Design for Environment (DfE) Methodology using Novel VE-based Product and Process Model, and TRIZ-based Innovation Principles in Consideration of Product Lifecycle

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Abstract

Reduction of environmental impact and energy consumption becomes a crucial issue. In the field of product manufacturing, development and improvement of products that reduce environmental impacts are called the design for environment (DfE). This paper proposes a systematic methodology of the DfE through identification and resolution of contradictions based on the concept of TRIZ (Teoriya Resheniya Izobreatatelskikh Zadatch) developed by Dr. Altshuller in the former Soviet Union. The proposed methodology consists of the following four steps: conceiving an original idea to reduce environmental impact or improve product functions, identifying the contradictions between the environmental impact and the product function using a product and process model, transforming the identified contradiction into a TRIZ problem, extracting the applicable TRIZ inventive principles and modify the original idea. It is found that the original TRIZ engineering parameters cannot be used because they are extracted mainly from examples of mechanical system inventions. So, we proposed to add environmental impact parameters customized for the DfE. The proposed methodology has been examined by the PET bottle lifecycle example. The engineer successfully comes up with the idea inspired by this inventive principle. Although the proposed methodology only considers the contradictions between the environmental impact and the product function, it is easily expandable to consider the cost as the additional factor, and further to apply for general design problems.

Keywords

Design for Environment, Product and process model, Structure and behavior, Idea generation methodology, TRIZ, Contradiction matrix

1. Introduction

Reduction of environmental impact and energy consumption in manufacturing industries is becoming a crucial issue. During the 60s and 70s, environmental problems were dealt with by so-called “end-of-pipe” technologies. In the 80s and 90s, companies tried to increase their eco-efficiency by refining and redesigning their already existing products and manufacturing processes [Lagerstedt 2003]. However, a drastic reduction of environmental impacts in product lifecycle is possible only if environmental aspects are taken into account in the early phases of product and process. Recently, a new concept of development and improvement of products and processes called the design for environment (DfE) that reduces environmental impacts throughout the product lifecycle has been proposed. The DfE is essentially a complex task. It is not enough to conceive an idea to reduce environmental impact because a reduction of environmental impact often degrades product functions, and an improvement of product function may increase environmental impacts of its product lifecycle. It is required to modify the original idea to solve such contradictions. Due to such a complexity, there is a need for efficient and easy-to-understand DfE methodology applicable to early product development phases. This paper proposes a systematic method for assisting designers to design or improve products and processes with less environmental impacts, while taking into account other requirements such as product functions and costs at the same time. Our approach is based on the identification of trade-off between environmental impacts and product functions by novel product and process model, and the resolution of those contradictions by the TRIZ modified to handle environmental aspects of products and processes. In the following section, an overview of the proposed DfE methodology is described. In section 3, a concept of novel product and process model is explained. And how contradictions between impacts and functions are identified using this model is described. In section 4, how TRIZ is modified to handle environmental aspects is described. And how product designers are assisted to solve the contradictions by the modified TRIZ is explained. In section 5, the proposed method is demonstrated and examined using the PET bottle as an example product. Finally, section 6 briefly summarizes the achievements done in this research.

2. Design Improvement Steps in DfE

A product design phases consist of basic design, detailed design, trial production/evaluation, and production design. The proposed method supports the earliest phase of design, basic design. In the basic design phase, the design specifications to be modified are determined to satisfy user requirements or market trends. Although the major design criteria are (product) function, (environmental) impact and cost, this research focuses on only function and impact. The proposed method consists of the following four steps as shown in the figure. These steps are repeated until a feasible design modification is generated.

STEP 1: In this step, an idea of design modification to reduce environmental impacts or improve product functions is conceived. Software tools such as Quality Function Deployment for Environment (QFDE) [Masui et al. 2001] are available to support this step.

STEP 2: The design modification intending to improve product functions may increase the environmental impacts and a reduction of environmental impacts may degrade product functions. In this step, the contradictions between impact and function caused by design modifications are identified. A novel product and process model is developed to support this step. Once a product and process model of existing product is constructed and the designer changes some model parameters according to the design modification, the model automatically reevaluate the impacts and functions from both product and process aspects.

STEP 3: In this step, the design guidance to solve the identified contradictions is extracted. A contradiction matrix of TRIZ is deployed. The product designer identifies the impact-function relationship in the contradiction matrix for the DfE from the most appropriate parameters intersection and obtains the inventive principles on the intersection.

STEP 4: First, the designer chooses the design guidance (inventive principle) from the inventive principles obtained in the previous step. Thereafter, the original idea is modified based on the inspiration given by the design guidance. The inventive principles enable designers create better solutions easier.

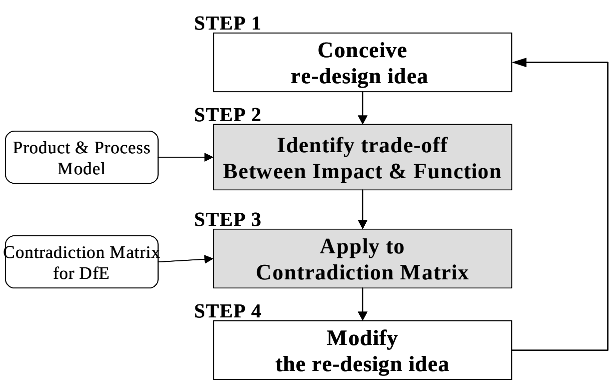

Figure 1. Design Improvement Steps in DfE and Supporting Tools

In general, the problem solving consists of 1) description of problem, 2) evaluation of problem, 3) solution of problem. The product and process model provides a mean to describe and evaluate the problem. The contradiction matrix for DfE provides a method of solution. Those tools are described in the following sections.

3. Product and Process Model

The identification of contradictions requires an evaluation of both the effects of design change on the product functions and environmental impacts. However, the current lifecycle assessment (LCA) cannot evaluate the product functions because its purpose is to evaluate the environmental impacts of fixed product design, and the model does not include the product model. So, we developed a new product and process model. The proposed model consists of product models corresponding to resources, intermediate products, final products, discarded products, recycled materials and wastes etc., and process models corresponding to the unit operations such as manufacturing, transportation, recycle and landfill. Those models have an internal structure based on the concept of Multi-Dimensional Formalism (MDF) that enables the explicit representation of structural and behavioural perspectives. The core of this formalism is based on the more general multi-dimensional object-oriented model (MDOOM) [Batres et al. 1998] that provides a conceptual and generic framework. What distinguishes the MDF from other artifact representation paradigms is that the knowledge for structure model is separated from the behavior or function model. This is the basis for the development of simulation environments in which different product lifecycles and evaluation schemes can be explored with little burden of model reconfiguration.

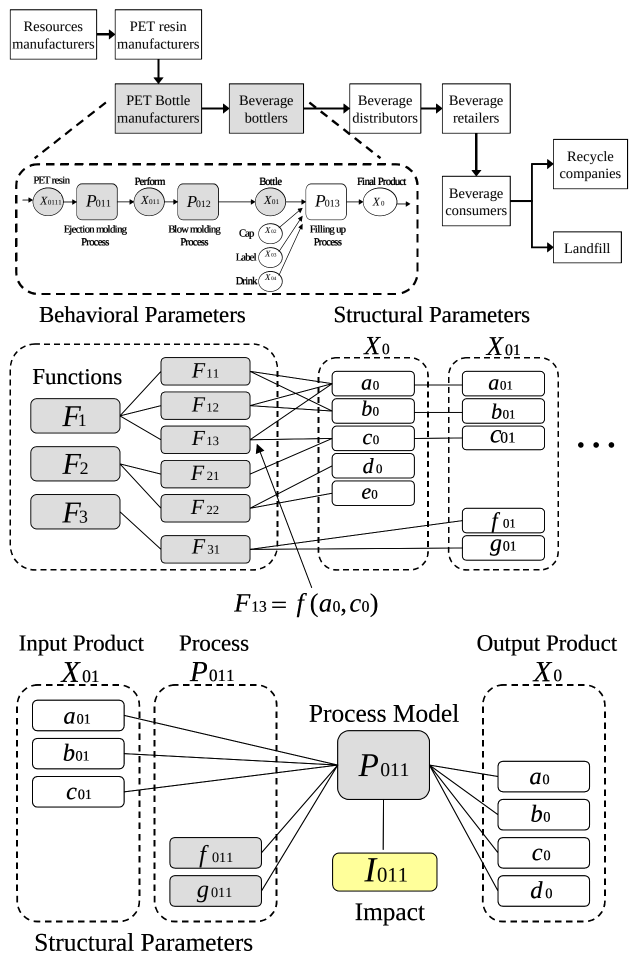

Figure 2. Product and Process Model

The structural part of product model expresses the elaborate design specifications such as shape, structure and component. The behavior part of product model expresses the functions of product such as structural

strength, density, transparency and gas permeability. The behavior part of product model relates product functions and design specifications. We have tried systematic definition of product functions using the value engineering (VE). The structural parts of other products (resources, intermediates, and final products) in the product lifecycle are interrelated so that the design changes of final product are automatically and immediately reflected on the structural and the function parts of resources and intermediate product. The structure part of process model expresses the design specification of equipment and operating conditions such as temperature, pressure and operation time. The behavior part of process model is used to evaluate the behavior of process such as energy consumption and emission from the structural part of process model. The structural parts of product models have a functional relationship to the structural part of process models so that the product deign modification may demand the changes of process deign and the process design modification may require the alternation of input product specifications and alter the out product specifications. The total impact of product lifecycle is calculated following the procedure used for the LCA.
The trade-off between environmental impact and product function is identified as follows. Firstly, a product design modification changes the structural part of final product and that change in turn triggers the modification of structural part of all the corresponding resources and intermediate products. These changes of product models demand the modification of structural part of process model. Then the changes in environmental impacts of product lifecycle are computed from the behavior (function) parts of process models while the changes in product function are computed using the function model of final product.

4. TRIZ for DfE

TRIZ (Theory of Inventive Problem Solving) restates the problem in terms of physical contradictions. The vertical items are improving parameters and the horizontal items are worsening parameters. The appropriate inventive principles are found at the intersection of contradicting engineering parameters in the contradiction matrix. TRIZ defines 39 parameters and 40 inventive principles.

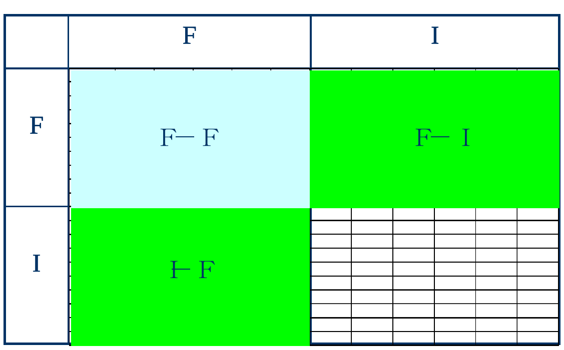

Figure 3. Contradiction Matrix for DfE

Although the general concept of TRIZ is suitable for the problem solving occurring in the DfE, it is found that the original TRIZ engineering parameters and inventive principles cannot be directly used. The parameters to express the characteristics of product lifecycle and environmental impacts are out of scope because the original TRIZ engineering parameters and inventive principles are mainly extracted from patent examples of mechanical system inventions. There are several trials to enhance TRIZ for the DfE [Bernard and Reiner 2001, Li et al. 2001, Liu and Lewis 2003, Kobayashi 2003]. The basic idea is to add environmental impact parameters to both improving and worsening parameters of contradiction matrix. So the contradiction matrix becomes a combination of Impact-Function, Function-Impact and Impact-Impact in addition to Function-Function matrix of the original TRIZ.
For the inventive principles, the original principles are satisfactory as far as the design problem is limited within the product design. However, the addition of inventive principles will be required if the design problem is expanded to include process and product lifecycle design. How a new environmental parameter is identified is illustrated in the next section although the allocations of inventive principles on the intersection of Impact-Function, Function-Impact and Impact-Impact are not a focus of this research.

5. Case Studies

The proposed methodology has been examined by PET bottle case studies. PET resin recovered from discarded PET bottles is cut, separated from other kinds of plastics, metal, paper and cleaned, and used to manufacture fibers and sheets. The user functions of PET bottle include strength, clarity and preservability of contents. These functions are closely related to the design specifications such as thickness of resin layer, resin crystallization ratio and bottle shape. Two case studies: reduction of oxygen permeability and reduction of PET resin usage per bottle have been carried out.
In the first case study, an idea of to increase the thickness of PET bottle resin layer to reduce oxygen permeability is conceived. A product and process model consisting of three final and intermediate products (resin, preform and bottle) and two processes (ejection molding and blow molding) has been developed. The structural part of product model has attribute information of resin specification, degree of resin crystallization and PET resin layer thickness. The behavior part of product model has attribute information of clarity, strength and oxygen permeability. The effects of design change on the user functions of PET bottle and the environmental impacts of PET bottle lifecycle have been evaluated using the product and process model It is found that increasing the thickness of PET bottle resin layer increases the resin consumption, and the weight and thickness of preform. An increase in resin consumption in turn increases the operation temperature of ejection molding process. The product and process model has shown that the increasing thickness of PET resin layer increases the environmental impacts in

resin procurement, ejection molding and disposal. The identified trade-off has been translated into a TRIZ problem. The reduction of oxygen permeability to increase the preservability of PET bottle corresponds to the improvement of the 27th engineering parameter of TRIZ, ‘Reliability’. The increased resin consumption as a result of increasing the thickness of PET bottle resin layer corresponds to the worsening of the 26th engineering parameter, ‘Amount of Material’. The invention principles corresponding to the intersection of those two parameters are ‘3: Local quality’, ’21: Rushing through’, ’28: Replace a mechanical system’ and ’40: Composite material’. The effective ideas to resolve contradictions are identified from those invention principles. The ideas of mixing of oxygen barrier material or introduction of oxygen barrier layer are conceived from the invention principles ‘Local quality’ and ‘Composite material’ where ‘Local quality’ means the transition from homogeneous structure to heterogeneous structure, and ‘Composite material’ means the replacement of homogeneous material to composite material. An introduction of oxygen barrier layer has been actually proposed by PET bottle manufacturers. The second case study shows the case where the initial motivation of design improvement is a reduction of environmental impacts. The thinner PET resin layer means the less use of PET resin and improving environmental impacts. However it turns out to makes a PET bottle too fragile. In this case, the improving engineering parameter is ‘Volume of stationary object’ and the worsening engineering parameter is ‘Strength’, and the corresponding inventive principle is ‘Spheroidality’. The engineer successfully comes up with the idea of redesigning PET bottle shape inspired by this inventive principle.

Worsening Parameters / Improving Parameters	F	I		Recyclability	
F					
Reliability				**Inventive Principles 1, 25, 26, 27, 33**	
I					

Figure 4. Introduction of Environmental Parameters

In the first case study, an introduction of oxygen barrier layer could make a recycle of resin difficult or impossible. One finds a difficulty to find an appropriate engineering parameter to this ‘Recyclability’ criterion because ‘Recyclability’ is not a characteristic of product but one of product lifecycle. It is necessary to add parameters to express the characteristics of product lifecycle. Design schemes to solve ‘Recyclability’ includes 1) use easily decomposed parts, 2) use homogeneous material, 3) use recyclable material, 4) effective use of waste and 5) use abundant material and these solutions can be inspired from the inventive principles of TRIZ: ‘1: Segmentation’, ’33: Homogeneity‘, ’26: Copying‘, ’25: Self-service‘ and ’27: Inexpensive, short-lived object for expensive, durable one‘ respectively. One can brush up the contradiction matrix for DfE by this way.

6. Conclusion

This paper proposes a systematic product design improvement steps for DfE. A novel product and process model to identify the contradiction is also designed. In addition a modification of the TRIZ has been presented to handle environmental aspects for DfE. The case studies show that the novice like the author come up with reasonable ideas to resolve trade-off that are proposed by the expert in the area flowing the proposed steps. Although the proposed methodology only considers the contradictions between the environmental impact and the product function, it is easily expandable to consider the cost as the additional factor, and further to apply for general design problems.

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