A QFD-centred design methodology for environmentally conscious product design

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Abstract:

As our society gets more environmentally conscious, manufacturers must incorporate "environmental qualities" into products. This paper proposes a general design methodology to support effectively environmentally consciousness design of products. The methodology employs three tools; LCA (Life Cycle Assessment), QFDE (Quality Function Deployment for Environment), and TRIZ (Theory of Inventive Problem Solving). QFDE is a tool developed by modifying and extending QFD, and is extended further in this paper. In addition, connecting consecutive two tools is realized by established relations among those tools. The presented methodology is proved through application to a hair dryer to support effectively the product planning and conceptual design stages. For instance, designers could utilize one of LCA results that the product has a high impact on the global warming through energy consumption during its use phase to define a requirement objectively in QFDE, "reduce the energy consumption" with a high weighting. TRIZ allowed designers to generate four improvement solutions. The most highly evaluated was using resonance frequency on the motor. This was obtained from a QFDE result that "dry quickly" and "dry quietly" have a contradiction. The methodology has a larger benefit than is obtained from utilizing those three tools independently.

Keywords: Ecodesign, environmental quality, QFDE, LCA, TRIZ

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1. Introduction

Over a couple of decades, environmental problems such as the global warming problem (IPCC 2001) and the waste processing problem (OECD 2001) have been quite serious. Thus, it is recognized that the system of our society including the production paradigm at present is not environmentally sustainable. In fact, the environmental issue has become one of the critical ones for manufacturers. They are required to decrease environmental impacts caused by their products while they compete in their markets. From quality viewpoints, "environmental qualities" such as the global warming potential and the rate of recyclable materials that had not been traditionally tackled on must be incorporated. In order to address this effectively, environmental consciousness must be taken into account during their design activities. This activity is called Ecodesign (environmentally conscious design), which is defined in this paper as "design activity reducing the environmental impacts throughout the life cycle of a product to be designed". Note that the target "product" does not include a service but refer to a physical product. In addition, this paper addresses improving design, namely redesign, not new product design.

In order to carry out design in general effectively and efficiently, methodical support is crucial in general (Pahl *et al.* 1996). Thus, a methodology suitable for Ecodesign is requested to be developed. To meet this need, several design guidelines have been actually already developed, while a large number of individual design methods and tools have been generated and some of them are implemented as a part of design activities in some manufacturers. However, most of them can be applied only to partial steps of the whole Ecodesign procedure or only with few limited aspects of product development. As a result, no method or tool available independently supports the whole range of Ecodesign effectively.

This paper proposes a general methodology for effective support of the whole range of product planning and conceptual design for product Ecodesign activities. To do so, the methodology is verified through application to an example product. Especially, it proposes a consistent design procedure whose core is the extended QFDE (Quality Function Deployment for Environment (Masui *et al.* 2003)) with employing LCA (Life Cycle Assessment) (ISO 1997) and TRIZ (Theory of Inventive Problem Solving) (Altshuller *et al.* 1996). In addition, connecting consecutive two tools is formalized by correlating the outputs of the preceding tool and the inputs of the following one. The rest of this paper consists of an overview of the current Ecodesign tools with their problem, explanation of the proposed design methodology, and application of the methodology to a product, a hair dryer. Then, it presents discussions and conclusions.

2. Existing Ecodesign Tools

2.1 Design Guides

A number of guides, manuals, and textbooks for Ecodesign are published, for instance, from ISO (International Organization for Standardization) (USEPA 1994, UNEP 1997, Simon *et al.* 1998, ISO 2002, IEC 2005), where some concrete methods and tools are referred to. These are in common effective for those who begin the Ecodesign activities to understand the benefits and methods of Ecodesign in an abstract manner. However, these do not support engineering designers effectively when they face specific and concrete problems to be solved for a given product. For example, ISO/TR-14062 (ISO 2002) suggests the use of some 30 various "tools". However, it does not provide how and in which situation to use them potentially in combination.

2.2 Checklist Methods

A checklist here means a set of items used for assessing a product from environmental viewpoints. This is used for product assessment which aims at improving the product on environmental aspects considering the possible environmental loads through the product life cycle. Those items include, for instance, "less material is used for the product than for the existing one?". Several checklist methods have been developed (e.g. (Wimmer *et al.* 2003)). This method, with its easiness, is one of those prevailing most for Ecodesign in industries. This is effective especially for systematizing environmental review in a firm. However, this is neither powerful for objective environmental assessment nor helpful for concrete problem solving.

2.3 LCA

LCA is a method to assess environmental impacts of a product or a service and standardized by ISO (ISO 1997). It requires quantitative information of the life cycle on the environment. Although it reveals a quantitative environmental profile relatively objectively based on the results of detailed design of a product, it has some drawbacks. First, it cannot be achieved in the early stage of new product design. In case of redesign, designers need a reference product such as a previous generation one in the early stage. Streamlined LCA (Graedel 1998) has been developed to solve these problems partially. Second, it addresses no other aspects than the environment. This is so critical that LCA alone cannot support product design.

2.4 QFDE (Quality Function Deployment for Environment)

QFDE (Masui *et al.* 2003) is a method to support Ecodesign developed by incorporating environmental aspects into QFD (Quality Function Deployment) (Akao 1990) and extending so as to evaluate improvement concepts. QFDE consists of four phases. In Phase I, voices of customers (VOC) with voices of the environment (VOE), and quality characteristics (QC) for traditional and environmental qualities are correlated, while QC and components are also correlated in Phase II. Components can be regarded as function units or part characteristics. The outputs of Phases I and II are identification of the QC and components that should be focused in product design when environmental as well as traditional qualities are considered. Following this, the so-called QFDE team will examine design improvement options for the product semi-quantitatively in Phases III and IV. To do so, the team determines redesign target and those changes are expressed by a combination of a QC and component to be improved. Then, they evaluate the effects of the design changes on the VOC and VOE using semi-quantitative information represented in the two correlation matrices in Phases I and II.

The drawbacks of QFDE include that generating concrete solutions is totally on designers in spite of some suggestions given from Phases I and II. In addition, other drawbacks originate from the motivations of developing QFDE including easy use in product design. First, the accuracy of the score calculated for each design improvement is low because the correlation strengths between VOC/VOE and QC, and between QC and components as well, are represented in only absolute number without considering whether they are positive or negative. Next, the correlation table for QC facilitated in QFD is omitted.

QFDE has been verified through several studies (Masui *et al.* 2003) and other QFD-based methods incorporating the environmental issues are available as well (Cristofari *et al.* 1996, Olesen 1997, Zhang *et al.* 1999, Bovea *et al.* 2005). Thus, the effectiveness of such QFD-based methods for Ecodesign is widely recognized.

2.5 EEA (Environmental Effect Analysis)

EEA (Environmental Effect Analysis) (Lindahl *et al.* 2000) is a method modified from FMEA (Failure Mode and Effect Analysis) (Stamatis 1995). EEA replaces failure modes in FMEA with hazards on environmental aspect so that it can support Ecodesign. Especially, it can help designers with the process to grasp negative effects on the environmental aspect qualitatively during an earlier stage of product design. However, it is impossible to address all the requirements from customers.

2.6 Eco-VA (Eco-Value Analysis)

The conventional Value Analysis (VA) (Miles 1971) intends to identify improvement options concerning productivity, benefit and quality. Its goal is improvement of the value of a product by realizing functions with minimal economic efforts. On the other hand, Eco-Value Analysis (Eco-VA) (Oberender *et al.* 2004) extends the traditional VA by incorporating environmental aspects. Eco-VA aims at a holistic approach, considering technical, environmental and economical aspects. The method supports product developers with attempting to fulfill environmental and customers' demands within lower economic cost and environmental impacts. Concretely, it evaluates each function of a product from the viewpoints of customer importance, economic cost, and environmental impact. Depending on the results of quantification from the three viewpoints, a function is placed in a prepared portfolio. According to the area in the portfolio, recommendations of strategies for the following product design stages are given. It is suggested whether to realize a function, to omit it or to realize it after a specific improvement.

2.7 TRIZ (Theory of Inventive Problem Solving)

TRIZ (the Russian acronym for 'theory of inventive problem solving') (Altshuller *et al.* 1996) is a series of tools and methods developed using over four hundred thousand world's most successful patents. The core of TRIZ consists of the 40 "inventive principles" and the "contradiction matrix" between 39 "engineering parameters". In addition, available is a “prediction” tool which helps designers with improve a performance or a function of a product by presenting some trends of system evolution. Furthermore, another tool is the “effects” database which provides users with technical solutions for a given functionality. Utilizing these sub tools, TRIZ supports designers with find ways of solving problems in designing a product in general, not only in Ecodesign. Its application can be found in Ecodesign. For instance, Chang et al. has developed a matrix between the 39 “engineering parameters” and generic strategies for eco-efficiency (DeSimone *et al.* 1997) to support Ecodesign using TRIZ (Chang *et al.* 2004). It should be emphasized that designers themselves must identify, in advance, contradictions, functions to be realized, and performances to be improved in a product to be designed.

2.8 Problems

Although a large number of methods and tools have been developed for Ecodesign, no method or tool available independently supports engineering designers during the whole range of product planning and conceptual design of a specific product effectively and consistently. Thus, as a result, the current methodical support in industries is not powerful enough. This is especially true in case of the checklist method, one of the most disseminated tools. In addition, the results of LCA often remain buried in the environmental section in a firm, who are normally in charge of achieving LCA, although they include much suggestion.

LCA, QFDE, and TRIZ, each of which has potential for supporting product planning and conceptual design, is associated with following drawbacks when applied independently. LCA is only for assessment as well as is critical due to its dominance by the environmental issues. QFDE can neither support designers to evaluate a product objectively from an environmental viewpoint nor help them to find concrete improvement options. TRIZ lacks the identification of which contradiction and which function/performance to be targeted.

3. Proposed Ecodesign Methodology

3.1 Reasons to Adopt the Three Tools

Ecodesign is a kind of design, which is an activity to determine attributes as a solution under various constraints when requirements are given (Yoshikawa 1981). Thus, Ecodesign is a kind of problem solving. Actually, Pahl and Beitz (Pahl *et al.* 1996) have pointed out that object analysis, problem definition, and solution identification are crucial to achieve effective design as a whole.

First, the analysis of a design object in Ecodesign requires collecting the information on environmental impacts of the product. Among others, it is crucial, by definition of Ecodesign, to consider the whole life cycle of a product from various environmental aspects. It is LCA that can fulfill this. The methodology proposed in this paper employs ISO-LCA, not Streamlined LCA, due to the quantitativeness and objectiveness of the obtained results. On the other hand, analyzing customer requirements adopts traditional tools for market analysis.

Second, the problem definition needs to incorporate the three major aspects of product development, namely, quality, cost, and speed, as well as environment. In addition, this must be carried out as early as possible in the whole product development. QFDE and Eco-VA are among few tools to meet such requirements. The methodology adopts QFDE because not only functions but also qualities can be addressed; improvement options can be evaluated; and contradicting effects can be generated.

Third, the solution identification need not address environmental requests if problems are well identified in the designers' language in the previous steps. Solution identification from time to time requires searching new technical solutions, not only improving the performance with keeping an existing mechanism. TRIZ can support designers with find such improvement solutions so that TRIZ is employed in the methodology.

Therefore, a design methodology containing a procedure using ISO-LCA, QFDE, and TRIZ is proposed in this paper.

3.2 Procedures

Figure 1 shows the overview of the procedures of the proposed Ecodesign methodology. The steps of object analysis, problem definition, and solution identification with the use of the three tools explained in the previous section are embedded in the upper stream (steps from 1 to 3). The outputs of those steps are explained in more detail in Table 1 with the inputs needed by the tools. It should be noted that the steps after "4. evaluating product concepts" are not explained in this paper. Identifying customers' requirements, whose results will be obtained by existing tools for marketing analysis and input into QFDE, is not explained in this paper, either.

In addition, Table 1 interrelates the inputs/outputs of the tools. For instance, the first output of LCA is used as the second input of Phases I and II of QFDE (denoted by QI-2), while the first input of Phases III and IV of QFDE include the first, second and third outputs of TRIZ (denoted by T-1, 2, 3). In case of TRIZ, an input and an output with an identical number are corresponding with each other. Each step of Figure 1 is explained below.

1. identifying requirements of customers and environment

The requirements both of the customers and of environment are identified. For the latter, a standardized set of 11 environmental requirements, namely VOE, is adopted, first. This set has been obtained by making the corresponding set in (Masui *et al.* 2003) more compact while it still covers most of the environmental problems and is applicable in general. Moreover, the voices from various stakeholders such as recyclers, production engineers, and users within the product life cycle have been integrated. Those VOE are as follows.

- less material usage
- easy to process and assemble
- easy to process wastes from production
- easy to transport and retain
- harmless to living environment
- high durability
- easy to reuse
- easy to disassemble
- easy to smash
- safe emission
- less energy consumption

Second, the set is adjusted according to the target product. Third, the semi-quantitative weighting (preferably four levels including zero) for each VOE is given to be smoothly input to QFDE in the next step. To do so, the environmental profile of the product is revealed from LCA of the product of the previous generation. It is preferred that LCIA is achieved to show impacts on environmental categories because some VOE are represented in a form close to environmental categories. For instance, "less material usage" is most highly weighted if the resource depletion was found to be among the serious environmental categories. In case the environmental burden during the production stage is larger, "easy to process and assemble" can be weighted higher. It should be pointed out that some VOE cannot be found out important directly from the results of LCA even though they are important in reality. For example, "high durability" is hard to put importance from the results of LCA. The reason is that engineering knowledge about a product is sometimes necessary to define requirements.

The weighting on a category of VOC and that of VOE can be differentiated with a given factor in this step depending on the design strategy. For instance, only the weightings of all the VOC can be multiplied by 3 (according to QFDE scale) if VOC are counted by factor 3 more than VOE.

2. identifying product specifications

Product specifications are identified using the results from the previous step. As an output, the focus in the design is determined using Phases I and II of QFDE. The design focus is represented in the form of important QC (quality characteristics) and components, as well as contradicting QC and VOC/VOE (voices). It is crucial to consider not only environmental aspects but also quality ones.

Environmental QC, which has to appear in Phases I and II, can be identified according to the standardized set in (Masui *et al.* 2003). The LCA results from the previous step are incorporated as the voices (VOE) with their weighting in QFDE.

Designers should discriminate the third output of LCA (in Table 1) and the first and second outputs of Phases I and II of QFDE (in Table 1). All of them show what designers should focus on. Of course, they are different, because QFDE addresses the requirements from the customers as well as the environment in contrast to the LCA's concerns dominated by the environment. Not only that causes the differences: A concept of functionality is not considered in LCA, while it is in QFDE as suggested in (Sakao *et al.* 2007). For instance, let us consider a small part which is made from materials with low environmental impacts but has a functionality influencing largely the environmental impacts. It cannot be evaluated important in LCA, while it is more likely in QFDE as such. The results from QFDE should be paid more attention to than those from LCA, since functionality is a core concept to drive engineering activities, not attributes of a product, as is widely recognized in the field of engineering design (Pahl *et al.* 1996). This does not necessarily mean that the results from LCA are of no use for such purposes due to the subjectivity in the results of QFDE, which originates from the expert judgment utilized to make matrices in QFDE and the arbitrariness to select VOE. The results of LCA are helpful to know the environmental profile of a product as it is and more objectively than those of QFDE, since the procedures of LCA are more objective and quantitative-data intensive.

It is useful as an input to the next step to grasp the contradictions among the QC and those among VOC/VOE in Phase I of QFDE. To represent these, this paper introduces extension on the existing QFDE: The former contradictions will be represented in the correlation table for QC. The latter will be represented in the correlation table for VOC and VOE. These have been added to QFDE in order for designers to identify more contradictions applicable to TRIZ. The latter contradictions are automatically obtained using the first contradictions and the matrix of Phase I with distinction of positive or negative number. This extension is explained in more detail in the following paragraphs.

First, the correlation table for QC, which QFD is originally facilitated with, is introduced. Then, not only correlations between two different QC (with synergetic effect, with contradicting effect, or else), which are normally considered, but also a correlation of an identical QC (always with synergetic effect), is considered. Here, the size of such an effect is not considered. Namely, a correlation table is introduced for QC whose element is denoted as mc_{j_1,j_2} $(1 \le j_1 \le j_2 \le J)$ determined by the equality (1), when QC are given as $\{m_j \mid 1 \le j \le J\}$. The value of mc_{j_1,j_2} is given by designers. Note that J stands for the number of given QC in Phase II. In addition, j, j_1, and j_2 mean an ordinal number of a QC element.

$$mc_{j_1,j_2} = \begin{cases} +1 & \text{, where a synergetic effect exists.} \\ -1 & \text{, where a contradicting effect exists.} \\ 0 & \text{, else.} \end{cases} \quad (1)$$

Next, the "correlation table for voices" is introduced: A correlation table is introduced for VOC/VOE whose elements are vc_{k_1,k_2} ($1 \le k_1 < k_2 \le K$) determined by the equality (2), when voices (VOC/VOE) $\{v_k \mid 1 \le k \le K\}$ are given. Note that K stands for the number of given voices in Phase I. In addition, k, k_1, and k_2 mean an ordinal number of a voice.

$$vc_{k_1,k_2} = \begin{cases} -1 & \text{, where either (3) or (4) is satisfied.} \\ 0 & \text{, else.} \end{cases} \tag{2}$$

$$a_{j_1,k_1} \cdot a_{j_2,k_2} \cdot mc_{j_1,j_2} \le -\gamma^2 \tag{3}$$

$$a_{j_2,k_1} \cdot a_{j_1,k_2} \cdot mc_{j_1,j_2} \le -\gamma^2 \tag{4}$$

A contradicting effect between voices exist in the case $vc_{k_1,k_2} = -1$. It should be noted that $a_{j,k}$ denotes the correlation strength between QC m_j and voice v_k, and takes any value from $+\gamma, +\beta, +\alpha, 0, -\alpha, -\beta, -\gamma (0 < \alpha < \beta < \gamma)$. Thus, vc_{k_1,k_2} is automatically calculated using the matrix and the correlation table for QC.

For instance, given are a matrix and a correlation table for QC (only for the concerned part) shown in Figure 2. Then, a contradicting effect between the two voices is obtained as shown in the correlation table for voices. In this case, assuming $\alpha = 1$, $\beta = 3$, and $\gamma = 9$, $vc_{1,2}$ is equivalent to -1 since the inequality (3) is satisfied from $a_{1,1} = +9$ (hatched cell), $a_{2,2} = -9$ (hatched cell), and $mc_{1,2} = +1$ (hatched cell).

Here, the intention for the right-hand side of (3) and (4) to be $-\gamma^2$ is extracting only the cases with the largest contradicting effect, namely obtaining the smallest number of contradicting effects. Thus, the right-hand side of (3) and (4) can be adjusted depending on the preferred number of contradicting effects obtained.

3. generating product concepts

Designers determine the concrete mechanisms, principles, and components according to the results from the previous step. In Ecodesign, they must pay attention especially to newly recognized trade-offs that did not occur before considering environmental consciousness. There are two paths below connecting the outputs from Phase II of QFDE and the inputs to TRIZ, which supports designers with searching technical solutions.

(1) inputting critical QC/components to "prediction"/"effects"

They obtain candidates for solutions by inputting the important QC, which have been identified in Phase I of QFDE, to the "prediction" tool or the "effects" database of TRIZ. In the case of "prediction", TRIZ presents designers with a set of the technology trends that are more related to the QC, which the designers wish to change. For instance, if the critical QC is "driving force", potentially related technology trends are shown prioritized from the viewpoint of "power increase". Then, the designers compare the trend with the current product and possibly incorporate the technology available in the "future" within the trend.

On the other hand, with "effects", TRIZ shows designers a variety of effects that influence on the focused QC. E.g. when they desire to lower the temperature, which is the QC in this case, such effects include Joule-Thomson effect[1]. After judging the presented effect is applicable to the product, they obtain a solution candidate. It is often especially beneficial for designers to know the effects applied in other types of products or industries.

It is more efficient for designers to focus on more influential components to improve a QC of a product. Thus, the important components, which are identified in Phase II of QFDE, are prioritized to be investigated. For instance, a component which is the most influential on the temperature of the product according to the results of Phase II should be investigated by priority to improve the temperature.

Furthermore, VOC/VOE with a high weighting can be input if the voice corresponds relatively directly to a QC. For instance, "lower the surface temperature of the product", a VOC, can be directly addressed in "prediction" or "effects", rather than a relevant QC, "surface temperature".

(2) inputting contradicting VOC/VOE to the "contradiction matrix"

It has a limitation to look at an individual QC or VOC/VOE by the first path above, because desired change on one parameter often results in not-preferred change, namely side effect, on another. Thus, tackling a set of two parameters with contradicting relation at the same time is beneficial.

Designers here obtain candidates for solutions by inputting contradictions of VOC/VOE found in Phase I of QFDE to the "contradiction matrix" of TRIZ. To do so, the corresponding two QC must be often discovered; otherwise VOC/VOE can be directly input. Then, the specific suggested inventive principles are applied to find technical solutions. Taking an instance from a vacuum cleaner, let us assume that designers try to solve a contradiction between "suck more dust" and "move nozzle smoothly". Two QC, "air velocity in the nozzle" and "friction resistance between the carpet and the nozzle", can be identified as a main source of such contradiction from Phase I of QFDE. Then, those two QC can be translated into "9. Speed" and "10. Force" in the 39 engineering parameters, respectively. One suggested inventive principle between the two engineering parameters is "#13 Inversion". This principle can let designers think of a physical structure in which the air flow in the inverse direction is realized simultaneously as the suction flow. This makes more dust sucked by the nozzle while preventing the nozzle from getting stuck on the carpet.

4. evaluating solutions

The feasibility of those design solutions (improvement options) generated in the previous step is evaluated from the viewpoints of requirements (from both customers and environment), economy, and technology. In case multiple solutions are obtained, one is selected. The paper explains evaluation only from the requirements aspect.

In order to discover the improvement effects on requirements, Phases III and IV of QFDE are

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[1] This is a physical process in which the temperature of a real gas, not an ideal gas, is decreased by letting the gas expand freely at constant enthalpy, and is actually applied in a refrigerator.

carried out. By doing this, the effects are calculated semi-quantitatively. A new method, which is improved from that in the existing QFDE, is adopted to obtain those effects. In this new method, the improvement rates of QC and VOC/VOE are calculated with incorporating plus or minus of each correlation strength between a voice and QC, and between QC and a component, while the equations remain identical to the original ones in QFDE (Masui *et al.* 2003). Note that being plus or minus of the correlation strength between QC and a component depends on a design solution, while that between a voice and QC does not. Thus, the improvement rates are calculated more accurately when negative improvements, namely disimprovements, on QC or VOC/VOE are included in a design solution. Note that in the existing QFDE they were calculated while ignoring whether a correlation strength is positive or negative. For example, when a design solution increases QC_A, which has positive and negative correlation strength with $voice_X$ and $voice_Y$, respectively, both the two voices were calculated to be improved.

4. Application

4.1 Example

The product taken as an example in this paper is a hair dryer. The reason is that the structure and the functionality are relatively easy to understand. This section verifies the design methodology through application to the product.

4.2 Results

The results obtained following the procedures of Figure 1 are explained below.

1. identifying requirements of customers and environment

First, LCA was carried out to determine VOE and their weighting. Table 2 shows partial assumptions for the LCA. JEMAI-LCA version 1.1.0 (Jönbrink *et al.* 2000) (see its theoretical explanation in (Kobayashi *et al.* 1996)) was adopted as the LCA software. As a result, it was revealed that the global warming (through the electricity consumption during the usage phase) was the most contributing of the environmental categories. Acidification (through the transport of oil for producing electricity), energy consumption, and solid waste (from the end-of-life (EOL) stage) were following the global warming. This means that solving these four environmental problems are relatively strongly required on this specific product. Responding to these four problems, the VOE of "less energy consumption", "less material usage", and "easy to smash" were weighted the most important (to be 9 in Phase I of QFDE).

2. identifying product specifications

Phases I and II of QFDE were carried out to obtain the design focus. Figures 3 and 4 show Phases I and II of QFDE, respectively. The results show that the QC of "amount of energy consumption", "air flow", and "air temperature" are the most important.

The correlation table for QC is seen at the top in Figure 3. The table shows, for instance, a synergetic effect between the QC of "air flow" and "amount of energy consumption", and a contradicting effect between "balance" and "volume". On the other hand, the correlation table for VOC/VOE, described in the left hand side, addresses only the contradicting relations with a symbol "-". Some contradicting effects in voices were revealed such as that between "less energy consumption" and "dry quickly". They have a strong correlation with "air flow" negative (-9) and positive (+9), respectively. In addition, "easy to smash" and "high durability" are contradicting from the synergetic effect between "hardness" and "physical lifetime".

In Phase II, the components of "motor" and "housing" were found to have the highest importance.

3. generating product concepts

In this step, technical solutions were generated through the two paths explained in Section 3.2.

(1) solutions from the "prediction"/"effects"

By applying the prediction tool of TRIZ to improve one of the top three important QC, "air flow”, a trend of technical systems named “mono-bi-poly”[2] was presented. This allowed designers to investigate the possibility of modifying the number of the blades. This even triggered designers to think of optimizing the blades including changing the blade shape. As a result, derived was an option to change the blade number and shape (called Solution #1). It should be noted that this solution would keep the level of “amount of energy consumption” (the most important QC), which has a synergetic effect with “air flow”.

(2) solutions from the “contradiction matrix”

The following solutions were obtained to solve the contradiction between “dry quickly” (with the weighting 9) and “dry quietly” (with the weighting 3) by applying the contradictions matrix. The synergetic or contradicting effects between QC that caused the two voices to have the contradiction include that between “air flow” and “noise, vibration, electromagnetic wave”, and that between “amount of energy consumption” and “noise, vibration, electromagnetic wave”. Those combinations were translated into the engineering parameters in TRIZ; “9. Speed” and “31. Harmful side effects”, and “21. Power” and “31. Harmful side effects”, respectively. Then, some inventive principles were obtained from the contradiction matrix as shown in Table 3. Examples of technical solutions using the suggested inventive principles shown in Table 3 include:

- Cancelling out the noise by generating the wave in the opposite phase from a “chamber” added on the housing (from Principle #2 “Extraction”); Solution #2
- Controlling the mechanical vibration from the motor’s rotation by resonance frequency (from Principle #18 “Mechanical vibration”); Solution #3
- Improving both the noise and air volume by newly-introduced fins’ controlling the turbulent flow (from Principle #24 “Mediator”); Solution #4

4. evaluating solutions

The evaluation of the improving effects of those four solutions were obtained from Phases III and IV of QFDE. Note that the improvement rate of QC was calculated in Phase III after introducing positiveness/negativeness into a correlation strength depending on a solution. For instance, in Solution #3, only “noise, vibration, and electromagnetic wave” (QC) of “motor” (component) is improved (and decreased). Therefore, the improvement rate of the QC was calculated after incorporating negativeness into the correlation strength. In addition, the improvement rate/effect of VOC/VOE was calculated in Phase IV using the matrix in Figure 3 containing partially negative numbers.

As a result, the sum of the improving effects on all the VOC/VOE was calculated to be -0.48, -16, +2.9, and -1.1 for Solutions #1, #2, #3, and #4, respectively. This means Solution #3 is the most promising followed by Solutions #1 and #4. In case that the score is negative, the solution is associated with the larger “disimproving” effects from “improvement” of QC (“disimprovement” already in some QC). For instance, Solution #2 is suggested to have a negative effect as a total partly because the increase of “volume” by the added chamber has a

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[2] This means that, for instance, the air flow and the power are increased as the number of propeller blades shift from one (mono) to two (bi), reaching more than two (poly).

negative impact on the VOC “portable”.

4.3 Discussing the Application

It has been demonstrated that designers can carry out Ecodesign effectively from grasping the environmental requirements objectively to generating and evaluating solutions by following the proposed design methodology. Among them, synergy from relating the inputs and outputs of the three tools was confirmed. For example, the outputs of LCA were effectively input to Phase I of QFDE, while the outputs of Phases I and II of QFDE were input to TRIZ. In other words, necessary was objective analysis for identifying VOE with their weighting in Phase I of QFDE, which was achieved by adopting LCA. In addition, generating concrete solutions in Phases III and IV of QFDE is critical, which would have been quite difficult for designers without any support tool such as TRIZ.

In spite of the proof on the effectiveness explained above, it may be also beneficial to mention something about the efficiency on generating solutions in step 3 from product specifications obtained from step 2. In generating solutions from the “prediction”/“effects”, one solution was obtained by looking at the top three important QC. By “contradiction matrix”, three solutions were obtained by looking at two relations between QC among the four relations[3] that are derived from the concerned contradiction between “dry quickly” and “dry quietly”. Furthermore, the contradiction between the two voices are selected from seven contradictions that are equally or more important according to the weighting on each voice[4]. Obviously, the efficiency still depends on designers’ knowledge and skills, which is a nature of TRIZ.

In addition, limitations of Phases III and IV of QFDE were discovered. Value on the quality table does not always hold valid for solutions investigated in Phases III and IV because the value assumes to some extent the realization physical structure of the reference product. Due to this, the accuracy of the calculation is decreased. For instance, the quality table in Figure 3 describes that QC of “noise, vibration, electromagnetic wave” has a strong positive relation with VOC of “dry quickly”. This does not always hold true. Rather, this assumes a certain realization physical structure. As a matter of fact, the structure in Solution #2 does not keep it true because it decreases “noise, vibration, electromagnetic wave” with keeping the level of “dry quickly”. Therefore, Solution #2 was calculated to generate negative influence on “dry quickly” due to the decrease of “noise, vibration, electromagnetic wave”. However, this includes difference with the reality. As such, the evaluation by Phases III and IV has approximation.

It was mentioned in Section 3.2 that designers should count more on the focus obtained from QFDE than that from LCA. However, this was not proved in this specific example because the focuses from the two tools have no significant differences. The reason is that the structure and how it was modelled were relatively simple.

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[3] The other two relations between QC exist between “air flow” and “amount of energy consumption”, and between “air temperature” and “amount of energy consumption”.

[4] Voices on the seven contradictions have weightings of 9 and 9 (e.g. “dry quickly” and “less energy consumption”), or 9 and 3.

5. Discussions

The application of the proposed design methodology demonstrated in Section 4 has revealed:

(1) The methodology can effectively support designers in a wide range of the earlier stages of Ecodesign including product planning and conceptual design. Remarkably, this methodology supports analysis and synthesis, which most Ecodesign methods fail although both of them are inevitable in design.

(2) It has a more benefit than is obtained from using those three tools of LCA, QFDE, and TRIZ independently due to the synergy from relating the inputs and outputs of the three tools. Absence of any tool would not be effective. It is LCA results, which are not so effectively utilized although they often exist in a firm, that can keep the set of VOE in QFDE objective. Without QFDE, designers would not grasp the relation between requirements from environment and customers, and then are more likely to generate harmful side effects on customer requirements. Furthermore, with no support by TRIZ, it is totally on designers to find improvement options.

(3) It is widely applicable to Ecodesign of assembled products in general because no limitation on the applicability was found except for those original limitations of LCA, QFDE, and TRIZ. Furthermore, a part of the methodology on the use of QFDE and TRIZ is applicable to design in general, not only to Ecodesign. In case of products with more complexity, the methodology will be applicable, as well. Rather, the methodology may be more effective in such cases since the correlation table for voices is more likely to be richer.

Next, it is explained how superior to existing research the proposed methodology is. Green QFD (Cristofari *et al.* 1996, Zhang *et al.* 1999, Bovea *et al.* 2005) is a QFD-based Ecodesign tool incorporating other tools such as LCA and LCC (Life Cycle Costing). Finster et al. (Finster *et al.*) proposed a method to identify the provided value in Ecodesign using the Kano technique (Kano *et al.* 1996). However, they lack support for generating a concrete solution, which was demonstrated using TRIZ in this paper. Chan et al. (Chang *et al.* 2004) and Chen et al. (Chen *et al.* 2003) have also proposed to adopt TRIZ in Ecodesign. However, the proposed methodology assures more objective identification of environmental requirements especially by employing LCA in the problem definition step before applying TRIZ. Another method integrating QFD and TRIZ has been also proposed for design in general (Yamashina *et al.* 2002). However, the proposed one especially has an advantage to produce more suggestions input to TRIZ such as identification of the contradictions among VOC/VOE as well as QC as demonstrated. This is one of the remarkable issues addressed in Ecodesign since environmental demands often contradict “traditional” quality demands. In addition, Fargnoli et al. (Fargnoli *et al.* 2005) have demonstrated an Ecodesign method which applies a set of generic improvement methods (e.g. substitute with recycled material) proposed in PILOT (Wimmer *et al.* 2003) to the outputs of QFDE. However, the suggestions generated from TRIZ as employed in this paper are more concrete. Furthermore, no existing method/tool explained in Section 2 can support Ecodesign concretely, consistently and effectively as the proposed design methodology.

In addition, Kobayashi (Kobayashi 2002), Rose et al. (Rose *et al.* 2002), and Sakao et al. (Sakao *et al.* 2006) have proposed methods to build a strategy for Ecodesign. However, all of these do not support the step of generating concrete solutions as is achieved in the proposed methodology.

6. Conclusion

This paper presented an Ecodesign methodology, which adopts LCA, QFDE, and TRIZ with utilizing the inputs/outputs mutually. It has been verified through application to an example product. From the application, it was proved that the proposed methodology supports effectively the wide range of product planning and conceptual design stages in the upper stream of Ecodesign. The methodology has a larger benefit than is obtained from utilizing those three tools independently. The methodology in part can be applied to design in general, not only to Ecodesign.

Future works include further verification of the methodology, namely verification of the whole methodology including the steps after the evaluation of product concepts. This will also let us discuss the results of quantitative evaluation of the obtained solutions from the customer and environmental aspects. Another work is implementation of the methodology on computer software.

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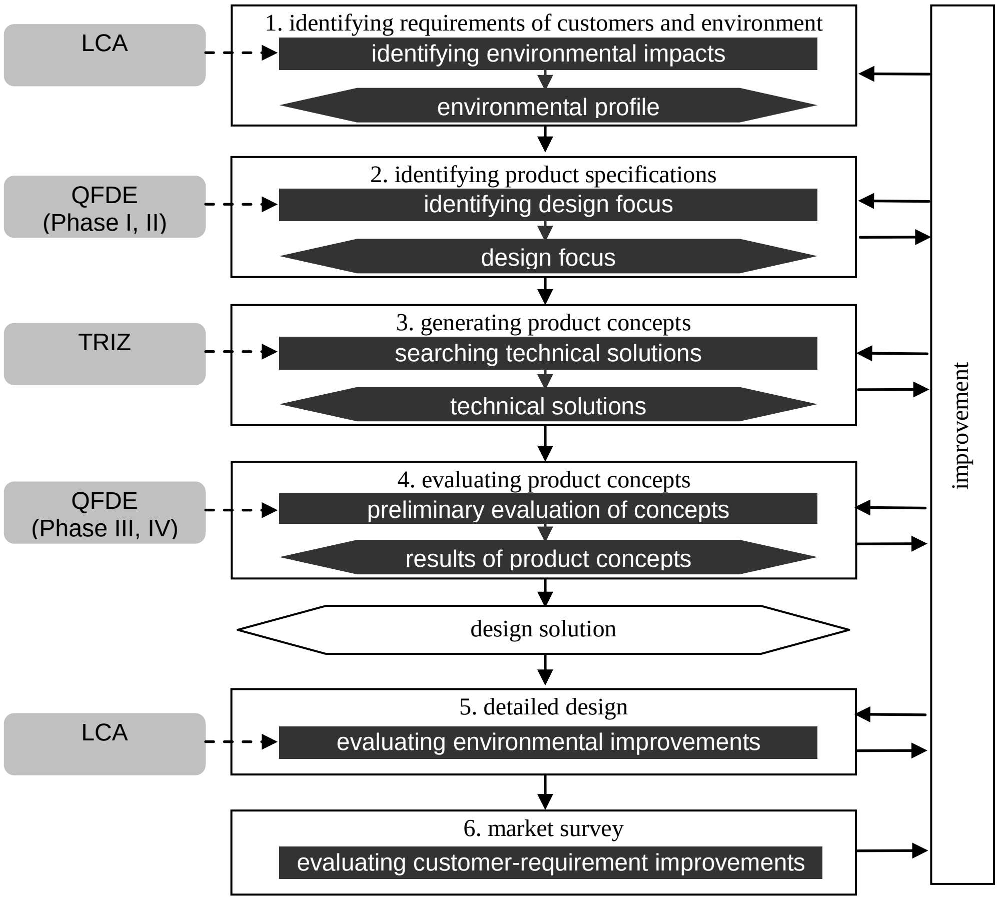


Figure 1: Procedures of the proposed Ecodesign methodology

Table 1: Major inputs/outputs of the three tools and the interrelations among them

	inputs	outputs
LCA	1. quantitative scenario for the life cycle 2. quantitative data for the parts (size, shape, types of materials, etc.) 3. adopted production processes	1. quantitative impacts on the environmental categories **(→QI–2)** 2. quantitative impacts on the life cycle stages **(→QI–2)** 3. processes with large environmental impacts **(→QI–2)**
QFDE Phase I,II	1. VOC and their weighting 2. VOE and their weighting **(←L–1, 2, 3)** 3. QC 4. components	1. important QC **(→T–1, 2)** 2. important components **(→T–1, 2)** 3. contradicting QC and VOC/VOE **(→T–3)**
TRIZ	1. performance to be improved **(←QI–1, 2)** 2. function to be improved **(←QI–1, 2)** 3. contradicting engineering parameters **(←QI–3)**	1. strategies to improve the performance **(→QIII–1)** 2. measures to realize the function **(→QIII–1)** 3. measures to solve contradictions **(→QIII–1)**
QFDE Phase III, IV	1. improving options **(←T–1, 2, 3)**	1. improving options with larger effects

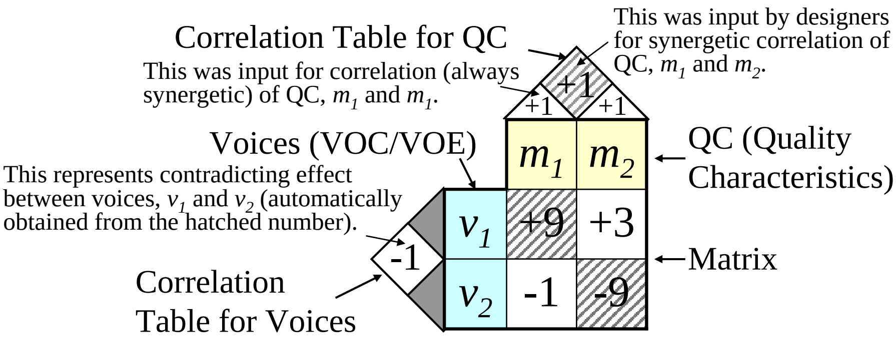


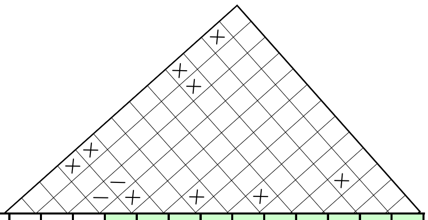
Figure 2: Example of contradicting voices on a quality table

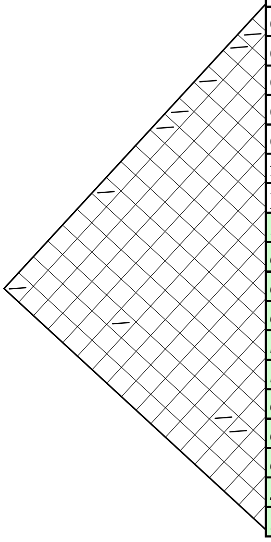
Table 2: Assumptions for the LCA (partial)

function unit	dry hair
system boundary	from material production to EOL treatment
material	ABS resin 0.1 kg, etc.
energy for production	electricity 0.1 kWh, heavy fuel oil 0.05kg
usage scenario	5 years' use for 20 minutes per day (electricity: 487kWh)
EOL scenario	conducting shredder on the whole product, and recovering steel scraps with the rest land-filled.
transport scenario	transporting from the material factory to assembling factory in 50 km, from the assembling site to the retailer in 600 km, and from the end user to EOL site in 100 km by a truck (10-ton capacity)

QFDE

Phase I





	weighting	air flow	air temperature	balance (torque)	weight	volume	number of parts	number of types of materials	hardness	physical lifetime	amount of energy consumption	rate of recycled materials	noise, vib., electromagnetic wave	toxicity of materials
dry quickly	9	9	9								9		9	
dry quietly	3	***9***									***9***		***9***	
operate safely	3	***1***	***9***	3					3	3			***9***	
operate easily	1			3	***1***								***1***	
comfortable to hold	1		***1***	9	***9***	***9***			3	3			***1***	
reliable	3	***1***	***1***				***3***	***3***		9	***1***		***1***	
portable	1				***3***	***9***								
less material usage	9				***9***	***9***	***1***	***3***				9		
easy to process and assemble	3						***9***				***3***			
easy to process wastes from production	1				***3***	***3***					***3***			***9***
easy to transport and retain	1				***3***	***3***					***3***			
harmless to living environment	3	***9***	***9***						3				***9***	
high durability	3								9	9				
easy to reuse	1									9				
easy to disassemble	3						***9***	***9***			***3***			
easy to smash	9								***9***		***3***			
safe emission	3							***3***						***9***
less energy consumption	9	***9***	***9***								***9***			
	raw score	222	220	21	100	105	72	72	129	75	243	81	167	36
	relative weight	0.14	0.14	0.01	0.06	0.07	0.05	0.05	0.08	0.05	0.16	0.05	0.11	0.02

Note:

1. The correlation strength; bold and italic numbers mean negative correlation, while others are positive.
2. The correlation table for QC; "+" and "-" mean synergetic and contradicting effects, respectively, while the correlation of an identical QC (always synergetic effect) are omitted.
3. The shaded parts are related to environmental issues including VOE written in italic.

Figure 3: Phase I of QFDE

QFDE Phase II	relative weight from Phase I	motor	fan	heater element	swith/ wiring harness	housing
air flow	0.14	9	1	1	1	1
air temprature	0.14	3	3	9	1	1
balance (torque)	0.01	9	3			9
weight	0.06	9	3	3	1	9
volume	0.07	9	3	1	1	9
number of parts	0.05	1	1		1	9
number of types of materials	0.05	1	1		1	9
hardness	0.08					9
physical lifetime	0.05	9	1	9	3	9
amount of energy consumption	0.16	9	1	9		
rate of recycled materials	0.05					9
noise, vib., electromagnetic wave	0.11	9	3			9
toxicity of materials	0.02	9			3	1
	raw score	6.17	1.64	3.54	0.73	5.10
	relative weight	0.36	0.10	0.21	0.04	0.30

Figure 4: Phase II of QFDE

Table 3: suggested inventive principles

improving e.p.	*worsening e.p.*	*inventive principles*
9. Speed	31. Harmful side effects	#2 Extraction
		#21 Rushing through
		#24 Mediator:
		#35 Transformation of physical or chemical states of an object
21. Power	31. Harmful side effects	#2 Extraction
		#18 Mechanical vibration:
		#35 Transformation of physical or chemical states of an object

e.p.: engineering parameters