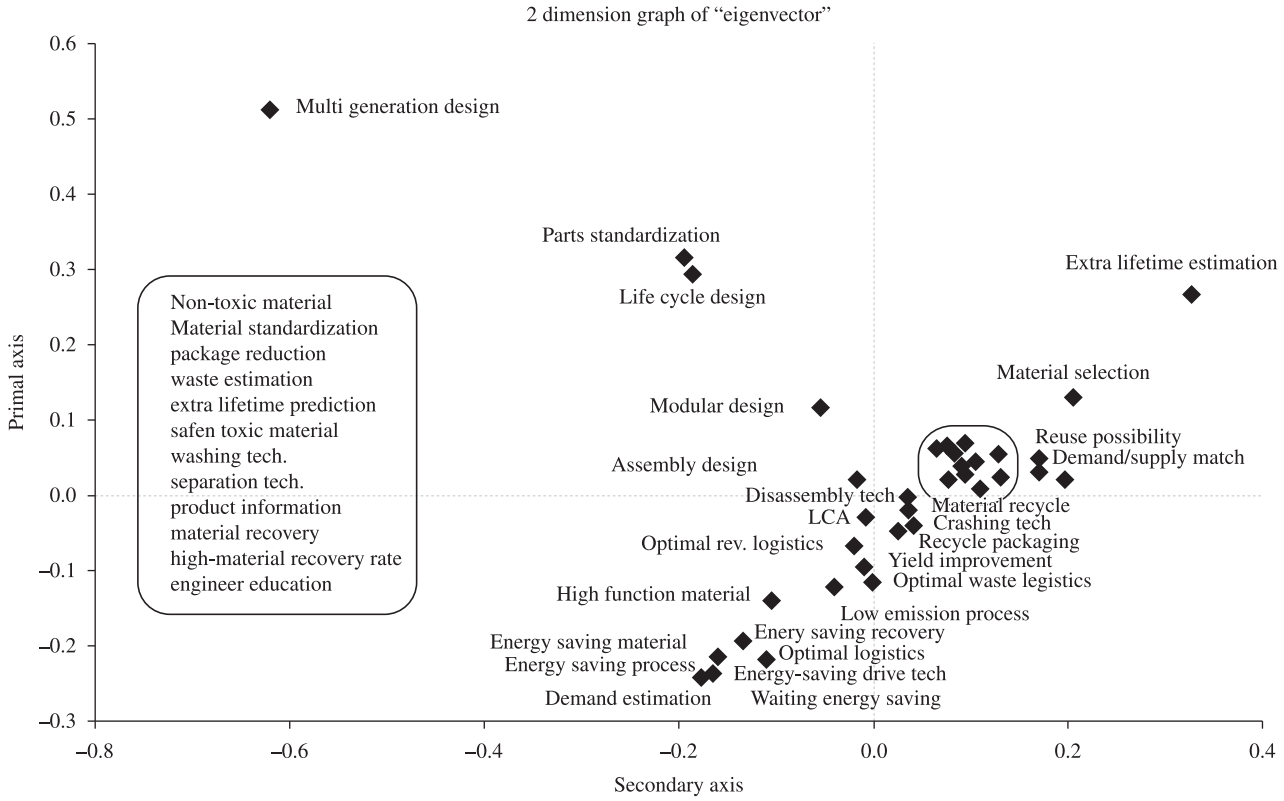

Figure 1. Quantification of requirements in the environmental QFD (KATO; KIMURA, 2003).

Sakao, Watanabe and Shimomura (2003) presents a method that considers RSP or 'Receive State Parameter' whose objective is to design services with environmental conscious by using QFD. Therefore, the main contribution of that proposal is to design services that are more environmentally suitable.

Ernzer and Birkhofer (2003) propose a method based on QFD, called of 'eco-QFD' to deploy market needs into design requirements that take into account product environmental issues. The structure of eco-QFD is not different from traditional QFD with regard to the way of applying it.

3D QFDE is published by Shih and Liu (2005). It is another method that is based on QFDE proposed by Masui, Sakao and Inaba (2001). It analyses a number of product designs under 3 distinct perspectives: quality, costs, and environmental issues. The results from product designs considering the 3 perspectives are plotted in a pyramidal form, where each vertice represents quality, costs, and environmental issues in order to assist in selecting the best product design.

The proposal of Sakao et al. (2005) aim at integrating life-cycle assessment to QFDE. Therefore, QFDE is to be used in the initial stages of new product development and, as soon more data and information are available, a qualitative assessment of environmental impacts is calculated through life-cycle assessment.

Cagno and Trucco (2007) developed a QFD environmental method that fixes the limitations of Green-QFD II. The main changes consist of excluding cost analysis and simplifying life-cycle assessment. The quality matrix is then divided into 4 parts, where the voice of customer is related to quality function and to the environmental goals as well as the voice of environment is related to quality function and to the environmental goals.

Similarly to the integration of QFDE to quality functions and life-cycle assessment, the proposal by Sakao (2007) tries to integrate life-cycle assessment and TRIZ (Theory of Inventive Problem Solving) to QFDE. Life-cycle assessment is initially used in early product design when customer and environmental issues and its impacts are determined. This is followed by phases I and II of QFDE, i.e. when quality product characteristics are defined. TRIZ is applied in the third phase in the search of design solutions. Phases III and IV of QFDE are then applied in the product concept evaluation, followed by phase V that is applied in the product detainment. Finally, life-cycle assessment is applied again to evaluate the proposed environmental improvements.

Wolniak and Sędek (2008) present a version of environmental QFD to list ecological information to product and service alternatives. From this relation it

identifies critical parameter under the point of view of the environment. Practically, there is no difference when comparing the proposal to traditional QFD, except for some requirements that are exclusively environmental issues that may be applied either to products or services.

Kuo, Wu and Shieh (2009) developed an environmental QFD that uses fuzzy logic to help in identifying and weight the level of importance of customer requirements either environmental or not. Each demanded quality is evaluated and transformed in a fuzzy output. This task is carried out by a group of experts. Those requirements are related to product specifications (quality characteristics) in the different stages of product life-cycle, namely: definition of raw material, design and manufacturing, distribution, usage and recycling.

Utne (2009) also proposes a method based on QFD. According to the author the main objectives are: to have a performance improvement of fishing fleet are well as to help management activities. This is accomplished by considering environmental issues, costs, and stakeholders.

4. Analysis of eco-design methods based on QFD

Before discussing the methods described in the previous section, the main characteristics of QFD is established. Those are important to be used for conducting the analysis.

Conceptually, QFD is a method that allows assuring quality in each stage of new product development with the objective of customer satisfaction by translating demanded quality into design goals (AKAO, 1990). As extensively established in the literature, the quality matrix is an important part of the method to relate demanded quality with quality characteristics. In doing so, there exist other elements which are also relevant such as the level of importance given to the demanded quality by customers, commercial benchmarking, quality planning as well as the design quality to prioritize product specifications (quality characteristics).

Quality matrix (also referred to 'house of quality' in the literature) is not the whole QFD. Quality Function Deployment is a generic name for quality deployment and narrowly defined quality function deployment. Quality deployment is defined as translating the user demands into substitute characteristics (quality characteristics), determining the design quality of a completed product, and systematically deploying the quality of each product system into that of each component and processes as well as the relationship among them. Narrowly defined QFD is defined as systematically deploying the job functions and operations that contribute to quality into step-by-step details. Figure 2 illustrates QFD definition by Akao (1998).

Quality deployment is the first step in QFD by initiating from quality matrix and others may be in place to deploy quality throughout the stages of product development (AKAO, 1998). Nevertheless, the application of QFD

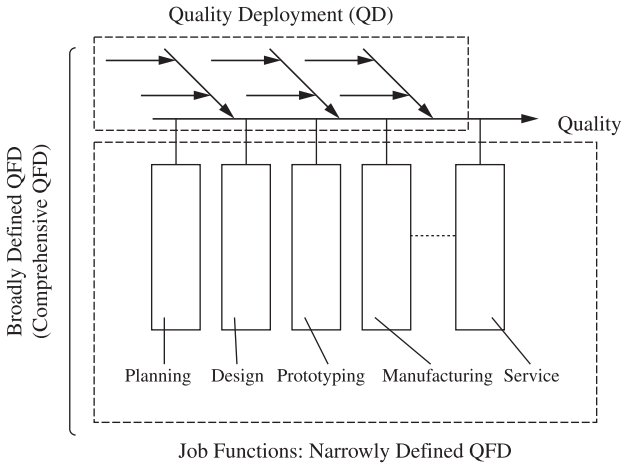

Figure 2. Definition of QFD (AKAO, 1998).

usually emphasizes the quality matrix as in the 17 eco-design methods proposed in the literature. Therefore, some important characteristics in the quality matrix were selected to analyze those proposals, namely: quality planning, design quality, deployment, etc. Those characteristics usually found in the traditional QFD applications were then considered in the analysis. To do so, a matrix was developed to compare the 17 eco-design methods, as showed in Table 5.

As can be seen in Table 5, none of the 17 eco-design methods presented all 5 QFD characteristics. The eco-design method more loyal to traditional QFD is the one of Hochman and O'Connell (1993), as expected since it is the oldest one published. Along the years, the others changed compared to original QFD from Akao (1990). Nevertheless, they incorporated other tools and techniques to be integrated into concepts such as life-cycle assessment, fuzzy logic, and TRIZ. Very few eco-design methods considered deployments so they are not properly QFD in essence but an application of only one matrix, which could be necessary but not enough.

Other issues are identified in the eco-design methods. One is the amount of data used for some of them. In the example of 'Environmental QFD' (KATO; KIMURA, 2003) 27 demanded quality items and 40 quality characteristics are presented that lead to 1,080 possible relations, which may be time-consuming. Some eco-design methods are prescriptive since they suggest a list of environmental demanded quality and/or quality characteristics, e.g. Masui et al. (2001). Although this could be useful it can also be a drawback since those requirements are not, in fact, developed. The more suitable thing to do would be to encourage the team to identify those requirements from the main stakeholders.

The use of more complex tools are usually welcome, e.g. life-cycle assessment, fuzzy logic, and so on. The downside is that may bring inherent difficulties to those who are not familiar with them. Sometimes, users who dot not know how

Table 5. Analysis of eco-design methods based on QFD.

Ecodesign methods basedon QFD	Tradicional QFD characteristics					Rating of ecodesign methods based on QFD
	Quality planning	Design quality	Deployment in phases	Correlation of technical requirements	VOC deployment in levels	
QFD (HOCHMAN; O'CONNELL, 1993)	V	V	X	V	V	4
Green QFD-II (ZHANG et al., 1999)	X	X	X	V	X	1
QFDE (MASUI et al., 2001)	X	X	V	X	X	1
GQFD (WONG; JUNIPER, 2002)	V	V	X	V	X	3
QFD-DfE (RAHIMI; WEIDNER, 2002)	X	X	X	V	X	1
Environmental QFD (KATO; KIMURA, 2003)	V	X	X	X	X	1
Eco-VOC (YIM; HERMANN, 2003)	X	X	X	X	V	1
EI2QFD (ERNZER et al., 2003)	X	X	X	X	V	1
QFD based on RSP (SAKO; WATANABE; SHIMOMURA, 2003)	X	X	X	X	X	0
Eco-QFD (ERNZER; BIRKHOFER, 2003)	X	X	X	X	V	1
3D-QFDE (SHIN; LIU, 2005)	X	X	X	X	X	0
Integration QFDE/LCA (SAKAO et al., 2005)	X	X	V	X	X	1
IGQFD (CAGNO; TRUCCO, 2007)	V	X	X	V	X	2
Integration QFDE/LCA/TRIZ (SAKAO, 2007)	X	X	V	X	X	1
QFD (WOLNIAK; SĘDEK, 2008)	X	X	X	V	X	1
Eco-QFD (KUO, 2009)	X	X	X	X	X	0
Eco QFD (UTNE, 2009)	V	X	X	V	X	2
# of QFD characteristics found on the ecodesign methods	5	2	3	7	4	

V - shows at least in part. X - shows nothing.

to apply them may choose not to deal with them. It can be observed that some eco-design methods may not deliver the environmental benefits they promise. It is well-known that some products do have environmental impacts in their use, e.g. a washing machine. So, not considering it in the stage of usage of a product is not suitable like the one showed by Masui et al. (2001). In addition, the eco-design method proposed by Wolniak and Sędek (2008) establishes some environmental requirements too general, e.g. 'air pollution'. This requirement may occur from a number of sources (e.g. fossil fuels, industrial activities, painting, etc.). The lack of defining a requirement more precisely (further deployments) may lead to incomplete or wrong decisions in new product development.

5. Conclusions

Under the emerging demand of developing eco-products, the development of eco-design is welcome. In this sense, current work presented eco-design methods found in a systematic literature review. Almost all eco-design methods cannot be considered as extensions of traditional QFD methodology. They do try to translate demanded environmental issues into design specification but, most of them are, in fact, simplified versions of a quality matrix where environmental requirements are introduced. Reaching environmental improvement with those methods is also questionable. This is due to a number of reasons such as over complexity, no consideration of some phases of product life-cycle (especially with regard to the VoC) or the use of generic terms to represent environmental issues. Another issue is that the effort for carrying the eco-design methods may be long and time consuming. A concluding point that rose is that most publications are theoretically weak and, in some cases, empirically as well. Based on the current analysis, future work will involve further development of QFD applied to eco-design methods in an attempt to contribute to environmental studies.

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