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An Environmental and Operational Analysis of Quality Function Deployment-Based Methods

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Abstract: Ecodesign consists of integrating environmental considerations into the product development process by means of practices that involve the use of methods, techniques, tools, and guidelines. However, many published practices do not incorporate important environmental issues, often resulting in a product development process that is ineffective from an ecodesign standpoint. This paper's aim is threefold: (i) Identifying environmental and operational criteria and determining weights to these criteria; (ii) assessing and selecting quality function deployment (QFD)-based ecodesign methods using environmental and operational criteria, and (iii) analyzing the practitioners' perception of the most suitable QFD-based method identified by the second aim. To that end, a comprehensive literature review of ecodesign practices based on QFD and its requirements was carried out, and a survey was conducted with environmental science and product development experts, whose answers enabled the prioritization of the characteristics those practices must meet from environmental and operational standpoints. Thereafter, a workshop was carried out with design engineers from an automotive company in Brazil. This study's findings indicate that many QFD-based ecodesign methods fail to consider the life cycle perspective, do not assess environmental impacts, and have not been tested before being published. Another finding from industry designers suggests that ecodesign methods should be easy to use and not time-consuming.

Keywords: design for environment; criteria; requirements; quality function deployment; automotive company

1. Introduction

There is an increasing demand from stakeholders, customers, governments, academic experts, Nongovernmental Organizations (NGOs), and shareholders for organizations to assume greater responsibility for their share of environmental degradation. In other words, companies and their products are seen as responsible for many environmental problems, including climate change, ozone layer depletion, and soil and water pollution. On that note, the European Union, for instance, has established concrete actions to reduce greenhouse gas (GHG) emissions by 2020 [1]. Environment-supporting directives have been in place, and their mandatory requirements have been pushing companies towards adopting ecodesign initiatives [2]. Taking directives from the European Union alone as examples, one can cite Directive 2009/1.25/EC, which has established a framework for the setting of ecodesign requirements for energy-related products, and Directive 2011/65/EU, regarding the restriction of the use of certain hazardous substances in electrical and electronic equipment. These have made existing products (also new products once they are developed) incorporate a certain level of improvement from an environmental perspective.

Moreover, environmental issues have become an important factor of competitive advantage. According to Porter and Van der Linde [3], products and processes must be rethought to reduce costs and create value, because resisting environmental innovation can lead, not only to environmental problems, but also to loss of global competitiveness. This means that the development of environmentally friendly products and processes is considered an environmental strategy that provides opportunities for cost reduction, optimization of resource use, customer loyalty, improvement of organizational image, and reduction of environmental violations and legal penalties [4–6]. Thus, the development of products with an environmental conscience allows companies to adopt sustainable measures.

In order to develop green products, designers began to address environmental aspects in the product development process [7], which became known as ecodesign or Design for Environment (DfE). Ecodesign has emerged as a proactive approach to develop more eco-friendly products, and this concept has received a large number of definitions. Proponents of ecodesign in organizations generally include sustainability teams involved in the ecodesign agenda [8]. Nonetheless, ecodesign usually exceeds the environmental dimension of business performance [9] and enables opportunities for improvements in a range of projects [10]. Nowadays, sustainability-driven approaches have been taken by organizations, and even more attention is now being paid to environmental responsibility [11]. Based on these definitions, several opportunities for product development emerge from this contribution.

The ecodesign concept adds environmental considerations to the product life cycle [12], enables the guiding of the product design [13], and can significantly reduce the environmental impacts of a product [14]. Making use of ecodesign techniques in companies is not trivial, because such techniques are usually neither easy to use nor quickly applicable [15]. Recently, research has shown the importance of reducing environmental impacts (see, for example, [16,17]), and ecodesign techniques, together with the pre-project of a product, seem to be promising and move in the same direction.

According to Ritzén and Lindahl [18], ecodesign sometimes improves a product's environmental performance but sometimes does not, whereas Knight and Jenkins [15] state that many ecodesign practices fail because they do not focus on product design. Moreover, Bovea and Perez-Belis [19] reported that ecodesign practices are rarely implemented and that case studies are often merely theoretical examples.

Although it appears that ecodesign tools need greater action in the early design stages [20], it is known that ecodesign is usually applied through a set of practices, many of which are based on original proposals, while others consist of modifications of practices already used in product development processes.

These ecodesign practices have been published extensively in the last two decades, and hundreds of ecodesign methods, tools, techniques, and guidelines are known today. Nonetheless, not all these methods necessarily promote environmental improvement, and not all of them can be easily adopted in practice by designers. Based on all the aforementioned, this paper's aim is threefold: (i) Identifying environmental and operational criteria and determining weights to these criteria; (ii) assessing and selecting quality function deployment (QFD)-based ecodesign methods using environmental and operational criteria, and (iii) analyzing the practitioners' perception of the most suitable QFD-based method identified by the second aim. The theoretical contribution of this paper refers to the approach used adjoined with the use of ecodesign and QFD, as well as reporting on the practical experience of a real case in an automotive company in southern Brazil. Moreover, the study contributes to the development of research in terms of ecodesign and QFD, and also with the industrial sector, with techniques and tools to improve product development methods.

A few reasons can be given in order to justify why ecodesign practices based on QFD were addressed. QFD is a tool widely used by quality and product development engineers for turning intangible customer needs into tangible engineering metrics. Currently, QFD has become a well-used quality management tool in product design and development around the world, and QFD-based methods are sources of research and comparisons in the academic literature [21].

When considering QFD for ecodesign purposes, these represent a significant portion of the universe of ecodesign practices. Pigosso [22] listed around 110 ecodesign methods, varying from Life Cycle Assessment (LCA)-based tools to new design practices, and five of them were based on QFD. Puglieri and Ometto [23] presented 17 QFD-based methods for ecodesign, while the same article identified only two Failure Mode and Effect Analysis (FMEA) methods, which are also adopted in industrial engineering areas.

The paper's introduction and objective have been presented in this first section. Looking to accomplish this study's objective, Section 2 depicts the methodology used to conduct the research. Section 3 presents the QFD methods for ecodesign, and their respective authors. Section 4 introduces the proposal and definition of criteria. Section 5 shows the scores of QFD-based ecodesign methods and a discussion of such results, together with the implications observed in the test of the method that scored best. Finally, Section 6 draws on the final considerations of this study.

2. Methodology

The methodology used to conduct this piece of research is comprised of five steps:

1) A literature review of ecodesign requirements and ecodesign methods based on QFD;
2) Analysis of ecodesign QFD methods under the traditional QFD characteristics;
3) Definition of ecodesign criteria for QFD methods;
4) Analysis of ecodesign QFD methods based on the proposed criteria;
5) Designers' perception on a QFD-based ecodesign method.

1). A literature review of ecodesign requirements and ecodesign methods based on QFD

The purpose of the first step, the literature review, was to identify ecodesign requirements for the development of environmental and operational criteria. A literature review was conducted to identify ecodesign practices based on QFD published between 1993 and 2018 in two databases (Web of Science and ScienceDirect).

These databases contained papers from journals and conference proceedings on engineering and environmental sciences, including product development and ecodesign. The search was conducted, considering all fields, using the following query, with boolean operators and truncation symbols: *("eco design" OR "eco-design" OR "ecodesign" OR DfE) AND ("quality function deployment" OR QFD)*. The query, and thus the number of searches, were adapted as needed, according to the idiosyncrasies of each database. QFD-based ecodesign methods were chosen because they comprise a large number of publications and are widely used for product development.

The Web of Science resulted in 48 articles and ScienceDirect resulted in 199 articles. These documents were exported to a reference manager software to exclude duplicated documents and articles published in sources other than peer-reviewed journals. In the sequence, a series of filters was applied to select only relevant literature: (i) title, keywords—all titles and abstracts were read, and articles that were aligned with the intent of this research were kept; (ii) all abstracts were read, and articles that were deemed relevant, i.e., potentially providing QFD-based ecodesign methods, were kept; and (iii) full reading—all articles were read, and only studies providing QFD-based ecodesign methods were selected.

Therefore, 29 documents made our final portfolio, which can be seen in Table 2.

2). Analysis of ecodesign QFD methods under the traditional QFD characteristics

After identifying the QFD-based ecodesign methods by means of the literature review, they were analyzed according to the traditional characteristics of Akao's QFD. To this end, the main QFD phases were identified from three QFD references [24–26]. Thereafter, using a relationship-matrix, each ecodesign QFD method was analyzed based on those traditional characteristics, with an aim to determine whether it really was a QFD method or simply part of one.

3). Definition of ecodesign criteria for QFD methods

The environmental and operational requirements were first identified by means of a literature review based on the same databases used to search for QFD-based ecodesign methods. These environmental and operational requirements for ecodesign practices were detailed in specific criteria for traditional QFD characteristics, thus allowing for the analysis of QFD-based ecodesign methods.

A survey comprising environmental and operational criteria for QFD methods was sent to product development and life cycle engineering experts. The purpose of that survey was to prioritize environmental and operational criteria for subsequent analysis of the QFD-based ecodesign methods. Eighteen experts were asked to answer the survey by e-mail, and eight researchers responded.

The criteria were prioritized on a Likert scale, with each expert ranking the environmental and operational criteria starting from the most important to the least important, according to the number of criteria. For example, if four criteria were identified, the most important criterion would be given the weight "4", and the least important criterion, the weight "1," as exemplified in Figure 1.

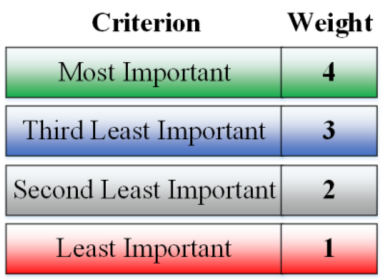

Figure 1. Likert scale for prioritization of environmental and operational criteria.

The methods were then analyzed based on the criteria weights defined in this step.

4). Analysis of ecodesign QFD methods based on the proposed criteria

The fourth step consisted of an analysis of QFD methods for ecodesign based on the prioritized environmental and operational criteria. This was done using a matrix based on the same principle as that of Akao's House of Quality (HoQ), correlating the QFD-based ecodesign methods with environmental and operational criteria. Table 1 shows an example of this matrix.

Table 1. Matrix used in the analysis of quality function deployment (QFD)-based ecodesign methods.

			QFD Methods
	Criteria	**Weight**	
Environmental			
Operational			
	Total environmental score		
	Total operational score		

The weight was defined from the sum of the all experts' prioritizations. The least important environmental criterion received a score of "1", the second least important was given a score of "2", and so on. The same principle was applied to the operational criteria.

The authors of this paper scored the correlation between the methods and criteria as follows: A score of "1" when the method did not consider the criterion; a score of "2" when the method considered the criterion only partially; and a score of "3" when the method fully considered the criterion. Thereafter, the most suitable QFD method for ecodesign (the one with the highest scores) was indicated.

5). Designers' perception survey of a QFD-based ecodesign method

Finally, in the fifth step, a workshop was carried out at a Brazilian automotive company. The aim of the workshop was (i) to present the company's design team with the most suitable ecodesign method based on QFD, indicated in Step 4; (ii) to apply the method using, as a product, an automotive engine assembled at the industrial plant; and (iii) to increase and register the designers' perceptions about the environmental and operational benefits of the most suitable QFD method chosen.

This workshop was attended by five engineers from several areas, including product development, project management, manufacturing, quality management, and industrial management, in addition to two researchers responsible for coordinating the application of the QFD-based ecodesign method.

The company did not make use of any QFD or ecodesign methods at the time the workshop was conducted. Thus, no biases were spotted for using a specific QFD-based ecodesign method. The method used in the workshop was the one that performed best, considering the environmental and operational criteria assessed in Step 4.

3. QFD Methods for Ecodesign

The goal of QFD, which was developed by Mizuno and Akao in the late 1970s, is to translate the customer's needs into product and process requirements [24]. The procedure for applying the QFD method consists of defining the Voice of Customer (VoC), i.e., the customer's desires, and through systematic deployments, determine product quality requirements, functions, control parameters, components, etc. In other words, it involves transforming the implicit into the explicit, and the informal into the formal, for product development professionals [25].

According to Miguel [26], one of the main definitions for QFD is the HoQ. HoQ is defined as the two-dimensional matrix of a required quality table and deployed quality characteristics. Its main goal is to transform each aspect of quality required by customers into quality characteristics expressed in engineering language [24]. The HoQ is represented basically by two triangles—required quality and quality characteristics—and a square, as illustrated in Figure 2.

However, the HoQ should not be understood as representing the entire QFD [24]. QFD encompasses two broader concepts known as quality deployment and narrowly defined QFD. On the one hand, quality deployment is defined as the translation of 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 process, as well as the relationship between them. On the other hand, narrowly defined QFD is the systematic deployment of the job functions and operations that contribute to quality in step-by-step details [26].

The development of ecodesign practices has grown since the early 1990s, and many of these practices are based on established methods, including QFD.

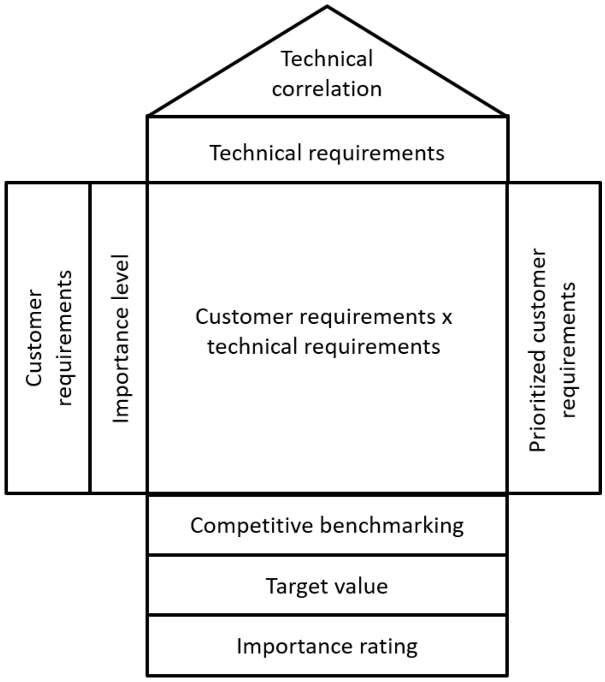

Figure 2. House of Quality (HoQ).

Based on a comprehensive literature review, twenty-nine QFD-based ecodesign methods were identified and are listed in Table 2 (a brief explanation of each method can be seen in the Supplementary Materials). These QFD-based ecodesign methods range from the simple application of Akao's House of Quality to more complex methods involving Life Cycle Assessment (LCA) and Life Cycle Cost (LCC).

Table 2. Summary of QFD methods.

Year	Name of Method	Authors	Country	Source
1993	**QFD**	Hochman and O'Connell [27]	USA	IEEE
1999	**Green QFD-II**	Zhang et al. [28]	USA	International Journal of Production Research
2001	**QFDE (Quality Function Deployment for Environment)**	Masui et al. [29]	Japan	IEEE
2002	**GQFD (Green Quality Function Deployment)**	Wong and Juniper [30]	Australia	8th International Interdisciplinary Conference on the Environment
2002	**QFD-DfE**	Rahimi and Weidner [31]	USA	The Journal of Sustainable Product Design
2003	**Eco-Innovative Design**	Chen and Liu [32]	Taiwan	INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
2003	**Environmental QFD**	Kato and Kimura [33]	Japan	Proceedings of Ecodesign Conference
2003	**Eco-VOC**	Yim and Hermann [34]	Germany	Proceedings of Ecodesign Conference
2003	**EI2QFD**	Ernzer [35]	Germany	Proceedings of Ecodesign Conference
2003	**QFD based on RSP (Receiver State Parameters)**	Sakao [36]	Japan	Proceedings of Ecodesign Conference
2003	**Eco-QFD**	Ernzer and Birkhofer [37]	Germany	1st International Workshop on Sustainable Consumption
2005	**3D QFDE**	Shih and Liu [38]	Taiwan	IEEE

Table 2. *Cont.*

Year	Name of Method	Authors	Country	Source
2005	**QFDE and LCA**	Sakao [39]	Japan	3rd International Symposium on Environmental Design and Inverse Manufacturing
2007	**IGQFD (Integrated Green & Quality Function Deployment)**	Cagno and Trucco [40]	Italy	International Journal of Product Life Cycle Management
2007	**QFD, LCA and Theory of Inventive Problem Solving (TRIZ)**	Sakao [41]	Japan	International Journal of Production Research
2009	**QFD Environmental**	Wolniak and Sędek [42]	Poland	Quality and Quantity (research note)
2009	**Eco-QFD**	Kuo [43]	Taiwan	Expert S
2009	**Eco-QFD**	Utne [44]	Norway	Journal of Cleaner Production
2010	**Environmentally Conscious Quality Function Deployment (ECQFD)**	Vinodh and Rathod [45]	India	Journal of Cleaner Production
2010	**LCA and Function Component Matrix+E-QFD**	Devanathan et al. [46]	USA	Journal of Mechanical Design
2011	**Eco- andInno-Design Information System (EIDIS)**	Trappey et al. [47]	China	Journal of Systems Science and Systems Engineering
2011	**QFD for Green Product Design**	Subramaniyam [48]	India	International Journal of Innovation, Management and Technology
2013	**QFDE + Fuzzy Analytic Hierarchy Process (FAHP)**	Bereketli and Genevois [49]	Turkey	Journal of Cleaner Production
2014	**ECQFD, TRIZ and AHP**	Vinodh et al. [50]	India	Applied Mathematical Modelling
2015	**Integrated Ecodesign Decision-Making (IEDM)**	Romli et al. [51]	UK	International Journal of Production Research
2015	**QFDE+FANP (Fuzzy Analytic Network Process)**	Younesi and Roghanian [52]	Iran	Journal of Cleaner Production
2015	**QFD with Modularity for the EoL (End-of-life)**	Yu et al. [53]	China	Journal of Cleaner Production
2016	**House of Quality Green Design (HOQGD)**	Wood et al. [54]	New Zealand	Journal of Cleaner Production
2017	**EcoCSP-QFD**	Popoff and Millet [55]	France	Procedia CIRP

An initial analysis of these 29 ecodesign methods reveals that most of them do not consider the characteristics of a traditional QFD method. Table 3 illustrates this comparative analysis.

These main QFD characteristics were identified as planned quality, designed quality, QFD deployment in phases, correlation of quality characteristics, and VoC (Voice of Consumer) deployed in levels. As a result, none of the 29 ecodesign methods were found to present all five QFD characteristics. Over the years, the other methods have changed vis-à-vis Akao's original QFD from 1990; nonetheless, these have incorporated other concepts, e.g. Theory of Inventive Problem Solving (TRIZ), LCA, LCC, and Fuzzy approaches. Most ecodesign methods do not consider deployments; they include the use of one matrix (arguably not sufficient), but they are not necessarily a QFD.

Table 3. Analysis of QFD-based ecodesign methods based on QFD characteristics.

Codesign Method	Does the Method Consider Planned Quality?	Does the Method Consider Designed Quality?	Does the Method Consider QFD Deployment in Phases?	Does the Method Consider Correlation of Quality Characteristics?	Does the Method Consider VoC Deployment in Levels?	Method's Final Score
Hochman and O'Connell's QFD	**Y**	**Y**	N	**Y**	**Y**	4
Green QFD-II	N	N	N	**Y**	N	1
QFDE	N	N	**Y**	N	N	1
GQFD	**Y**	**Y**	N	**Y**	N	3
QFD-DfE	N	N	N	**Y**	N	1
Eco-Innovative Design	**Y**	N	**Y**	N	N	2
Environmental QFD	**Y**	N	N	N	N	1
Eco-VOC	N	N	N	N	**Y**	1
EI2QFD	N	N	N	N	**Y**	1
QFD based on RSP	N	N	N	N	N	0
Ernzer and Birkhofer's Eco-QFD	N	N	N	N	**Y**	1
3D-QFDE	N	N	N	N	N	0
QFDE/LCA	N	N	**Y**	N	N	1
IGQFD	**Y**	N	N	**Y**	N	2
QFDE/LCA/TRIZ	N	N	**Y**	N	N	1
Wolniak and Sedek's QFD	N	N	N	**Y**	N	1
Kuo's et al. Eco QFD	N	N	N	N	N	0
Utne's Eco-QFD	**Y**	N	N	**Y**	N	2
ECQFD	N	N	**Y**	N	N	1
LCA and Function Component Matrix+E-QFD	N	N	N	**Y**	N	1
EIDIS	**Y**	N	N	**Y**	N	2
QFD for Green Product Design	N	N	N	N	N	0
QFDE+FAHP	**Y**	N	**Y**	**Y**	N	3
ECQFD, TRIZ and AHP	N	N	**Y**	N	N	1
IEDM	**Y**	N	**Y**	**Y**	N	3
QFDE+FANP	**Y**	**Y**	**Y**	**Y**	N	4
QFD with Modularity for the EoL	**Y**	**Y**	**Y**	**Y**	N	4
HOQGD	**Y**	N	**Y**	**Y**	**Y**	4
EcoCSP-QFD	**Y**	N	**Y**	N	**Y**	3
Sum of the characteristics met by the methods	13	4	12	14	6	

Legend: **Y** = considers at least partially; N = does not consider. Source: Elaborated based on Puglieri et al. [56].

Moreover, ecodesign methods are generally data-intensive. Take, as example, [33] "Environmental QFD", which presents 27 quality items and 40 quality characteristics, leading to 1080 correlations. Other methods, yet, are prescriptive, imposing a list of characteristics (either environmental or quality-related) (e.g., [29]). On the positive side, this can be useful for having a list of requirements for assessment in place. On the negative side, though, these can be obstacles because they might be just left aside and not developed. An appropriate strategy would be to consult with the main stakeholders and identify relevant requirements.

4. Proposal and Definition of Criteria

As mentioned earlier, the third methodological step consisted of a literature review to identify the requirements that ecodesign methods should address to ensure the development of products with better environmental performance and that are easily applicable to product development. The identified requirements are listed in Table 4.

Table 4. General requirements for ecodesign methods.

		Description	References
Environmental requirements	Life cycle perspective	To meet this criterion, an ecodesign method should consider all product life cycle phases. It means that raw material extraction, transportation, manufacturing, use, and disposal phases should be included in the method's analysis. End-of-life strategies such as recycling, remanufacturing, and reuse also need to be considered.	Pigosso [57]; Waage [58]; Vezzoli and Sciama [59]; Griese et al. [60]; Talbot [61]; Maxwell and Van der Vorst [62]; Ritzén and Lindahl [18]; Rivera-Becera and Lin [63]
	Environmental laws and regulations	The method should consider environmental laws and regulations for the product. Specific country laws and regulations where the product is manufactured, used, and discarded should be included.	Knight and Jenkins [15]; Rivera-Becera and Lin [63]
	Environmental impact analysis	The ecodesign method should identify and assess environmental impacts during the entire product life cycle. Some impact categories can be used, such as natural resources and energy consumption, global warming potential, human toxicity, and other emissions to air, water, and soil.	Pigosso [57]; Waage [58]; Vezzoli and Sciama [59]; Byggeth and Hochshomer [64]; Griese et al. [60]; Maxwell and Van der Vorst [62]; Rivera-Becera and Lin [63]
Operational requirements	Easy to use	An ecodesign method is considered easy to use when the procedures for its application are detailed, e.g., using pictures or images, describing each activity, and avoiding complex mathematical models or other scientific languages unfamiliar to product designers.	Knight and Jenkins [15]; Lofthouse [65]; Hauschild et al. [66]; Lindahl [67]; Fargnoli [68]; Boks and Pascual [69]; Ritzén and Lindahl [18]
	Low application cost	An ecodesign method does not meet this criterion when its application requires time-consuming training, hiring experts or consultants, or a new software tool is required to be bought.	Knight and Jenkins [15]; Pigosso [57]; Hauschild et al. [66]
	Already validated in real cases	An ecodesign method should be applied and validated in real cases before being published.	Pigosso [57]; Hauschild et al. [66]
	Short time required	A method meets this criterion when its application requires less time than an LCA study or other similar quantitative ecodesign methods.	Pigosso [57]; Lindahl [67]; Fargnoli [68]

Source: Adapted from Puglieri et al. [56].

As can be seen in Table 4, many authors agree that several environmental and operational requirements should be addressed in ecodesign methods. The environmental requirements range from the product life cycle to specific legislation and environmental impact analysis, while the operational requirements say that the method should be easy to use, inexpensive, easily applicable, and not time-consuming.

Based on the general requirements listed in Table 4, a set of criteria was defined as environmental criteria and operational criteria, respectively. These criteria were proposed based on the traditional characteristics of QFD, in order to allow for the analysis of the 29 identified ecodesign methods. Table 5 lists the proposed criteria.

Table 5. Environmental and Operational criteria for QFD-based ecodesign methods.

	Subject	Criteria
Environmental criteria for QFD methods.	Life cycle perspective	Are environmental requirements considered for the entire life cycle (not only the use phase)?
	Environmental laws and regulations	Are environmental laws, regulations and standards considered as a product requirement?
	Environmental impact analysis	Are environmental impacts considered as a technical characteristic to allow for their correlation with the client's quality requirements?
Operational criteria for QFD methods	Easy to use	Does the method have detailed stages of implementation, without the use of complex mathematical language (unfamiliar to designers)?
	Low application cost	Does the method require the purchase of software, hiring of experts, and/or special training?
	Already validated in real cases	Was the method applied in practice during the product development process?
	Short time required	Does the method comprise more steps than the traditional QFD?

The three environmental criteria and four operational criteria were ranked by academic experts to identify the scale of importance for each criterion (according to Step 4 in the methods section), thus, determining how important each environmental and operational criterion is for ecodesign, compared to one another. This approach was used to bring the opinions of experts to the analysis of the QFD-based methods, as presented in Section 5.1.

Each environmental and operational criterion was given a score according to the number of criteria (from the most to the least important). In this context, since three environmental criteria and four operational criteria were proposed, the most important environmental criterion received a weight of 3, the second most important received a weight of 2, and the least important, a weight of 1. The same procedure was applied to the operational criteria, with the most important criterion receiving a weight of 4 and the least important, a weight of 1. Finally, adding up the weights from the eight responses to the survey, the environmental and operational criteria were organized into the following order of importance:

- Environmental criteria: Environmental impact analysis (Weight 3), environmental laws and regulations (Weight 2), and life cycle perspective (Weight 1);
- Operational criteria: Already validated in real cases (Weight 4), short time required (Weight 3), easy to use (Weight 2), and low application cost (Weight 1).

5. Results and Discussion

5.1. Method Ranking

After prioritizing the environmental and operational criteria, a correlation matrix, based on the example of Akao's House of Quality, was used to analyze the QFD-based ecodesign methods. The scores for each criterion can be seen in Table 6.

Table 6. Analysis of QFD-based ecodesign methods.

		Weight	**QFD of Hochman and O'Connell**	**Green QFD-II**	**QFDE**	**GQFD**	**QFD-DfE**	**Eco-Innovative Design**	**Environmental QFD**	**Eco-VOC**	**EI2QFD**	**QFD based on RSP**	**Eco-QFD of Ernzer and Birkhofer**	**3D-QFDE**	**QFDE/LCA**	**IGQFD**	**QFDE/LCA/TRIZ**	**QFD of Wolniak and Sędek**	**Eco QFD by Kuo et al.**	**Eco QFD de Utne**	**ECQFD**	**LCA and Function-Component Matrix+E-QFD**	**EIDIS**	**QFD for Green Product Design**	**QFDE+FAHP**	**ECQFD, TRIZ and AHP**	**IEDM**	**QFDE+FANP**	**QFD with Modularity for the EoL**	**HOQGD**	**EcoCSP-QFD**
Environmental Criteria	Life cycle consideration	1	1	3	3	2	3	1	3	3	3	1	3	3	3	2	3	1	2	1	1	3	3	1	3	2	3	3	3	2	3
	Regulations	2	1	1	1	2	1	1	2	1	1	1	1	1	1	1	1	2	1	1	1	1	1	2	1	1	1	1	1	2	1
	Environmental impact assessment	3	1	2	2	1	1	1	1	1	2	1	1	2	3	2	3	2	1	2	1	2	3	1	2	2	3	1	1	2	2
Operational Criteria	Easy to use	2	3	2	3	2	3	2	2	3	2	3	3	2	2	2	2	3	1	3	2	2	2	3	1	2	2	1	2	2	3
	Low cost	1	3	1	3	3	3	2	1	3	2	3	3	3	1	3	1	3	2	3	2	2	2	3	1	2	2	2	2	2	2
	Little time required	3	2	1	2	3	3	2	2	2	1	2	3	2	1	2	1	3	2	2	2	2	2	3	2	2	1	3	2	1	2
	Applied	4	1	1	3	1	1	2	3	1	1	3	2	1	1	3	3	2	3	1	3	2	2	1	2	2	2	3	2	2	2
	Environmental Criteria Score		6	11	11	9	8	6	10	8	11	6	8	11	14	10	14	11	7	9	6	11	14	8	11	10	14	8	8	12	11
	Operational Criteria Score		19	12	27	20	22	20	23	19	13	27	26	17	12	25	20	26	22	19	24	20	20	22	17	20	17	25	20	17	22

Among the environmental criteria, “environmental laws and regulations” was the criterion least considered by QFD methods, i.e., 83% of the methods did not consider it. This criterion is followed by “environmental impacts analysis”, which 45% of the methods did not consider. However, the criterion “life cycle perspective” was identified in most of the QFD methods (76%).

Among the operational criteria, most of the analyzed methods were considered “easy to use”, inexpensive, and not time-consuming. However, 34% of the QFD methods were not applied to real cases of product development, i.e., not validated in real cases.

Another finding is connected with a trade-off between environmental and operational performance. The analysis in Figure 3 (containing the 29 methods) shows the environmental and operational criteria—see Table 3. Those who adhere less to a certain criterion are given lower scores (see Section 2, Item 4). Therefore, a comparison of ecodesign QFD practices based on environmental and operational criteria can be seen in Figure 3.

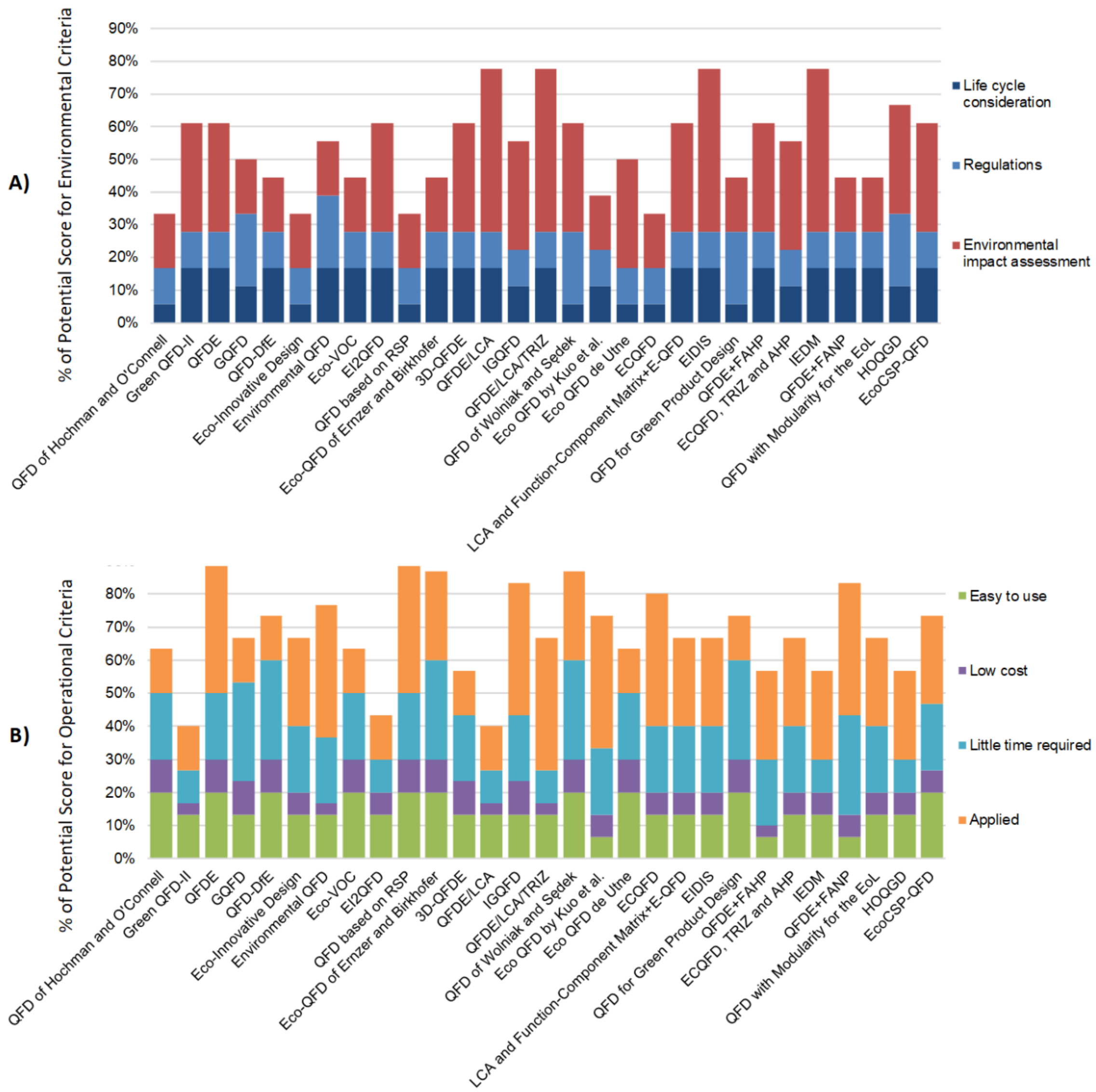

Figure 3. Comparison of ecodesign QFD practices based on environmental and operational criteria.

This situation reveals that, in many cases, the greatest possibility of bringing environmental benefits to product development gives rise to problems of application, increasing costs, time consumption, and complexity.

It can be noted that QFDE was the method that performed best when considering the environmental and operational criteria. Therefore, it was the one used in the workshop to test its applicability.

5.2. Testing the Method with the Best Performance—QFDE

From the practitioners' perspective (during the workshop, as described in Step 5 of the Methods Section), QFDE steps were quickly understood by the design team and its application happened smoothly. One of the designers was familiar with traditional QFD, which made the understanding process easier, since QFDE was considered similar in many aspects to its precursor. None of the designers knew either QFDE or any other QFD-based method for ecodesign.

Analyzing the time-consuming criterion, QFDE took just two afternoons (around six hours) to be fully applied by the design team, which was considered fast for a product design method. The first day was used to work with the Voice of Customer definition, assigning the weights for each identified requirement. The second afternoon was used to finish the QFDE application.

Costs involved in the QFDE application were only associated with the working hours of the design members. This was viewed well by the company because no extra experts and/or consulting hours were necessary, and software acquisition was not required.

Regarding the environmental benefits of QFDE application, designers considered the method useful for generating ecodesign alternatives. One designer stated that QFDE allowed the identification of technologies for product improvement, generating better environmental performance, cost reduction, quality enhancement, and new market opportunities. Another designer said that QFDE supported a critical analysis of the company's product from an environmental point of view. According to him, improvement opportunities could be noticed for cost reduction (in particular for reduction of material consumption in the manufacturing phase, and fuel consumption in the use phase) and environmental issues (reduction of emissions), mainly because QFDE incorporates a life cycle perspective. In that sense, one criterion adopted for the analysis of QFD-based ecodesign methods, which was "life cycle perspective", was reported to be important for an ecodesign method to promote economic and environmental opportunities.

It is interesting to note that, contrary to criteria prioritization by ecodesign experts, the operational criterion "already validated in real cases" was not cited as very important to designers, although the criteria assessment was not part of the workshop purposes. Other environmental and operational criteria were mentioned at least once at the workshop as important elements for QFDE and its application.

On those grounds, the authors believe that one of the most important practical contributions brought to light during the workshop was the unperceived need to test/validate QFD-based ecodesign methods. Even designers did not signal such need, although the very same professionals pointed out that it would be necessary for the method to meet some criteria (both operational and environmental), which could be perceived during the process of testing/validating.

Further practical implications noted by designers, over the product under analysis and the product development process, included the need (and opportunities) to use certain technologies for product improvement, as well as opportunities for cost reduction (mentioned a few times) and for quality improvement. Moreover, it was reported that the application of QFDE signaled new market opportunities for the company. Furthermore, and on top of everything, the designers could spot opportunities for environmental improvement for the product system under analysis.

Given the successful use of the method, the designers also expect to extend QFDE application to other automotive components in the future.

6. Conclusions

This study sought to analyze ecodesign practices based on QFD and the designers' perception of one of those methods using environmental and operational criteria. The methods used in this piece of research comprised four steps to conduct an analysis of QFD methods for ecodesign.

Ecodesign is considered a product development approach aimed at the design of greener products, reducing their environmental impacts throughout their entire life cycle. However, these environmental benefits are not always achievable. The main barriers are found in ecodesign practices, which do not consider a set of environmental and operational requirements such as the life cycle perspective, environmental impact assessment, and application of the method to real product development cases.

It is reasonable to conclude that ecodesign practices should consider a set of factors, requirements, and criteria during their conceptualization and development, so that they can lead to real environmental gains, reduction of GHG emissions, and other impacts throughout the product's life cycle.

The factors make up (i) the detailing of environmental assessment and (ii) the costs associated with applying the method. The greater the ability of a method to objectively assess environmental impacts in the product life cycle, the more difficult it is to implement in view of training costs, software requirements, hiring of experts, application time involved due to the increased number of steps and activities, mathematical language, and other information unfamiliar to designers.

The requirements were identified as (i) considering the entire life cycle, and (ii) being easy to use. Considering that authors generally define ecodesign as an approach for product development aimed at reducing environmental impacts throughout the product's life cycle, it can be concluded that practically 24% of the QFD methods analyzed in this paper could not be considered an ecodesign practice because they do not consider the entire product life cycle. It was also found that operational requirements such as time and cost are related to ease of use because one affects the other. In other words, the more difficult the application of a method, the lengthier and costlier it will be.

It was also found in this research that QFD-based ecodesign methods should meet certain environmental and operational criteria. The environmental criteria are: (i) Considering the life cycle perspective, (ii) meeting environmental laws and regulations, and (iii) environmental impact analysis. The operational criteria are (i) easy to use, (ii) low application cost, (iii) being already validated in real cases, and (iv) short time required.

Moreover, the identification of many methods that were not tested in practice prior to publication indicates a lack of concern in testing methods in real cases with the help of product development professionals. The perception of designers indicated that an ecodesign method that is quick to apply, easy to understand, similar to other known methods, and does not require extra costs is desirable. Life cycle perspective is seen as a valuable element for the design team as well because it allows the identification of economic and environmental opportunities from cradle-to-cradle.

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