M.S. THESIS

METHODOLOGY FOR PRIORITIZING DfE STRATEGIES BASED ON LCA AND AHP

AN APPLICATION OF LIFE CYCLE ASSESSMENT (LCA) AND ANALYTIC HIERARCHY PROCESS (AHP)

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by

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Abstract

Recently environmental problems as well as resource depletion problems have become international issues. Corporations producing products and services are considered as the major contributors to these problems; thus, they are charged with the responsibility of producing products in environmentally friendly manner. Accordingly, it has been recognized by the industry that design for environment (DfE) not only provides opportunities for improving environmental aspects of a product but also for enhancing the product competitiveness.

Establishing an appropriate DfE strategy for the design of an environmentally friendly product is a decisive factor in determining environmental aspects of the product. In addition, establishing DfE strategy is a complicated process and requires tough decision making. Research on establishing a systematic DfE strategy, however, is scant.

This research proposes a systematic methodology for setting priority of DfE strategy in designing an environmentally friendly product by considering both environmental and business aspects of a product. The process of establishing DfE strategy consists of consideration of environmental as well as business design factors, and then integrating both factors to prioritize DfE strategies.

The proposed methodology is based on Life Cycle Assessment (LCA) and Analytic Hierarchy Process (AHP), and consists of five steps. They include identification of the environmental design factors (1^{st} step), identification of the business design factors (2^{nd} step), determination of the relative significance of both environmental and business design factors (3^{rd} step), rating DfE strategies per design factor (4^{th} step), and derivation of global priority score (GPS) of each DfE strategy from 3^{rd} and 4^{th} steps (5^{th} step). A total of five DfE strategies were used including material use optimization, clean manufacturing, efficient distribution, clean use and operation, and end-of-life optimization.

Environmental design factors are identified in the 1^{st} step. Normalized environmental impacts of a product system have been allocated into material use, product manufacturing, distribution and packaging, use, and disposal stages of a product life cycle. This results in a total of five environmental design factors.

Business design factors have been divided into two aspects in the 2^{nd} step; investment requirement and added benefit. Level of technology required, R & D time required, hardware required, personnel training required, and cost invested are considered as design factors in the investment requirement aspect. Technology know-how, product quality improvement, customer perception, cost reduction effect, preparation to future regulations are considered as design factors in the added benefit aspect. This results in a total of ten business design factors.

Relative weights of three strategic factors and fifteen design factors are determined based on AHP analysis in the 3^{rd} step. Environmental significance, investment requirement, and added benefit are three strategic factors. Relative weights of the strategic factors, higher level in the AHP analysis, are determined by pair-wise comparison. Relative weights of the design factors or criteria belonging to each strategic factor, lower level in the AHP analysis, are determined by pair-wise comparison. Instead of a pair-wise comparison, LCA results are

applied to the relative weights of the environmental design factors. Global weight of a criterion is a product of the relative weights of criterion and strategic factor.

DfE strategies belonging to each criterion are rated in the 4th step. Prior to the rating, however, rating scale of five rating yardsticks including outstanding, good, average, fair, and poor, is determined through pair-wise comparison. This pair-wise comparison is the same in concept as that used in determining relative weights. Relative weights of the rating yardsticks or rating scores are obtained in this process. Then scores to DfE strategies per criterion are assigned using the five rating scores.

Finally GPS value is computed per each DfE strategy in the 5th step. GPS value is a product between relative weight of a criterion and rating score of a DfE strategy, followed by summation for all criteria. This is shown in the equation below.

$$GPS_k = \sum_j (GW_j \times RS_{j,k})$$

GPS_k : global priority score of k^{th} DfE strategy

GW_j : global weight of j^{th} criteria

$RS_{j,k}$: rating score of k^{th} DfE strategy with respect to j^{th} criteria

The outcome of this research is the proposition of a DfE strategy prioritization methodology applicable to an environmentally friendly product design. Application of the design factors and DfE strategies evaluated in the proposed methodology should be modified relevant to a specific situation of a product design.

Ⅰ. Introduction

A. General Descriptions

Environment and Design for Environment

It is well known fact that global environmental carrying capacity as well as natural resource has their own limit. Problems we have faced today are how to manage our environment including natural resources, ecosystem, human health and safety. Sustainable development is the only one answer emerging from the question. Sustainable development was defined as 'development which meets today's needs without placing the ability of future generations to meet their needs at risk' in the Brundtland report[1]. The higher level of prosperity is in society, the heavier demand on the earth's natural resource is required. Irrational resource consumption together with irresponsible environmental pollution resulting from the industry is the main cause of exceeding the global carrying capacity and depleting natural resources.

The traditional end-of-pipe technology for environmental management are being questioned according to increase concern about potentially significant environmental problem – from global one to local and regional one. These approach alone are unlikely to provide satisfactory and cost-effective protection of ecosystem and human health in the near future. Integration of environmental aspect of product into the product development process has been recognized as one of the most important catalyst in transforming societal patterns. The concept of Design for Environment (DfE) or Ecodesign is considered as a promising approach for improved product performance towards sustainable production and consumption.

General DfE Procedures and DfE Strategy

DfE provides a systematic method for companies to reduce the environmental impact of their products and process while simultaneous cutting cost, increasing the marketability of their products and becoming more innovate.[2] Generally DfE is playing with design process which is from product planning, conceptual design, detail design, finally to market launch – those procedures will be described in detail in chapter **Ⅱ**. In the product planning stage, design strategy dealing with which design direction should be taken through whole design process by identifying product features and market position in terms of environment, cost, performance of product. Product concept and design structures are roughly determined in conceptual design stage. Finally, the product concept is developed in detail to generate product detail design drawing and manufacturing system document.

Set up design strategy at product planning stage- i.e. design objective is starting point of implementing DfE. After that designer define the strategic design target, the critical

[1] World Commission on Environment and Development (1987)
[2] Canadian DfE approach, Website (http://www.nrc.ca/dfe)

success design factor can be defined for meeting the target. In other words, strategy formulates all the actions to be taken to realize the vision in a given period. Strategy formulation starts with a tough analysis of the current environmental position of the product line up, both in technical, industrial and commercial terms. The results of the external and internal analysis are taken into account at the same time. In a number of literatures and guidelines, importance of DfE strategy is mentioned with no exception, however, there have been few researches on methodology for set up and prioritize DfE strategies

Need of systematic decision on prioritizing DfE strategy

Many companies have recognized DfE as an inevitable business strategy. For this purpose, establishing DfE strategy is essential and usually based on environmental aspects of product. Today, this form of intervention is no longer acceptable because of certain critical business elements such as cost and benefit. The most production costs are determined in product specification stage where DfE strategy is established. The managers and designers conducting DfE have to prioritize and select the best DfE strategy from a set of possible alternative strategies. It is particularly difficult to choose the best mix of DfE strategy when this choice is only based on environmental aspects. Even the decision will have significant consequences in the short-medium term for matters such as resources (i.e. budget) allocation, technological choice, managerial and organizational procedures, etc. Several business attributes must be taken into account systematically at this starting point of design procedure. It is therefore clear that the analysis and justification of DfE strategy selection is a critical and complex task due to the great number of attributes to be considered, many of which are intangible. Bevilacqua & Braglia [3] had discussed the application of analytic hierarchy process (AHP) to select optimal maintenance strategy considering maintenance criteria such as cost, reliability and availability. As an aid to the resolution of this problem, multi criteria decision making (MCDM) approaches are required In this study AHP is used to integrate environmental aspects and business aspect systematically into prioritizing DfE strategy.

B. Objectives and Limitations of the study

1. Objectives

DfE activities and DfE strategies are widely well known concepts used in product development processes. However, the prioritizing procedures of DfE strategy has not been fully examined in any prior researches, even though nobody doubts the importance of product development strategy in design process. For that reason, the major efforts were given to develop a systematic prioritizing process including weighting relevant criteria and evaluating the trade-off between environmental attributes and business attributes of DfE strategy.

The main objective of this work is to frame for prioritizing DfE strategies with which corporations can balance product development strategies when they integrates environmental

[3] M. Bevilacqua (2000)

aspects into their product development process. For the framework Analytic Hierarchy Process (AHP) was adopted and attributes of DfE strategy were analyzed and classified into environmental aspects and business aspects which can be decision criteria for prioritizing. Life Cycle Assessment (LCA) was used to identify environmental aspects that are able to affect to selection of DfE strategy. Then environmental aspect and business aspects were integrated together and evaluated in a hierarchical structure of AHP. The detail procedure was described in chapter 4.

2. Limitations of the study

As mentioned above emphasis was given to frame the systematic procedures for integrating environmental aspects and business aspects into prioritizing DfE strategy. Several limitations exist in this study are followings.

First, the choice of criteria and a set of DfE strategies are somewhat subjectively defined. And it is notable that the relative importance between each parameter varies with the product category and business strategy of a company, which means results of this approach are different from case by case. As for set of alternative DfE strategies, five DfE strategies that are representing optimization strategy for each product life cycle stage. The proposed methodology is generally applicable to any set of DfE strategy that decision maker wish to evaluate, as it covers the critical strategic factors and related criteria for DfE strategy selection. The model provides the flexibility to include any specific criteria and alternative DfE strategy to be evaluated.

Second, A five-point rating scale of outstanding (O), good (G), average (A), fair (F), and poor (P) is adopted to determine relative importance of lowest level of hierarchy where alternative DfE strategies are assessed for each criterion. The rating system instead of direct pair-wise comparisons among alternatives can be found in Maggie et. al (2001)[4]. The major advantage of this method is to overcome the explosion in the number of required comparisons when the number of alternatives in large. For this system, the priority weights of these five scales determined using pair-wise comparisons. Therefore, A potential complication might arise when assigning the rating scales. For example, the relative rating of an "out standing" VS. a "good" rating may differ for different criteria. But such fine discriminations in judgement would be very difficult. Furthermore, prioritizing DfE strategy is not needed detail evaluation that is like selection of design alternative. The rating system make the assessment process as simple as possible. For that reason, one set of rating system was taken in this study.

[4] Maggie (2001)

II. Design for Environment in Practice

No business that strives to remain competitive, open to new markets and new opportunities, can afford to ignore the global demands for environmental quality of society. The international market for low-impact products – which are more energy-efficient, which reduce water consumption, decrease pollution and reduce end of life waste) is growing at an astonishing rate. In established industrialized markets such as Europe, the USA, Canada, and Japan, the demand for such products – and the investment to create them – is driven by increasingly stringent regulations that would otherwise limit the rate of development.[5]

Therefore, demand for 'cleaner and greener' products is also growing because investment in research, design and innovation is delivering new competitive products with greatly improved environmental efficiencies. Major international companies, organizations as well as governments of developed countries have given emphasis on research and development in this field. Some companies such as Philips[6,7], IBM[8], etc. have had even their own guidelines and established applicable databases, too. In this chapter brief description and current situation in DfE field, especially for companies in the world are summarized. Popular DfE tools and guideline such as Life Cycle Design Guidance Manual[9], Ecodesign[10], ISO TR 14062[11] were described and compared.

A. General Description of DfE

In this section following topics were briefly introduced.

- What is DfE and Definitions of DfE
- Synergy effect toward DfE; customers, governments, companies
- Levels of DfE
- "Where" and "How" to integrate into traditional design process
- Barriers of DfE
- DfE activities in major companies

[5] T.E Graedel & B.R. Allenby (1995)
[6] Herman (1997) – Philips EcoDesign guidelines.
[7] Pascale & Herman (2000)
[8] web resources (http://www.ibm.com/ibm/Environment)
[9] Keoleian & Menerey (1993)
[10] Brezet et al. (1997)
[11] ISO TR 14062 N21 documents

What is DfE

It's widely recognized that industry should reduce the environmental impact of its activity and products. The most advanced companies have changed their attitude on environment moving beyond the compliance mentality and being proactive in shaping future markets consumer needs and influencing legislative developments. They have considered environment as an opportunity rather than a threat. Xerox, HP, IBM, Philips etc. are well known companies with their proactive environmental concerns as well as their products. They recognized that 'prevention is better than cure'. This has seen a shift from end of pipe solutions to the front end of the product development in order to manage environmental problems which is called DfE or Ecodesign. It is to integrate environmental aspects into product development process.

A number of authors have defined DfE or Ecodesign:

Fiksel[12] defined DfE as systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life-cycle

Dewberry and Goggin[13] described ecodesign as "Ecodesign is an approach to design where all the environmental impacts of a product are considered over the products life"

By Allenby[14] of AT&T,

"A practice by which environmental considerations are integrated into product and process engineering design procedures. Design for Environment (ecodesign) practices are meant to develop environmentally compatible products and processes while maintaining product, price, performance and quality standards".

Recently by Chris and Evans[15]

"Eco design is the design of a product, service or system with the aim of minimizing the overall impact on the environment."

Moreover, a lot of literatures and DfE guidance[16,17,18,19] etc. have defined DfE as systematic method for companies to reduce the environmental impact of their products and processes while simultaneous cutting cost, increasing the marketability of their products

[12] J. Fiksel (1996)
[13] Dewberry & Goggin (1996, pp.12-17)
[14] Graedel & Allenby (1995)
[15] Chris & Stephen (2000) (quoted Simon, M., S. et al., Ecodisign Navigator. A key resource in the drive towards environmentally efficient product design, report published by manchester Metropolitan University, Cranfield University and EPSRC (1998)
[16] Design for Environment Guide, National Research Council Canada (web page http://www.nrc.ca/dfe)
[17] Brezet et al. (1997)
[18] Jeremy M. Yarwood, Minnesota Technical Assistance Program (MnTAP).
[19] Keoleian & Menerey (1993)

Being various, those definitions commonly suggest several key concepts. they are:

- To integrate environmental concerns of a product into it's early design process
- To consider environmental concerns together with other product requirements such as quality, cost, safety, etc.
- To deal with the whole impact of a product through it's whole life cycle from 'cradle to grave'.
- To start at the front end of design process

Levels of Design for environment

In the design approach for the environment, there are several levels accordance with degree of design innovation and with design tasks. Charter[20] proposed 4 step models of DfE approaches named each repair, refine, redesign and rethink while Ab Stevels[21] described the total DfE process as going up a staircase with four steps. Those levels or steps are much similar with each other and summarized in the Table 1.

Table 1 Levels of DfE presented by Chater and Stevels

	Chater	Stevels	features
1	Repair – minor alterations or substitution of material and components only for single environmental issue.	Incremental improvements of product	Problem identification then improvement
2	Refine – redesign product itself using more environmental sensitive concepts for material or product life time	(Complete) redesign of existing product concepts	Design product considering Eco-efficiency
3	Redesign – redesign looking to reduce whole impact across the life cycle stages		Consider product system (production, transport and disposal system)
4	Rethink – exploring completely new way to satisfy customer	Alternative fulfillment of functionality, new concepts	New concept development servicing identical function of existing product
5	-	Functionality designs completely fitting in the sustainable society.	Sustainable use of material Lower impact by carrying capacity of earth

[20] Martin Chater (1997) – Editorial of J. of SPD.
[21] A. L. N Stevels (2000)

Charter classified 4 types of DfE which are focusing on product orient DfE while Stevels stated 4 levels of DfE accordance with degree to achieve ecoeffiency through whole of product system. Both literatures mentioned product innovation as task of first level and consider product redesign as that of the next step. Charter divided this step into two types of DfE with respect to design attention field whether the field covered one single DfE concept i.e. a single DfE strategy or covered whole of product lifecycle with balancing several appropriate DfE strategies. As the highest level of DfE, both of them considered functionality change for sustainable society, which means to explore completely new way to substitute existing function.

When companies start to perform DfE, most of all level of DfE has to be set up. In other words, certain level of DfE that companies will perform is dependent on their resources available such as information, time, cost, expertise etc. The results of DfE, ecoproduct is also dependent on the levels of DfE which company focuses on. In general, because of complexity of today's products and the departmental organization of most companies and institutes, DfE is essentially a cross-functional activity.

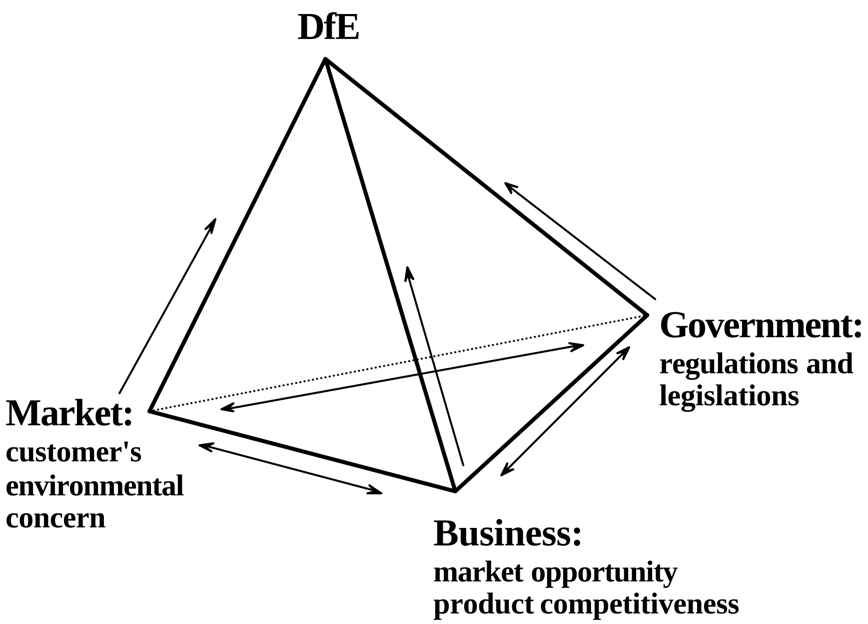


Figure 1. Synergy effect toward DfE

Synergy effect toward DfE

In this section, the need for DfE was highlighted as for perspectives of business, customers and government. Those three elements of society have concrete mutual relationship. The Fig. 1 shows the need of DfE as a synergy effect among the elements.

In business perspective – Concerns of society including consumer and government about environmental issues are growing so far, even more in the future. Pioneering company already recognized that it would be a competitive asset for companies. In fact, a number of prior research have reported good example of improvement environmental aspect of product with cutting cost and higher product quality at the same time. Many examples would be obvious evidences of proving environmental and economical interests are not mutually exclusive. DfE which is proactive design practice integrating environmental aspects of product into product and process design stage can create considerable cost savings both in the long term and short term.

In customer requirement – one of the most important things for products is having marketing competition. Because the consciousness of environmental protection is increasing by consumers, all the products must match the requirements of environmental protection in order to be accepted in market. Therefore, it is necessary that companies have useful and practical environmental strategies and make products more environmentally friendly with degree that is appealed to customers.

In government attitude change – Ordinance of environmental protection is getting stricter because government has reliability for leading society to more sustainable one and people (i.e. consumer) want higher quality of life. Then, Government has forced company to cover also other stages of a product life cycle than production. For example, Expanded Producer Responsibility (EPR) forces industrial companies to have physical and economical responsibility to develop product take-back systems. Through the take-back system products at their end-of-life may be collected and processed in order to recover materials and energy with a minimum of extra resource use.[22]

[22] Knut et al.(1999)

'Where' and 'How' to integrate environment into traditional design stages

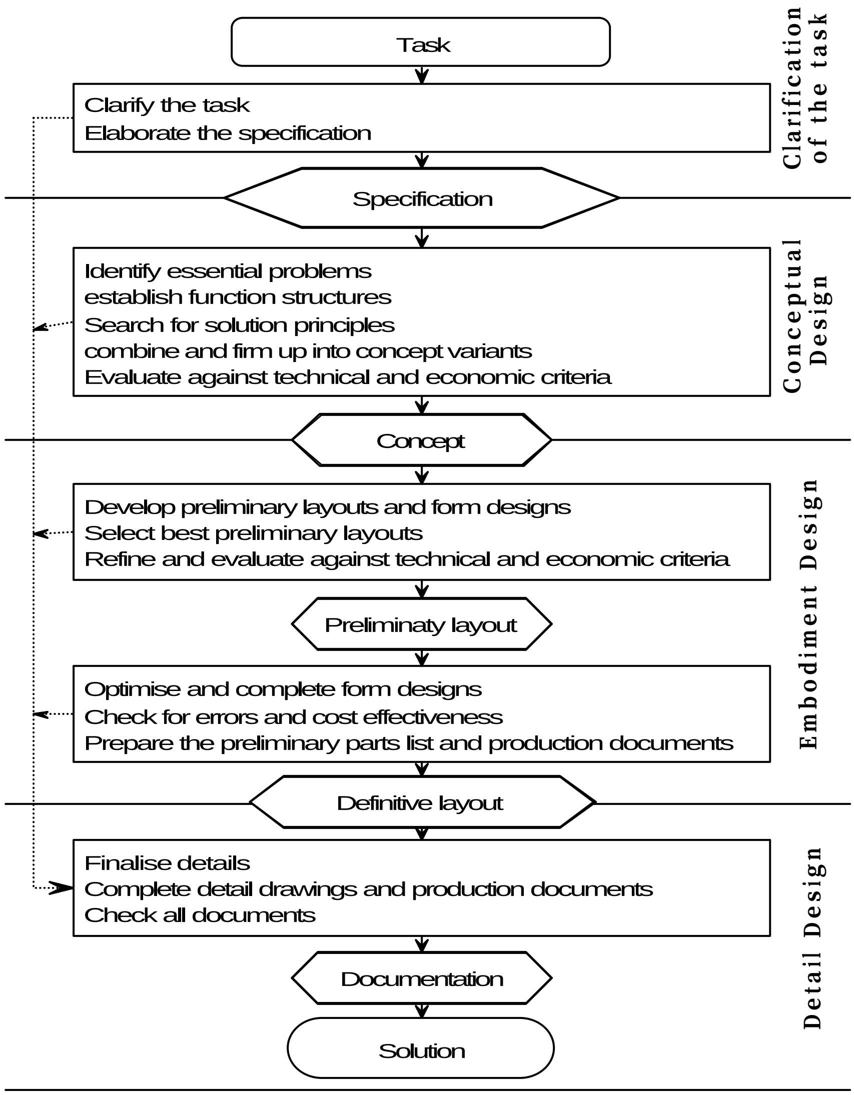


Figure 2. Steps of the design process (adopted from G.Pahl & W.Beitz)

Pahl & Beitz[23] split the design process into four main phases, which have been translated as following descriptions and steps of design process showed in Fig. 2.

Clarification of the task involves the collection of information on the requirements to be embodied in the solution and about the constraints. It is followed by the drawing up and

[23] G. Pahl, W.Beitz, (1998, pp.41)

elaboration of a detailed specification or requirements list. Conceptual design involves the establishment of function structures, the search suitable solution principles and their combination into concept variants. Concept variants that do not satisfy the demands of the specification have to be eliminated and the rest must be judged by the systematic application of specific criteria based on the wishes of the specification. During the embodiment design, the designer, starting from the concept, determines the definitive layout and develops a technical product or system in accordance with technical and economic considerations. The definitive layout selected in this stage provides a check of function, strength, spatial compatibility and so on.

A typical product design process does not incorporate environmental assessments until late into the design process, if at all. Environmental information is often introduced to a design after much of the design work has already been completed. At this point, it is difficult and costly to make substantial design modifications to improve environmental performance.

For DfE, it is necessary to know the whole process until the product is launched into the market. However, a variety of other design considerations related to the product life cycle is relevant as well. DfE have to consider all of phases of a product from raw material acquisition phase to end of life stage. Spath et. al. [24] proposed a model for an integration of the product innovation process and the product life cycle that is shown in Fig. 3 below.

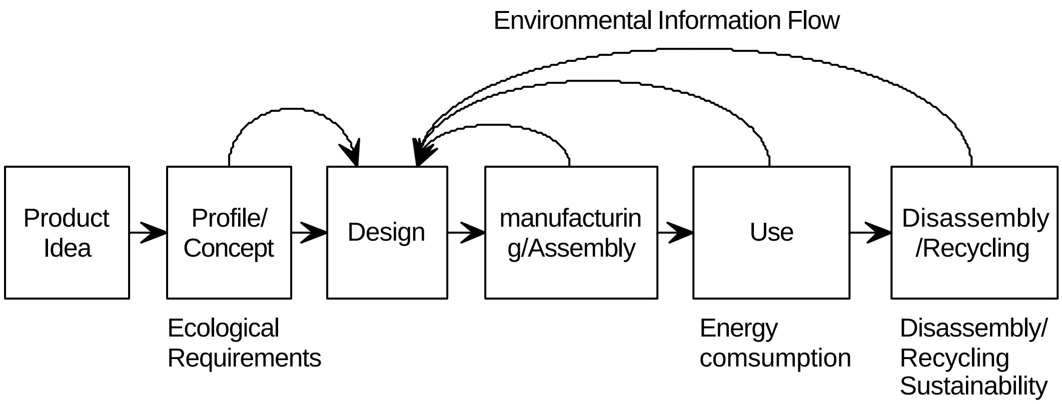
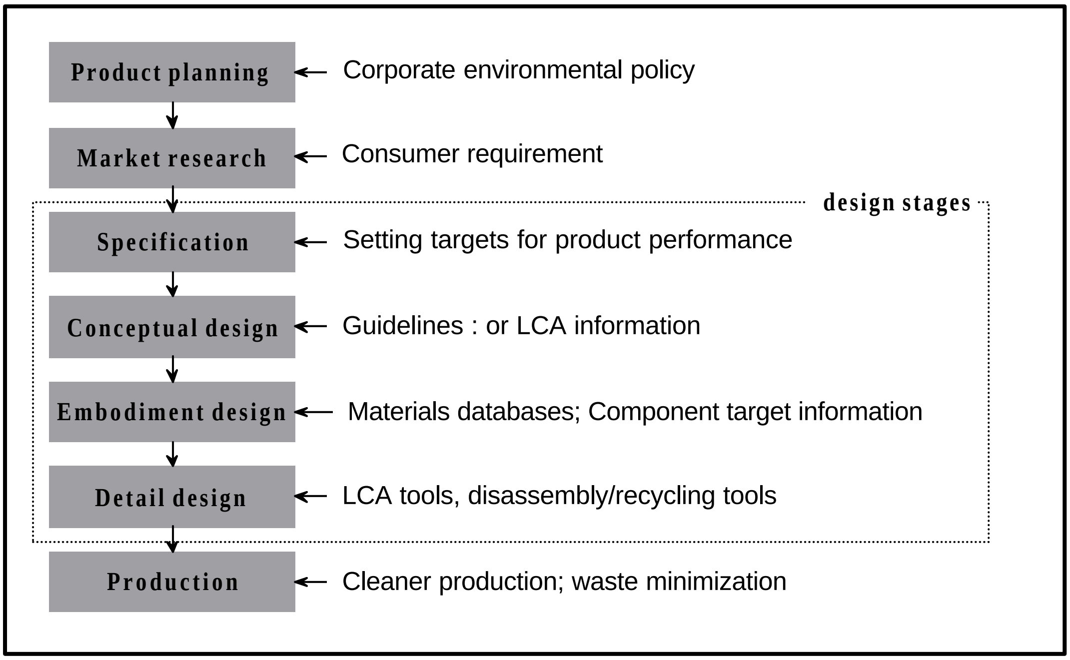


Figure 3. Information flow for integrating product life cycle and product development.

The aim of DfE is to make product designers aware of the interaction between product development, its use and disposal[25]. Information on environmental effects of the product needs to be provided at an early stage. Furthermore Pogner and Simon[26] described which information and tools are needed in a specific design process. Fig. 4 shows stages of the engineering design process and environmental information required for each stage.

[24] Dieter Spath et al.(1999)
[25] Keoleian & Menerey (1993)
[26] Pogner,J., Simon,M.(1995)

Figure 4. Environmental information required for each design stage



Barriers for DfE

Numerous barriers to the widespread adoption of DfE practice have been identified.[27] G. Ries[28] has reported survey result on DfE barriers. The result showed there are four general types of DfE barriers including low knowledge of environmental impact of a specific product, cross functional nature of design procedure, cost oriented business nature and finally lack of method for early planning stages. The biggest problems that designer face with regards to DfE is a lack of reliable data on environmental impact of materials, parts, and components, needed for tradeoff decisions. Although data gathered for life cycle analyses offers one way to breach this knowledge gap, the subjectivity, complexity, and expense often associated with this technique make it sometimes unattractive.

These problems are often compounded by unfamiliarity with environmental issues among product development personnel. To engineers, designers, and managers, the 'environment' falls into the domain of regulation/compliance and there is a failure to perceive the strategic benefits from the adoption of DfE practice. This failure manifests itself in the resistance to adoption by business unit managers. They may feel that environmental concerns are not applicable to their product lines. Furthermore, the uncertainty of environmental design presents challenges to performing DfE consistently and effectively.

[27] J. Fiksel (1996)
[28] G.Ries et al. (1999)

For the effective integration environmental information into design process, the following aspects should be considered when starting to plan how to integrate environmental issues more systematically into different phases of the product design process.[29]

- Ensure motivation and commitment
- Assess environmental burdens along the product life-cycle
- Specify design goals and respective indicators
- Draw up instructions and guidelines for the different stages of the product design process
- Ensure implementation

First, the product design team and management team should have short term and long term goals in integrating environmental issues into the product design. They must be convinced of the relevance of environmentally oriented product design and of the benefits that can be gained by implementing it.

Second, environmental aspects of the current product models should identified in order to be able to set environmental goals in the product design. Qualitative and quantitative life cycle assessment methodology should be conducted. The results of life cycle assessment are used when determining which properties of the product should be focused on in product design.

Third, long term and short term goals should be set up then indicator for measuring the achievement have to be developed. Goals and means to achieve them should be consideration not only within the product design team, but also with representatives of other functions, such as production, marketing, and purchasing staff and other product stakeholders.

Forth, from the short term and long term goals, instructions and guidelines should be established for the different stages of the product design processes. Many large companies are developing their own ecodesign manuals. The aim is that the designer considers environmental issues along with other instructions right from the beginning of the design process. This is easiest when the environmental requirements have been integrated into other design instructions and they are not treated as a separate entity.

Finally, Ensuring that the procedures developed to assist designers in their work are adopted is very important. This is easier if designers are given adequate in-house training in environmental issues. Even more importantly, they must be motivated to integrate environmental aspects into their product design work.

[29] Anna Karna (1998) (quoted Kaila Susanna, produce manager, Nokia Telecommunications, Switching Platforms, R&D. Interview 16.10.1996)

DfE activities in companies

The practice of DfE is becoming essential in today's industrial environment, as Europe and Japan move aggressively to integrate environmentally conscious technology and products into their strategies for future competitiveness.[30] Ries[31] in Swiss, however, reported only 8% of companies in Swiss have environmental goals in the product development process although 80% of them are generally aware of environmental problem in the survey. In this section, DfE activities that are performed or being performed now were summarized.

Toshiba have established decision supporting system for Environmentally Conscious Product (ECP) which is considered energy and resources consumption, recyclability of material. For this purpose, effective design tools helping designer make decision are developed. Additionally, Information database relating material purchasing, product design, manufacturing, distribution etc. have been established for supporting these tools.

Hewlett Packard (HP)[32] has incorporated design improvements that facilitate disassembly. The company disassembles and refurbishes HP and non-HP equipment. In doing so, it processes 12,000 tons of equipment annually, less than 1% of which enters the waste stream. Some of the environmental attributes designed into HP products include:

- Using a foam chassis that reduces the parts needed for some products, simplifies disassembly, and reduces the amount of protective packaging required during shipping.
- Identifying the resin content of plastic parts by marking instead of using a paper labels to facilitate recycling.

Xerox[33,34] is taking greater responsibility for its products at end-of-life by employing DfE principles and increasing take-back and remanufacturing of its durable as well as consumable products.

Xerox's asset recycling program is encouraging customers to return a wide range of products, including printers and toner bottles. Employees disassemble and sort parts from returned equipment that meet internal criteria for remanufacturing. Remanufactured parts are incorporated into new products. Parts that do not meet remanufacturing criteria and cannot be repaired are ground, melted, or otherwise converted into basic raw materials. The company integrates remanufacturing into the same assembly lines that produce new products. To achieve the company's zero waste goal, the eventual recycling of products is anticipated in product design.

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[30] Joseph Fiksel, Design for Environment: An Integrated Systems Approach, 1993, IEEE. (quote : Office of Technology Assessment, Green Products by Design; Choices for a Cleaner Environment, OTA-E-541, October 1992,p.116.
[31] Barriers for a Successful Integration of Environmental Aspects in Product Design
[32] US EPA Website (http://www.epa.gov/epaoswer/non-hw/reduce/epr/elec-bus.htm)
[33] John Ehrenfeld et. al., The development and implementation of DfE program, the Journal of sustainable product design, 1997
[34] Jack Azar et.al, Agent of change: Xerox Design for Environment Program, IEEE, 1995

IBM[35,36,37] has incorporated several Design for the Environment principles into their products, such as:

Using fewer materials;

Using recycled materials;

Coding plastics for recycling;

Closed loop recycling;

Packaging reduction, recycling and reuse; and

Considering upgradability to extend product life.

IBM extended product take-back services to U.S. commercial customers in 1997. The trend toward leasing is increasing product take-back and facilitates a higher degree of reuse and recycling. Through its network of materials recovery/recycling centers, the company expects increased product take-back to enable it to meet its recycled content standards for new products. In March 1999, IBM unveiled a desktop computer that uses 100% recycled resin for all of its major plastic parts. The new CPU contains three and a half pounds of plastic that were converted from a prime resin to 100% recycled plastic at no extra cost. One of the eight recycled parts of the system unit is now 20% less expensive to manufacture. Recycled resin used in the system unit is formulated to IBM specification by its supplier from both pre- and post-consumer resin sources.

Philips launched its EcoVision Program in 1998 by setting a series of targets for manufacturing improvements, including:

- A 35 percent waste reduction by 2002.
- A 25 percent water reduction by 2002.
- A 50 percent reduction in emissions of hazardous substances to air and water.
- A 25 percent energy efficiency improvement in 2000 (year of reference for all targets: 1994).

To achieve these targets, Philips is applying EcoDesign principles to its product line of color television sets, lighting, electric shavers, color picture tubes for televisions and monitors, and one-chip TV products. The EcoDesign initiative is focused on making improvements in product weight, use of hazardous substances, recycling and disposal, energy consumption, and packaging. As of 1998, each line of business had defined a substantial percentage of its product portfolio to be EcoDesigned. In addition, energy consumption in

[35] John Ehrenfeld et. al., The development and implementation of DfE program, the Journal of sustainable product design, 1997
[36] Martin Chater, Managing the eco-design process, the Journal of sustainable product development, 1997
[37] Web resource (http://www.ibm.com/ibm/Environment)

manufacturing had already been reduced by 23 percent and industrial waste by 28 percent.

Sony[38] is aiming to make its products and production processes more sustainable. The eco TV is halogen-free, eliminates hazardous materials, uses less total material to product, is 99% recyclable, and is designed for easy disassembly. In addition, the units are less costly to produce. Sony also offers a variety of other products under its "Green project", which is focused on designing products that reduce the use of materials (particularly those with adverse environmental impacts), improve energy efficiency, and use environmental packaging and accessories.

Additionally case of Volvo[39], Motorola[40], Akzo Nobel[41] has been reported in literatures.

[38] Web resource , US EPA (http://www.epa.gov/epaoswer/non-hw/reduce/epr/elec-bus.htm)
[39] Orley Kantz (2000)
[40] W.F.,Hoffman & Angela Locascio (1997)
[41] Jacqueline Cramer et al. (1999)

B. General DfE methodology

1. Brief Description of existing DfE procedures

In this section typical DfE procedures including Ecodesign manual[42], Life Cycle Design Guidance[43] and ISO TR 14062[44] were briefly described first. Then those procedures, especially general frame and DfE strategy selection step were discussed, compared to each other, and compared to the traditional design model that was developed by Pahl & Beitz[45] mentioned in chapter 2.

a. Ecodesign manual (Brezet et al., 1997)

The ecodesign manual suggests 7 steps to design environmentally friendly product. In the first step, ecodesign project is initiated then multi disciplinary team and elaborate planning is formed. Commitment from management is highlighted in this manual. Thus, the manual gives an emphasis on formulation of environmental policy. Product is selected in second step. Product ideas that have a high marketing potential and potentially low environmental impact are preferred. This increases the chance for success. A checklist is given for selection of a product.

During product analysis and setting priorities of DfE strategies, the environmental aspects of the reference product are determined, and the main environmental improvement options are identified. Those environmental improvement options that are considered feasible for implementation are incorporated in the requirements.

Product ideas are generated and roughly evaluated, using the criteria in the requirements in the stage of the generation of ideas. To aid the elaboration of the ideas, and the selection and detailing of a concept, design strategies are introduced again. Finally, the detailed concepts are evaluated on their environmental, technical and economical feasibility, and a choice is made. The ecodesign manual adds two more stages to the ecodesign model. These are communication & market introduction and evaluation of project and the organization of a follow-up. The model for the ecodesign manual was shown in Fig. 5.

[42] Brezet et al. (1997)
[43] Keoleian & Menerey (1993)
[44] ISO/PDTR 14062 N21 document, 2000
[45] G.Pahl, W.Beitz (1988).

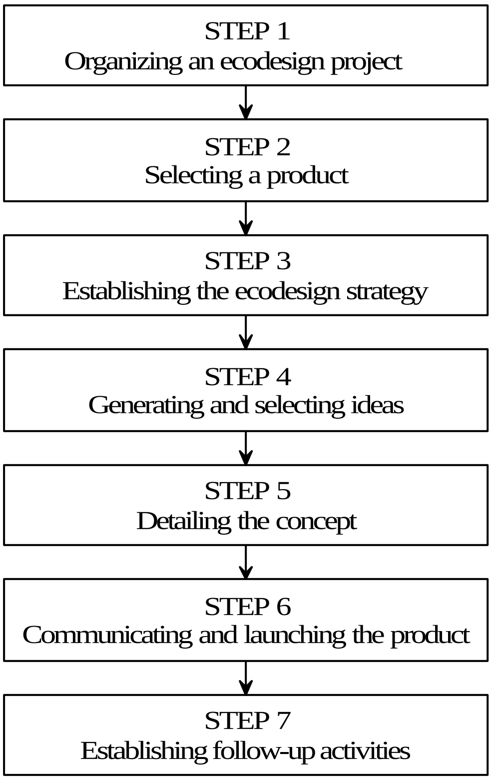

Figure 5. Steps for DfE procedure of Ecodesign manual

b. Life cycle design guidance manual (Keoleian & Menerey, 1993)

The manual focuses on designers and managers involved in product development in general. The manual adopts a systems approach to design, taking into account all 'upstream and downstream' effects of design actions. The manual furthermore stresses the need for integration of environmental aspects in the design process and the need for concurrent design in general. According to the manual, "a typical design project begins with a needs analysis, then proceeds through formulating requirements, conceptual design, preliminary design, detailed design, and implementation." This process is illustrated in Fig. 6.

The manual emphasizes the importance of commitment from all levels of project management. According to the manual, management exerts a major influence on all phases of development. Therefore, appropriate corporate policy, strategic planning, and measures for success is needed to support design projects, as well as a concurrent approach towards design. During the need analysis, the purpose and scope of the project are defined, and customers and their needs are clearly identified. The design can then focus on meeting those needs. In the requirements phase a program of requirements is built. The manual advises to incorporate environmental criteria in as early a stage as possible. On the design and implementation stages, the manual gives little details. The manual stresses the need to evaluate the design actions.

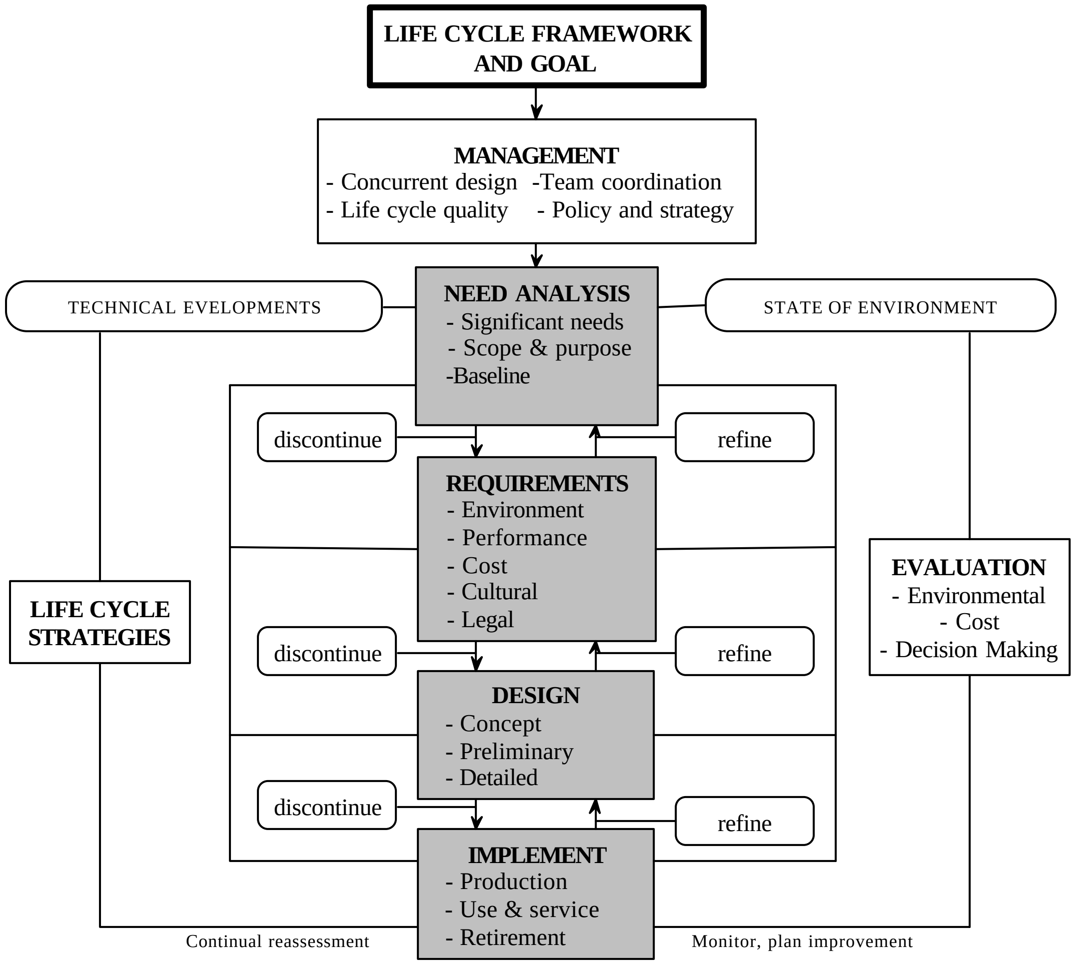

Figure 6. Life Cycle Design Process (adopted from Life cycle design guidance manual)

c. ISO TR 14062

ISO TR 14062 – Guidelines to integrating environmental aspects into product development is being developed so far by ISO/TC207/WG3 but conceptual frame work was generated so that the procedures was able to compared with other existing guidelines. The document describes several stages for integrating environmental aspect into product development as shown in Fig. 7.

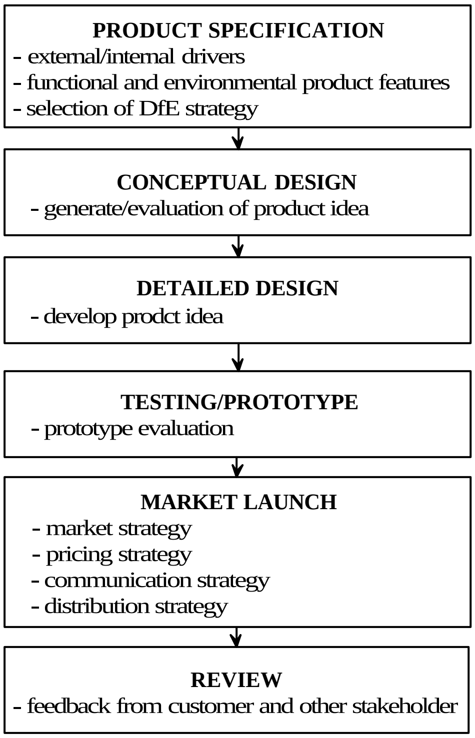

Figure 7. DfE procedures of ISO TR 14062

Product specification stage encompasses project planning and formulating product specifications. Based on the insights gained in the project definition stage and the strategies selected. The next step, conceptual design is to realize the requirements defined for the project. This process may start with a feasibility study and lead to precise engineering and procurement requirements. The key task of the conceptual design stage is the evaluation of the developed ideas against each other and in comparison with existing solutions on the market. During detail design phase, the solutions selected from the conceptual design are developed further in order to specify the product prior to production. Next stage is testing/prototype in which product alternative designed is tested and evaluated. Prior to and parallel to the prototype evaluation, testing occurs on multiple levels, including material properties, wear resistance, functionality, quality, lifetime, as well as on different elements, such as material, process and product. Market launch involves the delivery of the product or service to the market place with consideration of marketing strategy, pricing strategy, and communication strategy and distribution strategy. Finally, feedback and criticism from customer and other stakeholder identified in the review stage.

2. Discussion

The Ecodesign manual (Brezet,1997), life cycle design guidance manual (Keoleian&Menerey,1993) and TR 14062 (ISO, 2000) were briefly described in the previous sections. In this section general frameworks of these design procedures and DfE strategy establishing steps were compared each other and with Pahl & Beitz as shown in Fig.8.

Overall framework

Although the terminology is rather different, the procedures are overall comparable in the way they subdivide the product development process in stages.

The Ecodesign and life cycle design guidance take the product planning stage into account while TR 14062 and Pahl&Beitz does not consider this stage. Pahl&Beitz begin with the task and TR 14062 with production specification. The first activity of the designer should be to further clarify the task and elaborate the specifications.

The life cycle design guidance manual pays a lot of attention to the formulation of requirements. This seems however of minor importance in the Ecodesign manual and TR 14062. In these manuals, the determination of the environmental priorities and the identification of environmental improvement options are considered more important.

Life cycle guidance manual distinguishes three design stages: conceptual, preliminary and detail design. However, Ecodesign manual distinguishes two. The Pahl&Beitz distinguished three stages: conceptual, embodiment and detail design. Finally, TR 14062 distinguishes three stages: conceptual design, detail design and testing/prototype evaluation. The choice between two or three stages seems rather arbitrary

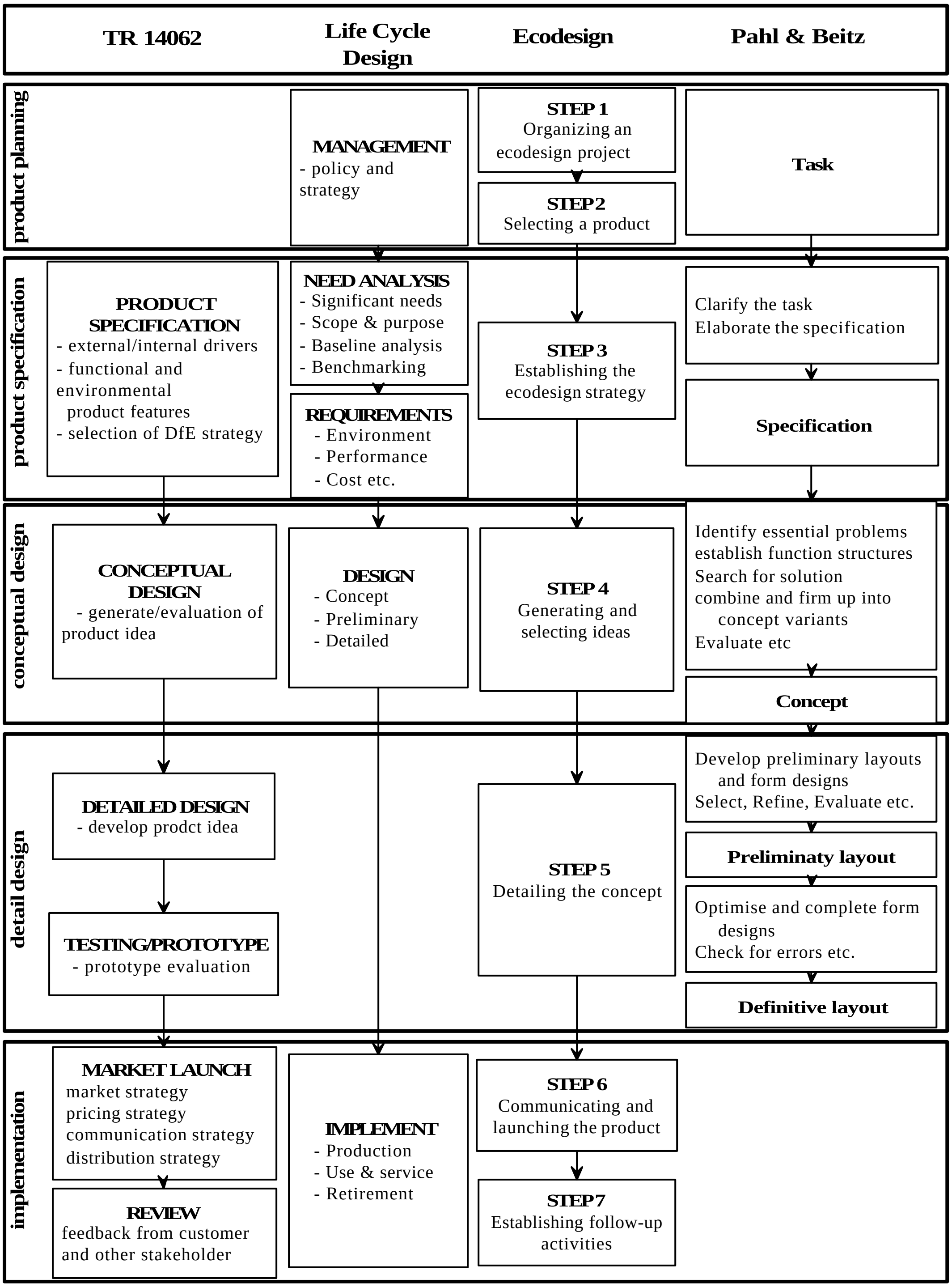

Figure 8. Comparison of general DfE procedures

Pre-design stages related to DfE strategy

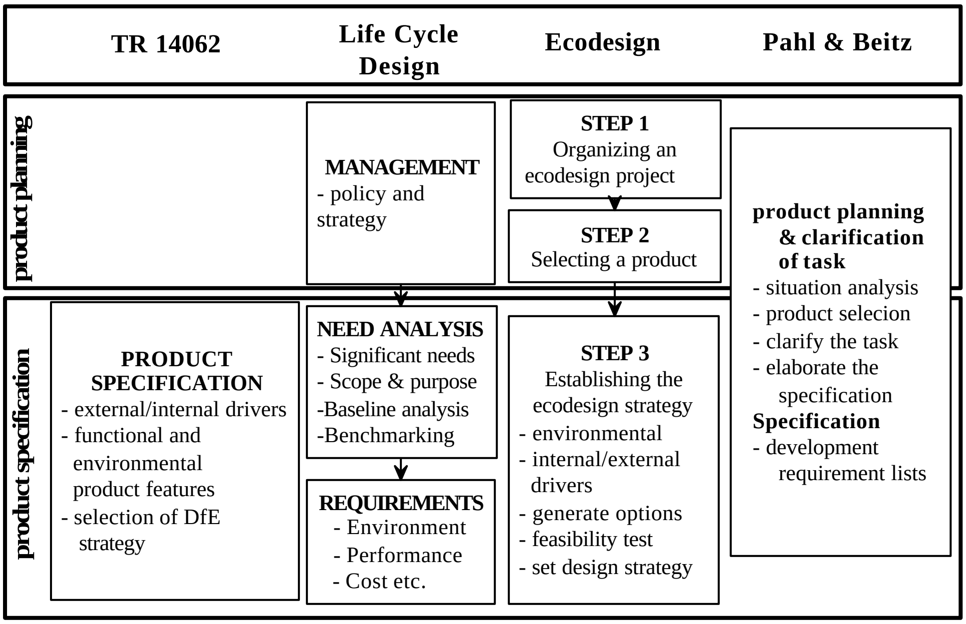

Figure 9. Comparison of Pre-design stages for establishing DfE strategy

Fig. 9 shows steps and detailed tasks for pre-design stage. DfE strategy usually are established in product specification step in all the DfE models but the information from the product planning stage is likely to be integrated into establishing DfE strategy. Only TR 14062 does not incorporate the product planning stage. In product planning stage a company formulates its product policy and decides what product or mix of products will be developed, and for which markets. The TR14062 do not focus on these concerns. Actual design phases were only considered in it. The product planning stage usually starts with the formulation of a product policy and proceeds with a ' strategic analysis' of the company' s external threats and opportunities in the market, and of the company' s internal strengths and weaknesses.

Both TR 14062 and Ecodesign manual explicitly mentioned DfE strategy and the procedures for establishing DfE strategy while life cycle design guidance manual and Pahl&Beitz did not in the product specification stage.

a designer tries to clarify and analyze the problem at hand and develops a set of requirements. All of DfE models except Pahl&Beitz recommend making an environmental analysis in this stage. As for Ecodesign, environmental aspects of reference product are analyzed with the objective to establish the process responsible for the environmental bottleneck. In life cycle design guidance, the environmental analysis is described as the "establishment of a base line of life cycle data through bench marking". Bench marking is a comparative analysis that shows whether a design is an improvement over the competition. It can be used to compare cost and performance, in life cycle design it also includes environmental criteria. TR 14062 suggests to identify functional and environmental product features.

A lot of attention is given to the formulation of environmental requirements in the guide. In Ecodesign, this activity is referred to as 'setting environmental priorities'. From these activities designers establish DfE strategy that can be the best design direction.

Ⅲ. Establishing DfE Strategy

A. General DfE strategies

DfE strategies are environmental improvement strategies tailored to the specific product's context. Each product has certain impacts on the environments. Effective strategies attempt to minimize these impacts. Strategies can enhance other design options at the same time.[46]

As mentioned above definition, DfE strategy is to strive to reduce environmental impact through whole of product life cycle and general DfE strategies that are found in prior literatures were summarized in Table 2. There is no correct answer to establish a set of DfE strategies for a DfE process so far. The set of strategies proposed in the prior literatures are can be generally categorized into seven provisional strategies for comparing.

Environmental burden from product lifecycle is classified into several ways so that DfE strategies are also distinctive accordance with how to identify and classify product's environmental burden. In this study several approaches including system approach, life cycle approach and environmental source approach were defined first for classifying set of DfE strategy. Then life cycle approach that was applied for the proposed DfE prioritizing methodology was described in detail.

[46] ISO/PDTR 14062

Table 2. Comparison of DfE strategies presented in prior literatures

	Brian 1999[47]	Anna[48] 1998	Keoleian 1993[49]	Brezet 1997[50]	Canadian[51]
Material Use Efficient	-Material use optimally -Select lower impact material	-Efficiency of material use -minimize toxic material	-Reduce material intensiveness -Material selection	-Lower impact material -Reduction material use	-Optimize material use
Material life extension	Material recycling	Recyclability	Material life extension	-	
Product life extension	Extending service life	Extending product life time	Product life extension	Optimize life time	Physical Optimization
Cleaner process /operation	Minimize impact in manufacturing ,deployment, disposal	-	Process management	Impact reduction during use	Reduce impact during use
		-	-	Optimize production technique	Optimize production
	Cleaner disposal	-	-	Optimize end of life	Optimize end of life system
Efficient energy use	Energy utilization	Minimize energy use	-	N/A	N/A
Efficient transport system	-	-	-	Optimize distribution	Optimize distribution
New concept	-	-	-	New concept development	New concept development

Note: ‘ - ‘ means ‘ not mentioned’

[47] Brian S. Thompson (1999)
[48] Anna Karna (1998)
[49] Keoleian & Menerey (1993)
[50] Brezet et al. (1997)
[51] Canadian approach, Website (http://www.nrc.ca/dfe)

1. Classification approaches for DfE strategies

System approach - product system, process system and transport system

Designers can choose between different approaches –i.e. strategies in order to integrate environmental concerns into their design choice of materials and processes. Environmental burden from product life cycle is able to be assessed and classified into product oriented one, process oriented one and transport oriented one. Therefore, design strategies to reduce those environmental burdens are also classified in same way. Similar approaches are found in Ab stevels[52]. In the paper, DfE strategies were classified into product related care and process related care and compared. The main differences between three system perspectives are summarized in Table 3.

Table 3. Characteristics of product, process and transport system care.

	Product system view	Process system view	transport system view
Character	Prevention	End of pipe	non point source
Professional category	Designers, product developers	Factory engineers	non specific easy to be ignored
Contribution to product quality	Yes	No	No
Financial aspects	Cost-neutral or brings money	Costs money	Cost-neutral or brings money
Main driver	Own initiative	Legislation, regulation	Legislation, regulation

It is to be realized that DfE primarily refers to product characteristics themselves rather than to processes or transport by which the products are manufactured and distributed. Product system environmental care, i.e. diminishing the environmental effects of a product before it is produced, distributed and used, is a major aspect. This is achieved addressing this issue in the design and development stage. The general experience is that when doing so the quality and the image of the products concerned improve most of the time at no extra cost or even at lower cost[53]. Therefore, the leading companies of the world have taken DfE on board as part of their global strategy.

Process system environmental care is mainly addressing emissions to air, water and soil of the processes. It is about remediation the negative effects of these, although nowadays also the prevention aspect is gaining ground. It is an activity in factories done by engineers. Its targets are driven by the national or local regulations. Bringing down the process-related emissions to the required levels mostly involves extra investment and exploitation cost.

Unlike Ab stevels, transport system environmental care was added to his view. Transport system environmental care is mainly addressing emission and energy consumption

[52] Ab Stevels, Design for Environment.
[53] Ab Stevels, Design for Environment.

oriented from material, component and product transport. This care seems to have not much relationship to product design. Transport system view is likely to be ignored because it is non-pointed environmental source. However, transport activities are often identified key environmental drivers through whole of life cycle stages.

Source approach - material, energy, wastes, emission etc.

Environmental impact resulted from product system, $E_{L,product}$, is defined by the sum of materials use (M), generated wastes (W), emissions (E_m) plus the sum of the withdrawn energy (E) from the environment during the life cycle. In other words, environmental burden of product system identified is classified to environmental problem source directly in this approach. This value is expressed by

$$E_{L,product\_System} = \sum_{n=1}^{N}[M]_n + \sum_{n=1}^{N}[W]_n + \sum_{n=1}^{N}[Em]_n + \sum_{n=1}^{N}[E]_n$$

Where,
n notes life cycle stage

1 : pre-manufacturing stage	M : impact from material use
2 : manufacturing stage	W : impact from waste generated
3 : Distribution stage	Em: impact from emission to air, water and soil
4 : Use stage	E : impact from energy consumption
5: End of life stages	

In this approach key environmental source are directly identified and the DfE strategy for the problem is also able to be directly set. For example, material use reduction, material life extension, renewable material use strategies are directly linked environmental impact from material use. From the source approach, designers are able to recognize environmental problem and easily to fine appropriate DfE strategy for the problem. However, source approach have limitation that product oriented problem and product oriented DfE strategy while very powerful approach for process oriented problem. Possible DfE strategies for each key environmental problem source were presented in Table 4.

Table 4. Possible DfE strategies in case of source approach.

Source approach	Impact from Material use	Impact from wastes generated	Impact from emission	Impact from energy consumption
Pre-manufacturing	Lower impact material	Cleaner process	Cleaner process	Cleaner process Energy consumption Reduction
Manufacturing	-	Cleaner process	Cleaner process	Cleaner process
Distribution	Cleaner transport mode	-	Efficient distribution Cleaner transport mode	Efficient distribution Cleaner transport mode
Use/Operation	Lower impact material	Cleaner operation	Cleaner operation	Energy consumption Reduction
End of Life	-	Cleaner process	Cleaner process	Energy consumption Reduction

Note: ‘ -’ means ‘ not mentioned’

Life cycle approach - material use, manufacturing, distribution, use, and end of life.

Life cycle approach is to classify environmental burden of product system into each life cycle stage with component that comprises product. Therefore, product oriented problem is found much better than process oriented one. One of defects of this approach is to be difficult to find specific DfE strategy because DfE strategy for this approach is to optimize corresponding life cycle stage. However, Specific DfE strategy is found by identifying correlation between environmental problem of a life cycle stage and specific DfE strategy. The environmental loads from product system, E_L, also consists of the sum of the loads during the life cycle so that[54]

$$E_{L,product\_system} = \sum_{k=1}^{k}[E_{L,preman.}]_k + E_{L,manu.} + E_{L,distribution} + E_{L,use} + E_{L,EOL}$$

k = components

Possible strategies and specific strategies for a specific life cycle stage is presented next section because the set of DfE strategy by life cycle approach was used to be prioritized in this study that will be described in chapter Ⅳ.

[54] Menno H. Nagel (1998)

2. A set of DfE strategies (life cycle approach)

All products contribute to a range of environmental problems. These problems arise from the creation, use and disposal of products – they are referred to as whole life cycle environment impacts. The environmental impacts of a product can be reduced through a variety of strategies. These strategies relate to different product life cycle stages. A set of DfE strategies of optimizing each life cycle stage and specific strategies are described as a life cycle approach in this section. Table 5 shows the set of DfE strategy and specific strategies and brief description of the strategy were followed.

However, the key to success is selection the most appropriate and effective strategies for a particular product to reduce the environmental impacts which have identified. In chapter 4, prioritizing methodology for this DfE strategies were discussed.

Table 5. DfE strategies with life cycle approach[55]

Life Cycle Stages	DfE strategies	Specific Strategies
Raw materials processing	material use optimization	Design for resource conservation Minimize material use Use renewable material Use recycled and recyclable material Design for low impact materials Avoid toxic and hazardous material Avoid ozone depleting substances Use material with low embodied energy Use easily re-used/recycled material
Manufacturing	Clean Manufacturing	Design for cleaner production
Distribution	Efficient Distribution	Design for efficient distribution
Use	Clean Use/Operation	Design for energy efficiency Design for water conservation Design for minimal consumption Design for low-impact use/operation Design for service/repair Design for durability
End of Life	End of Life Optimization	Design for re-use Design for re-manufacture Design for disassembly Design for recycling Design for safe disposal0

[55] Gertsakis, J.(1997).

a. Material Use Optimization

The first stage of the product life cycle is the extraction and processing of raw materials. Strategies to minimize environmental impact at this stage can be divided into those concerned with conserving resources and those using low-impact resources.

Design for resource conservation

- Use minimal material

  Weight reduction is one of the critical objectives in the design of a product. It reduces the cost of manufacture, the cost and weight for transport, saves resources and energy, and results in less material at the end of life.

- Use renewable resources

  Renewable resources include materials manufactured from plant or animal sources that are harvested on a sustainable basis. Renewable energy resources include solar, hydro, tidal and wind power.

- Use recycled and recyclable materials

  Commonly used materials can be found in a recycled form such as; steel, aluminum, paper, cardboard, plastics, rubber and glass. Recycled materials can save resources and energy. Products should also use recyclable materials which are not only technically recyclable but for which there is a viable collection and reprocessing system in place

Design for low impact materials

- Avoid toxic or hazardous substances

  Toxic substances may cause serious effects on the health of humans and the environment such as poisoning, respiratory problems cancer, nervous system damage or birth defects.

- Use materials with low embodied energy

  consider the energy used directly or indirectly to produce a material ('embodied' in the material)

b. Manufacturing optimization

This is closely related to 'cleaner production', which began with a focus on environmental impacts in the manufacturing stage, but now encompasses a more integrated range of approaches to increase production efficiency and reduce risk to humans and the environment. The strategies that are to reduce environmental impacts during the production stage of the product life cycle include waste minimization, recycling, optimizing material flow and reducing energy consumption.

Design for cleaner manufacturing

- Minimizing the variety of materials

  Minimizing the variety of materials in a product simplifies ordering and stock keeping, and can reduce waste generated through obsolescence and over-ordering. It also makes it easier to recycle waste materials from the factory, and to recycle the product at the end of its life.

- Avoiding waste of materials

  When a shape has to be cut from a roll or sheet, it is normal practice to ensure that cutting is planned to use the maximum area of the sheet or roll. If different components use the same sheet or roll specification, this multiplies the variety of shapes and gives greater flexibility in planning to avoid waste.

- selecting low impact ancillary material and process

  The designer can also minimize environmental impacts by specifying low impact ancillary materials and low energy consumption processes.

c. Distribution optimization

Design for efficient distribution

- reduce the weight of the product and its packaging

  Reducing weight means less energy required for transport. Choosing strong, lightweight materials and designing efficient packs can reduce primary packaging material. Consideration should also be given to re-useable and/or recyclable packaging.

- ensure that transport packaging is re-usable and/or recyclable

  The environmental impact of transport packaging can be reduced through source reduction (light weighting), designing re-useable packaging or recycling.

- ensure efficient distribution

  optimizing logistics and cleaner transport mode can reduce energy consumption and emission

d. Use phase optimization

Design for energy efficiency

Products that consume energy during use (such as domestic appliances and commercial equipment) have a significant impact on the environment. Gaining maximum efficiency can be achieved by this strategy.

Design for water efficiency

Many of the principles listed above also apply to water efficiency. The aim at all times should be to minimize water usage, in production, use and reuse. Water should be recovered and reused. Consumers' use of a product is also critical. Energy and water labels encourage consumers to buy the most efficient product, but consumer education is also required to ensure that the product is used in the most efficient way.

Design for minimal consumption

The quantity of ancillary products consumed during use should be minimized; detergents, coffee filters, batteries, toner, etc.

Design for low impact use

Products may emit harmful substances during use; for example; volatile organic compounds (VOCs) from paints and other products containing solvents; ozone from electronic equipment, etc. select materials free from volatile substances and design out emissions.

Design for durability (extending or optimizing product life)

The durability of a product can be extended by identifying and elimination potential weak points in the design, particularly for operational parts and ensuring the product is designed for likely misuse as well as the intended use.

e. End of Life Optimization

Design for disassembly

At end of life, products need to be disassembled so that different materials can be separated for recycling, reuse, repair, or remanufacture.

- Minimizing the number of separate components and materials
- Avoiding glues, metal clamps and screws
- Making fasteners from a material compatible with the parts connected
- Designing interconnection points and joint so that they are easily accessible
- Designing the product as a series of blocks or modules
- Use of in mould identification symbols for plastic resins(based on 14043)
- Locating non-recyclable parts in one area that can be quickly removed and discarded.

Design for remanufacture

Remanufacturing is another way of avoiding way of avoiding waste. Remanufacturing involves collection of used products, disassembly, replacement or refurbishment of damaged components, assembly and resale.

Design for recycling

Materials used in a product could have a secondary use at end of life, either for the same product or for a different product

Design for safe disposal

Products should also be designed for safe disposal at the end of their life. Products that contain toxic materials should be labeled with instructions for decontamination and disposal.

B. Establishing DfE strategy

The designer must choose the most appropriate environmental design strategies for each product. These will depend on the environmental impacts associated with each stage of the product life cycle, cost constraints, marketability and other design consideration. Selecting and synthesizing design strategies for meeting those requirements is a major challenge for the designer.[56]

Various techniques are used in the DfE process to prioritize and establish design strategy. The importance of being able to prioritize the strategy is stressed since these strategies will be employed when choosing among product ideas and product concepts. Several DfE guidelines[57] and literatures have suggested steps to establish DfE strategy. All of steps suggested by those prior methods can be classified to three general steps; environmental aspect identification, internal/external design consideration and integration those factors into prioritizing procedure as shown in Fig. 10.

In this section, a range of various tools and methods used was discussed and example was shown for each step and finally suggested Analytic Hierarchy Process (AHP) for integration step.

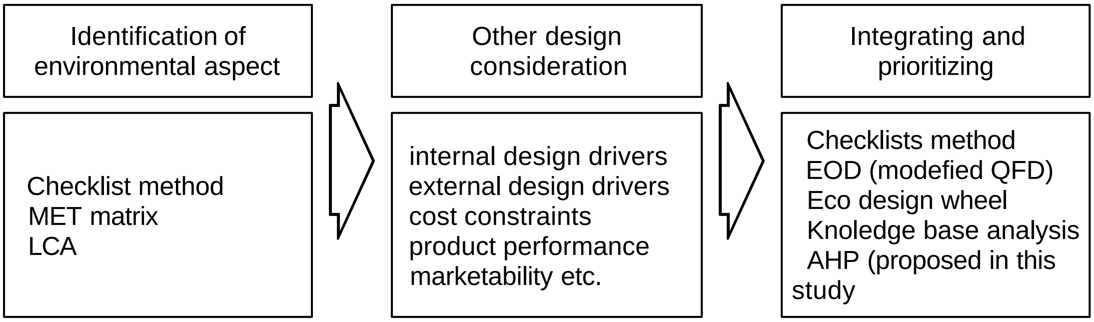

Figure 10. General steps for establishing DfE strategy

1. Environmental aspect identification methods

Whole of product life cycle should be taken into account for identifying environmental aspects. Environmental aspects can be identified in various ways and with a varying level of detail. The main types of life cycle assessment of product are quantitative life cycle assessment generally known as LCA and qualitative life cycle assessment such checklists method and MET matrix. A qualitative life cycle assessment provides an overview of the

56 Keoleian et. al (1995)
57 Keoleian & Menerey, Brezet et al.(1997), Gertsakis J.(1997).

environmental impact and shows the most important environmental issues on which measures must be taken. On the other hands, quantitative method can give detailed information while it is more time consuming to perform, and requires special expertise.[58]

a. Qualitative assessment

The environmental burden of a product or process can be assessed qualitatively by making a list of the environmental issues to be analyzed in different phases of the product life cycle.

Checklist method[59]

The simplest and most common qualitative assessment tool is a checklist of criteria stated in the form of questions or points to consider. The use of checklists is often one of the first DfE initiatives undertaken by DfE practitioners because checklists require only modest resources and are easy to understand and implement. Despite these advantages, checklists do have important limitations:

It is qualitative in nature, although it is possible to compute numeric scores. This means that they provide only crude measures of environmental performance. In addition, it provides no guidance to DfE practitioners regarding the relative importance of different issues or the degree of effort that is warranted in addressing a specific issue.

Nevertheless, checklists are effective starting point for encouraging DfE practitioners to think about environmental issues and begin taking positive actions. A part of Ecodesign Checklist[60] was shown in Table 6 as an example.

Table 6. An example of checklist (adopted from Ecodesign manual)

For Life cycle stage 2: IN-HOUSE PRODUCTION
What problems can arise in the production process in your own company?
■ How many and what types of production processes are used? (including connections, surface treatments, printing and labeling) ■ How much and what types of auxiliary materials are needed? ■ How high is the energy consumption? ■ How much waste is generated? ■ How many products don' t meet the required quality norms?

[58] Ab stevels, Han Brezet, Jeroen Rombouts (1999)
[59] Fiksel, Brezet, Keoleian & Manerey, Canadian approach etc.- most guidelines and literatures have mentioned this is the most popular method.
[60] Brezet et al. (1997)

***MET matrix*[61]**

MET matrix developed as a result of the ecodesign demonstration project in the Netherlands. The aim is to find the main environmental bottleneck within the product life cycle and identify options for the environmental improvement of products or processes. In the matrix, environmental interventions are grouped into three categories: material cycle, energy consumption, and toxic emission.

The assessment of the material cycle involves scarcity of raw materials and renewability, degradation of the landscape, reuse and recycling, use of recycled materials, life span of the product and the amount of materials used in the product. The energy consumption assessment involves the energy consumed in the production processes, the energy consumption of the product during its use and the energy contents of different materials. For toxic emission, toxic emissions that occur during the different stages of the product life cycle are listed. An example of MET matrix is shown in Table 7.

Table 7. An example of MET matrix for photocopier (adopted from bakker[62])

	Material cycle	Energy Consumption	Toxic Emission
Production	Depletion of raw materials Recycling of production wastes	Energy contents of the materials Process energy	Flame-retardants
Use	Paper consumption Toner waste	Energy consumption Energy used during transport	Ozone emission
Disposal	Recycling of the machine		Selenium drum

b. Quantitative method (Life Cycle Assessment; LCA) [63,64,65]

In quantitative life cycle assessment, the environmental aspects and potential impacts associated with the product, process or activities are assessed through the life cycle of the product. Quantitative life cycle assessment as a method has been especially developed by Society of Environmental Toxicology and Chemistry (SETAC), and the method is being internationally standardized by the International Organization for Standardization (ISO). Four main stages can be distinguished in a life cycle assessment study: goal and scope definition, inventory analysis, impact assessment and interpretation of result as shown in Fig.11.

[61] Brezet(1997), Gregory&Manery(1993) Anna (1998) mentioned.
[62] Bakker, C. (1998)
[63] Nord, Nordic Guidelines on Life-Cycle Assessment (1995)
[64] ISO 14040 Series
[65] Suh, S. (2000).

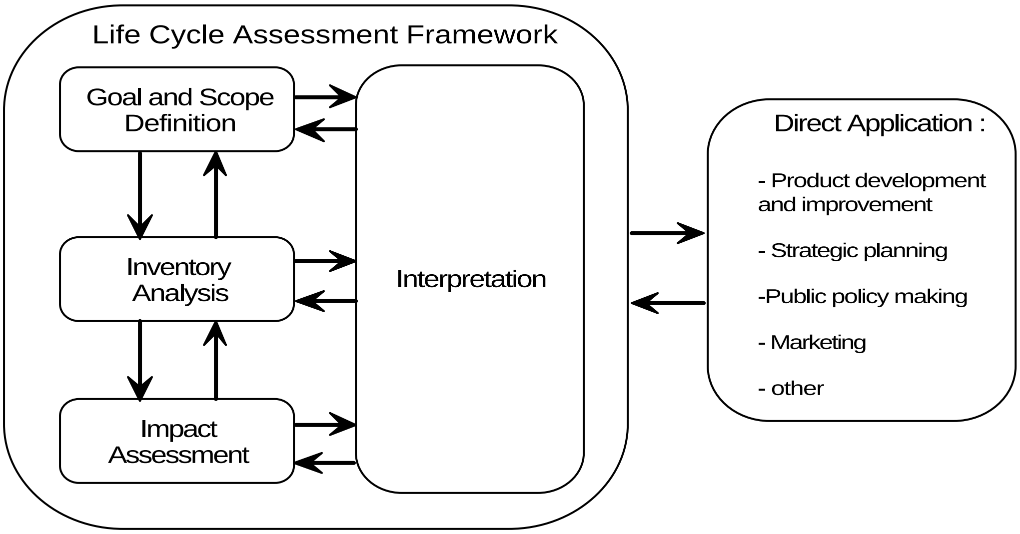

Figure 11. General framework of Life Cycle Assessment (LCA)

In the goal and scope definition, the objectives and scope of the analysis are determined. It clarifies what the goal of the analysis is. Also it specifies the functional unit to be used in the analysis. For instance a functional unit can be a television set or one bit of data of the performance of the functional outputs of the product system. A functional unit provides a reference to which the inputs and outputs are related and it must be measurable. In addition to defining the product system and the functional unit studied, the product system boundaries and study limitations should be clearly described.

In the inventory analysis, the product system studied is divided into sub processes that are interrelated (e.g. mining, transportation, assembly of a product). For each sub process, the raw materials used, energy used and the emissions to the atmosphere, water system and soil are calculated. Many life cycle studies have been confined to this inventory analysis, especially when the product system in question has been a complex one.

The impact assessment phase aims at evaluation the significance of potential environmental impacts using the results from life cycle inventory analysis. This phase involves association inventory data with specific environmental impacts. The impact assessment phase may include elements such as classification – assigning of inventory data to impact categories. These impact categories can be, for instance, use of renewable and non-renewable natural resources, climate change, ozone depletion and acidification. The significance of the various inputs and outputs to various environmental problems is defined in the characterization stage. Finally, in the weighting stage different environmental problems are compared against each other by giving different weighing values to them. This can be done numerically or verbally.

In the interpretation, the findings from the inventory analysis and impact assessment are combined consistently with the defined goal and scope in order to reach conclusions and recommendations. The interpretation of the findings may take the form of conclusions or recommendations for decision-makers.

In principle, the stages of the life cycle assessment follow each other, but in practice, it is often necessary to return to the findings and definitions of the previous stages and to modify them. Life cycle assessment studies are essential for analyzing a single product because the impact of all of materials and processes are studied.

2. Other design consideration

There is no formal framework for identifying other design consideration because it varies with company situation, product category studied and a number of corresponding regulations. All of existing method has given only conceptual frame and example with ambiguous categories. Categories of other design considerations generally include product performance, cost, society and legal. Keoleian&Menerey(1993) determine legal, cultural, cost, performance requirements for this elements while ecodesign manual classified into two of internal/external design drivers even though objective and contents of both design guide are not much different from each other.

Identification of other design consideration except environmental one is carried out by workshop of product development team. – i.e. development team should choose a format that is appropriate for their project. An example of other design consideration was shown in Table 8.

Table 8. An Example of other design drivers except environmental one (adopted from Ecodesign manual)

	Design drivers
Internal drivers	Managers' sense of responsibility The need for increased product quality The need for a better product and company image The need to reduce cost The need for innovative power The need to increase personnel motivation
External drivers	Government legislation and regulations Market: industrial customer and end-user demands Social environment: responsibility towards the environment Competitors: set the trend or follow? Trade organization: cooperation or opposition? Suppliers: technological innovations

3. Establishing DfE strategy

Environmental aspects and other design considerations must be integrated into establishing optimal DfE strategy and prioritized to consider trade offs among each others. Several methods could be found in DfE guidelines and literatures varied with level of detail and with decision-making characteristics. In this section, those methods were described and compared. Then Analytic Hierarchy Process (AHP) methods are newly introduced to integrate environmental aspects and business aspects into prioritizing procedure in this section.

a. Checklists method[66]

A checklist method is a series of prompts to which designers can refer in their work. In all literature on DfE, checklists method is given a lot of attention.

DfE checklist provides guidelines for giving direction to the product development process and for finding environment benign product ideas in the product planning stage or the design stage. Examples of such checklists can be found in the ecodesign manuals of Brezet and Keoleian. In both manuals, these checklists are referred to as 'design strategies'. Although the strategies differ in some respects, on the whole they correspond reasonably well. Each of the strategies can be broken down into an extensive checklist with guidelines that helps the designer with the realization of the strategy. Another examples of guidelines that aid the finding of DfE strategy are the Ecodesign checklist by Tom Clark, CfSD[67] as shown in Table 9.

Table 9. An example Ecodesign checklist for DfE strategy (adopted from Tom Clark, CfSD)

No	Design criteria/attributes	**Y**	N	N/A	Comments
1	System design: simplicity multi-functional products source reduction				
2	Procurement: specifying recycled or renewable materials avoiding harmful substances				
3	Manufacturing and distribution design for manufacturability design for energy conservation design for pollution minimization design for waste minimization				

[66] Brezet(1997), Fiksel(1996), Anna(1998) etc. stated.
[67] Tom Clark (1999)

	design for reusable containers - design for accident prevention				
4	Use design for energy conservation design for pollution minimization design fir waste minimization design for accident prevention				
5	'End of life' design for material recovery design for component recovery design for disassembly design for recovery design for separability design for waste recovery and re-use				

b. Matrix (QFD or modified type of QFD)[68]

Qualitative matrices are a useful technique for trade off analysis in design decisions. There are many variations on this basic technique. While matrices have many of the same advantages and limitations as checklists, they do provide a means for evaluation trade offs and representing more subtle interactions among design strategy.

One popular approach that employs such matrices is quality function deployment (QFD), which uses a "house of quality" model to make explicit the relationships between customer desires and product design parameters.[69] For searching design attention field and establishing DfE strategy, QFD is able to be one of method. Bengt[70]presented modified QFD and FMEA for DfE application in his dissertation and Karlsson[71] has suggested modified quality function deployment for determine environmental design objectives so called Environmental Objectives Deployment (EOD).

According to the method at first DfE team identify the activities of stakeholders in the product life cycle and with respect to the life cycle stakeholders within. This is presented in the three matrix cards much similar with requirement analysis of Keoleian&Menerey(1993). The matrix cards include an inventory of the three areas: 1) stakeholders' preferences, 2) stakeholders' liability, and 3) environmental impact. Based on the information, environmental oriented deployment (EOD) is carried out in order to aid selecting efficient DfE strategy for meets all the requirements in each area.

68 Fiksel (1996),Bengt (1998),Karlsson (1997) stated similar matrix.
69 Fiksel, Design for Environment (1996)
70 Bengt Davidsson (1998).
71 Marten Karlsson (1997).

c. Ecodesign wheel method.[72]

Design strategy wheel so called LiDS (Life cycle design strategy wheel) method, suggested by Brezet, has been applied in many guidelines and literature. Furthermore, similar approach using wheel have been found such as "composite target plot" developed by AT&T[73]. The ecodesign wheel is a tool to visualize a product's environmental characteristics, using different ecodesign strategies on the axes. The outcome of an environmental assessment (for instance an improvement assessment) can be indicated on the axes of the 'ecodesign wheel'. While composite target plot uses abridged LCA result so that 5 criteria including material, energy, solid, liquid, gaseous residues are indicted on the axes for each life cycle stage. These kind of amoebae-like visualization results are referred to as the 'product profile'. The ecodesign wheel can be used to generate ideas, for instance, by focusing on the different axes of the ecodesign wheel during a product planning stage. It also used to balance between strategies. Ecodesign strategy wheel and composite target plot was shown in Fig.12 and Fig. 13.

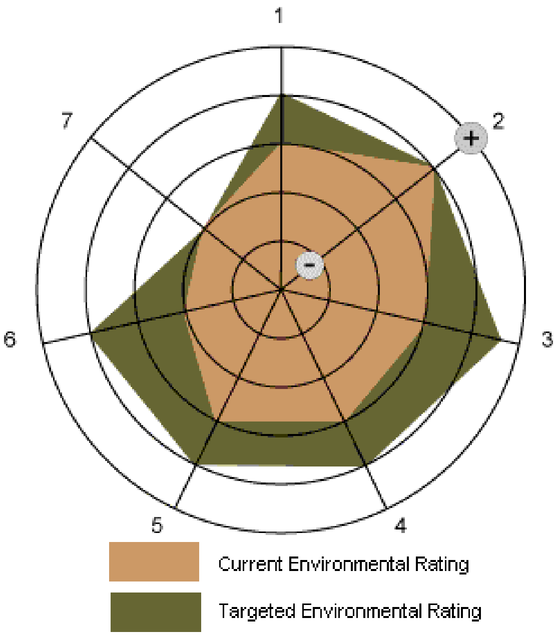

Figure 12. Ecodesign strategy wheel (adopted from Ecodesign manual)

[72] Brezet (1997), AT&T
[73] T.E. Graedel, B.R. Allenby (1995)

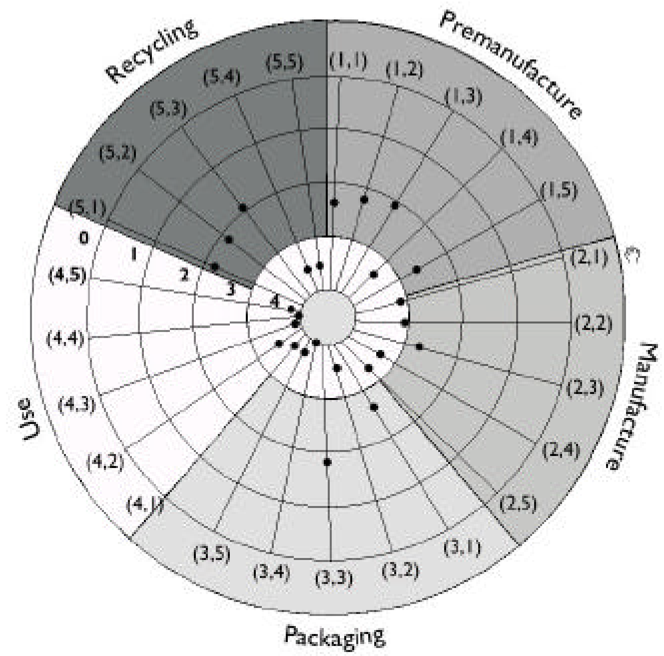

Figure 13. A "composite target plot" (adopted from Graedel (1995))

d. Knowledge based selection (expert system)

Jeroen[74] have developed expert system that enables product designers to assess the potential of different DfE-options. The concern of managers and designers practicing environmental product development is which combination of options for improvement leads to the best balance between environmental, economical, and other product characteristics. This system evaluates products from an environmental point of view and leaves the responsibility for weighing the environmental priorities against other criteria to the product developer. Similar studies using expert knowledge for selecting optimal DfE strategy. Catherine[75] developed methodologies that aid in formulating the end of life strategies across a wide range of products and Julian et. al.[76] has reported how to set up DfE strategy using Environmental Product Development Strategy (EPDS) while describing the tool in the report. For the EPDS, a tree data structure is modeled, which allows the design team to set an environmental strategy for product's development based on the product's specifications and the facilities available to the company. For the system, design strategy is prioritized by expert knowledge database associated with environmental issues selected by user, which means, in this system user make decision answering question of which and how serious environmental

[74] Jeroen P. Rombouts (1998)
[75] Catherine Michelle Rose (2000).
[76] Julian R. Poyner and Matthew Simon (1999).

issues are for their own product. Fig. 14 shows information flow using knowledge-based system for selecting DfE options i.e. DfE strategy.

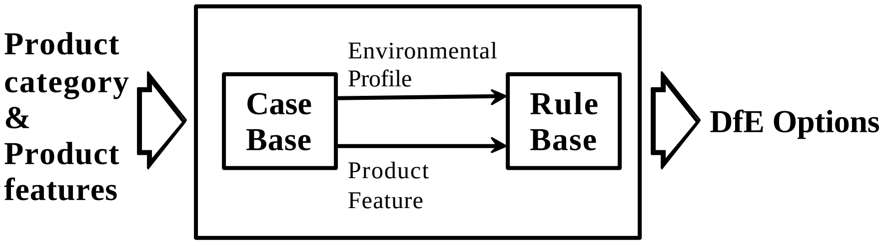

Figure 14. LEAD-II System layout

e. Comparison of strategy selection methods

As described above, there are several methods to prioritize and establish DfE strategy. Checklists method is the easiest and cheapest one while results are so loose that it has a possibility of misleading the decision. As for decision-making characteristic, EOD – modified type of QFD matrix, is quantitative one making trade off easily. Ecodesign strategy wheel also quantitative but strategies are prioritized by individual subjectivity through expert group discussion. LEAD have a distinctive feature that decision-making is based on expert knowledge database. Characteristics of the methods are summarized in Table 10.

From investigation of DfE strategy selection methods, several critical factors which are necessary to prioritize DfE strategy can be found. Fundamentally, decision criteria have to take into account not only environmental aspect but also business aspect. Absolutely, No designer will consider the best DfE strategy striving against environmental concern if too much company resources are needed for the strategy. Another critical factor is availability of trade off analysis. In most cases, a single strategy will not be best for meeting all of design requirement.[77] Therefore appropriate DfE strategies should be weighted by it's preference then have to be taken account with resolving conflicts between strategies through whole of design process.

[77] Gregory A. Keoleian et al (1995)

Table 10. Characteristics of existing DfE strategy prioritizing methods

	Checklists	EOD (QFD)	Eco-Wheel	LEAD-II
decision making	- qualitative	- quantitative	- semi-quantitative	- case and rule base
criteria	- environment	- environment - stakeholders' preference and liability	- environment - inter/external design drivers	- environment (case and rule based on product features)
Pros.	- less time and expenditure	- systematic - the most quantitative	- easy to visualize	- quick and easy
Cons.	- too loose - no trade offs	- too specific	- subjectivity	- too much DB needed

4. Discussion and suggestion; AHP methodology

It is generally believed that set up all of company strategies is so complicated that we need to think in a complex way to make decisions. Simple thinking leads to combinations of collections of ideas that give rise to a structure which components are strands that are separate, but tangled. However, most of prior studies have not focused on explicitly comparing the significance of each internal and external design consideration.

Ecodesign manual suggested listing up all of internal and external drivers as shown in section 2 and then taking into account them using Ecodesign wheel. However, the information input into the wheel is only environmental bottlenecks of reference product. Internal/external drivers identified take a role of supporting to only narrow controllable problem area where are sources of mitigation plan and alternative design solution. In other words, internal and external drivers are implicitly excluded from prioritizing DfE strategies although those are another important variables for decision making on DfE strategy.

On the other hands, keoleian&Menerey suggest to identify all of design requirement as a form of matrix then make designer decide which one is urgent requirement and which one is not - so called must requirement and want requirement. In the system, requirements are grouped with numerical boundaries to ease analysis with quantitative rating system. For example, want requirements might extend from .6 or .7 to 1, while ancillary and want requirements are assigned a priority less than .6. Therefore, it is possible to characterize priorities and estimations but the system focused on evaluating and prioritizing design alternatives and all of design requirements identified are too detail to use establishing strategy.

Absolutely, environmental key design drivers of product must be identified. In addition, in business perspective other design drivers must be taken into account systematically to set up DfE strategy. Furthermore, those internal and external drivers which can reflect business perspective should be identified as a factor of decision making, then integrated into DfE strategy prioritization procedures explicitly and systematically. For the purpose of overcoming defect of prior DfE selection methodologies, AHP methodology was suggested in this study. It was described in detail in chapter 4.

Ⅳ. Prioritizing DfE Strategies Based on LCA and AHP

A. Introduction to AHP

The AHP is a powerful and flexible multi-criteria decision-making tool for complex problems where both qualitative and quantitative aspects needed to be considered. The AHP helps the analysts to organize the critical aspects of a problem into a hierarchical structure similar to a family tree. By reducing complex decisions to a series of simple comparisons and rankings, then synthesizing the results, the AHP not only helps the analysts to arrive at the best decision, but also provides a clear rationale for the choices made.[78]

Briefly, the procedure of using AHP is as followes.

Firstly, decision criteria must be defined in the form of a hierarchy of objectives. The hierarchy is structured on different levels: from the top (i.e. goal) through intermediate levels (i.e. criteria and sub-criteria on which subsequent levels depend) to the lowest level (i.e. the alternatives);

Secondly, the criteria, sub-criteria and alternatives are weighted as a function of importance in terms of the corresponding element of the higher level. For this purpose, AHP uses simple pair-wise comparisons to determine weights and ratings so that the analyst can concentrate on just two factors at one time. One of the questions which might arise when using a pair-wise comparison is; how important is the "investment required" attributes with respect to the "environmental significance" attribute, in terms of the "optimal DfE strategy selection" (i.e. the problem goal)? The answer may be "equal important, moderately important", etc. The verbal responses are then quantified and translated into a score via the use of discrete 9 point scales as shown in Table 11.

Finally, after a judgement matrix has been developed, a priority vector to weight the elements of the matrix is calculated.

Furthermore, the AHP enables the analyst to evaluate the goodness of judgements with the consistency ratio CR. The judgements can be considered acceptable if CR less then 0.1. In cases of inconsistency, the assessment process for the inconsistent matrix is immediately repeated or eliminated from the analysis. An inconsistency ratio of 0.1 or more may warrant further investigation.[79]

AHP has been widely used in many applications. Designed to reflect the way people actually think, the AHP was developed more than 20 years ago and it is one of the most used

[78] Thomas L. Saaty & Luis G. Vargas (1991)
[79] Saaty TL (1980).

multi criteria decision making techniques. This fact is probably due to some important aspects of AHP such as: (1) the possibility to measure the consistency in the decision maker's judgement: (2) it does not, in itself, make decisions but guides the analyst in his decision making; (3) it is possible to conduct a sensitivity analysis: (4) AHP can integrate both quantitative and qualitative information: (5) it is well supported by commercial software programs. However, it is necessary to remember some possible problems with AHP (rank reversal, etc.) which are currently debated in the literature.[80]

Table 11. Judgement scores for pair-wise comparison (9-point scale suggested by Saaty[81])

Judgement	Score	Explanation
Equally	1	Two attribute equally to the upper level criteria
	2	
Moderately	3	Experience and judgement slightly favor one attribute over another
	4	
Strongly	5	Experience and judgement strongly favor one attribute over another
	6	
Very strongly	7	An attribute is strongly favored and its dominance demonstrated in practice
	8	
Extremely	9	The evidence favoring one attribute over another is of the highest possible order of affirmation

Integrating quantitative and qualitative information

The pair-wise comparison approach is able to fully adopt to evaluate priorities according to all, both quantitative and qualitative criteria. However, in a decision context where various partial priorities derived from conversion of quantitative assessments are combined with priorities obtained by applying the eigenvector method to pair-wise comparisons of qualitative information. Perogo[82] showed empirical evidence that the final priorities highly depend on the choice of the measurement scale when qualitative criteria significantly affect to final decision. In that case, the report suggested elicitation procedure - i.e. match the partial ratings of the quantitative measures with those of the qualitative one. It facilitates to calibrate the numeric scale that has to be associated with the semantic scale for assessing qualitative factors. The report has suggested several different approaches to

[80] M. Bevilacqua & M. Braglia (2000)
[81] Saaty TL (1980)
[82] Alessandro Perogo (1996)

integrating qualitative and quantitative information in the AHP framework as shown in Fig. 15. The approaches are guided by correlation between qualitative and quantitative criteria and final decision.

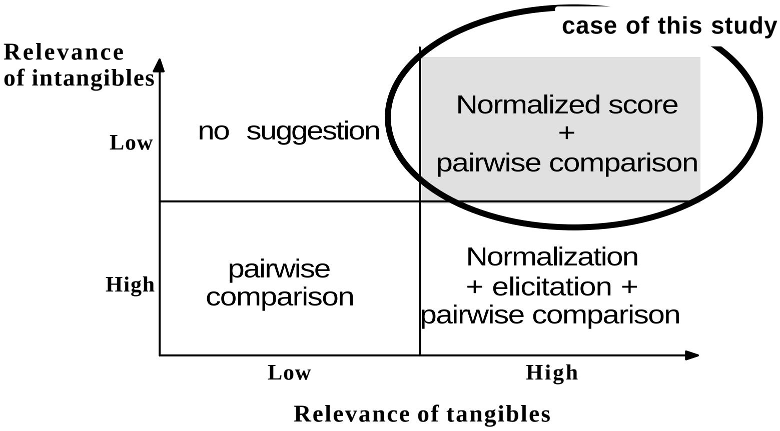

Figure 15. Approaches for integrating quantitative and qualitative information based on relevance to final decision. (adopted from Perogo)

In this study, tangible criterion[83] - i.e. environmental significance of product has higher correlation than other intangibles such as business aspects. It is because the goal of DfE is to minimize environmental impact through product life cycle and all of strategies are related to environmental concern. For evaluating relative significance of decision criteria, normalized score of environmental impact for the environmental significance criteria and pair-wise comparison for other criteria are adopted in this study. A research on material selection by David[84] has given a good example of integrating qualitative and quantitative information. In the study environmental impact of material with each life cycle stage and business impact such as cost, performance etc. were considered at the same time in a hierarchical decision model.

Consequently, in this study LCA results were adopted to evaluate the relative importance of criteria for environmental significance in the third level because environmental significance and its criteria are expected to have higher impact on selection of DfE strategy. Quantitative evaluation of relative importance will be able to give the most promising results rather than evaluation based on preferences by pair-wise comparisons.

[83] It's because environmental aspects are assessed quantitatively by LCA in this study
[84] David Newman (1998)

B. Methodology

Basic framework of proposed methodology follow steps for DfE strategy selection as mentioned in chapter 3. Environmental aspect of reference product is starting point and business aspects so called internal/external business criteria are identified. Then, environmental aspect and business aspects are integrated into prioritizing DfE strategy based on AHP. Those procedures were shown in Fig.16.

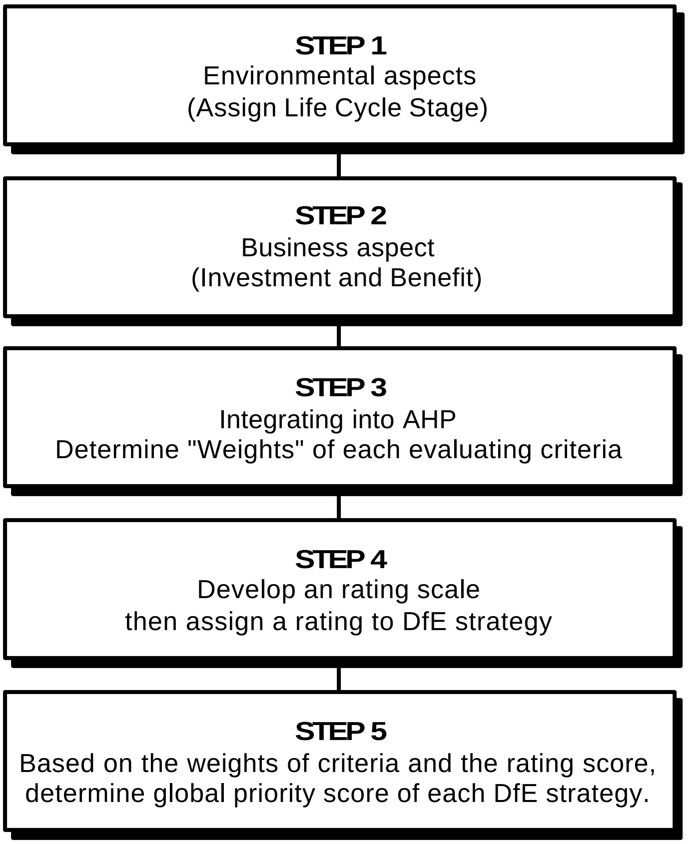

Figure 16. Proposed steps for prioritizing DfE strategy based on AHP

The overall hierarchy scheme for this study

In designing the AHP hierarchical tree, the aim is to develop a general framework that satisfies the needs of the designer to solve the selection problem of the best DfE strategy. As for this study, environmental design considerations and business design considerations are identified and evaluation criteria are determined in the STEP 1 and 2. Then relative weights of evaluation criteria are determined by LCA study and pair-wise comparison in AHP hierarchy scheme. In STEP 4, rating scale is determined by pair-wise comparison and assigned to DfE strategy with respect to each criterion so that rating score are calculated. Finally, global priority score of DfE strategy are determined based on weights of criteria and rating score in STEP 5. Fig. 17 shows proposed steps within AHP model and detailed description for each step will be followed step by step.

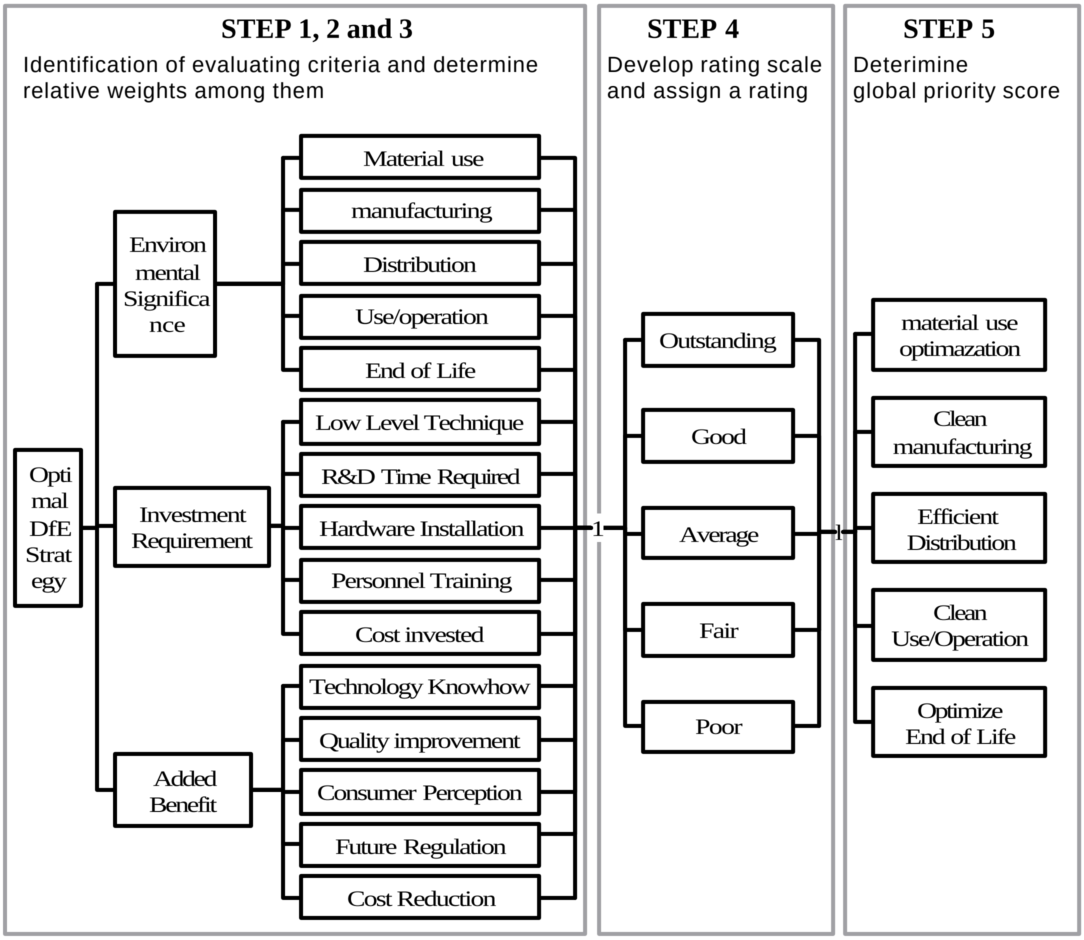

Figure 17. Overall hierarchy scheme and steps for this study

1. Identification of environmental aspects of product design (STEP 1)

A number of tools and methodologies for identifying environmental aspects of product were presented in chapter 3. Environmental aspects of product are one of the most important variables affecting to selection of DfE strategy. Environmental aspects as decision criteria are preferred quantitative measure to qualitative one because environmental bottlenecks must be key decision factors in selecting DfE strategy. Furthermore, the more specific results are generated, the more detailed strategy will be able to prioritize.

LCA as mentioned in chapter 3 is the most systematic analysis methodology for product environmental aspects. Although it is time-consuming work and much more effort is needed than any others are, the accurate and quantitative results are able to guide decision-maker to the most promising way. As for this study, quantitative results of LCA are directly introduced into AHP procedure for a criterion reflecting environmental significance instead of pair-wise comparison. The strategic factor, environmental significance" was divided into five criteria that are representing life cycle stages of product shown in Fig. 18. The relative significance of each criterion is determined by LCA contribution score with respect to each life cycle stage. The normalized contribution score will be introduced to AHP decision hierarchy (STEP 3) together with criteria for business aspects identified in next STEP 2.

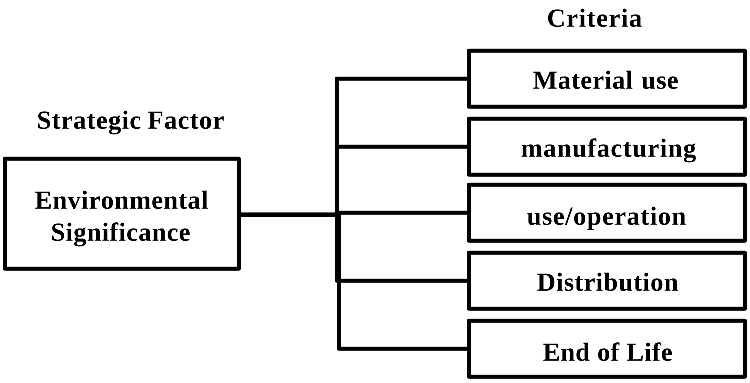

Figure 18. Decision tree for environmental significance

The strategic factors and criteria for environmental aspects used in this study were described in detail below.

1. Environmental Significance as strategic factor

Environmental burden from product and product system is one of key decision criteria when prioritizing DfE strategy. Probably selection of DfE strategy can be affected by environmental significance of product. Managers and designers must make a decision on how much effort will be given to improvement environmental aspects of product.

2. Criteria for environmental significance

Environmental problems are generated through all of life cycle stages and selection of appropriate DfE strategy will vary with environmental significance of life cycle stages.

- **Material use**

  Environmental impact from material extraction to material use for a product including material processing
- **Manufacturing**

  Environmental impact from product manufacturing – may be air and water emission, solid wastes.
- **Use/operation**

  Environmental impact from product use and operation – may be energy consumption
- **Distribution**

  Environmental impact from product distribution
- **End of life**

  Environmental impact from product end of life stage, which is may be from recycling process and disposal process.

2. Identification of business aspects of product design (STEP 2)

Business aspects of product design are dependent on environmental aspects and each of them is mutually affected. As mentioned chapter 3, Brezet(1997) have provided worksheet for identify internal and external design drivers and Keoleian & Menerey have categorized all of design requirement into 4 groups; performance requirement, cost requirement, cultural requirement and legal requirements. For the prioritizing DfE strategy in product specification stage, business aspects of product design can not be described in detail as well as are not required. Business aspect can be conceptually classified into investment and benefit. The best-optimized DfE strategy is to minimize investment of company resources and to intensify possible benefit while minimizing environmental burden from product system that is the goal of DfE.

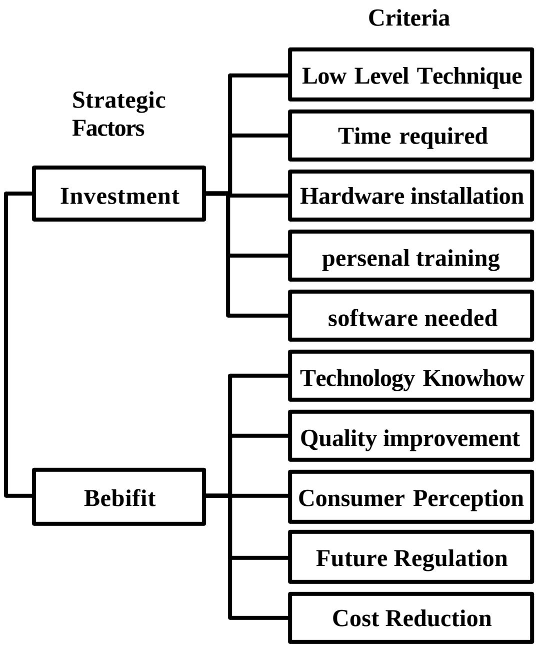

Figure 19. Decision Tree for Business aspects; "Investment Required" and "Added Benefit"

In this study, design considerations reflecting business aspects are categorized into company's resources investment and possible benefit from the investment. Those business aspects are separated to quantitatively measurable criteria then relative significance among them will be calculated in STEP 3 that will be described in next section. The categorization of business aspects was shown in Fig. 19 and described in detail below.

1. Investment Requirement as a strategic factor.

'Investment Requirement' represents that how much effort should be made while applying for a specific DfE strategy. In business perspective less cost needed and less time to market to realize a specific strategy are preferred.

1.1. Criteria for "Investment Requirement."

- **Level of Technology required**

Level of Technology required represents which kind of technology there are and how easy to access the technology in order to apply for a specific DfE strategy. If there are many common technologies for a DfE strategy, the strategy will be preferred to others.

- **R&D time required**

R&D time also could be critical decision criteria relating to cost needed and time to market launch. Common technology availability for a specific DfE strategy can also affect to R&D time needed. A DfE strategy that requires less R&D time must be preferred to others.

- **Hardware installation required.**

Hardware installation might be required to realize a specific DfE strategy. For instance, recycling process for optimizing end of life, wastes treatment process for clean manufacturing etc. Hardware installation must be cost driver so that company probably does not want to take.

- **Personnel training required.**

Personnel training might be required for a specific strategy. In manufacturing, distribution, use/operation and end of life stage, individual usually treat sources of environmental burden so that personnel training are required for a most DfE strategies.

- **Cost invested**

Product development projects always need expenditure while project budget is limited. With respect to the strategy, cost needed to apply for a specific strategy will be different and cost-effective strategy will be preferred to others.

2. Added Benefit as a strategic factor

DfE strategy basically aimed at improving environmental aspects of product but it is well known fact that application of DfE strategy for product development process is likely to achieve another benefit such as cost reduction, quality improvement, technology know-how etc. The more those benefits the strategy has, the higher preference will be assigned to the strategy.

2.2. Criteria for "Added Benefit"

- **Cost reduction effect**

Effective DfE strategy is able to reduce manufacturing cost or distribution cost. It is usually originated from reduction of material purchased, hazardous material must be treated, weight of product distributed etc. If application of a specific strategy is able to reduce those cost, the strategy will have higher preference.

- **Product quality improvement**

Product quality can be improved by effective DfE strategy as well as cost reduction. Design for disassembly or design for maintenance is usually applied to optimize end of life stage but those strategies make product life longer. Those benefits might make DfE practitioner inspire to select a specific strategy.

- **Technology Know-how**

While DfE strategy is realized through development process, some strategies would be set as company's own know-how but others would not. For example, Design for disassembly for optimizing end of life stage or reduction of electricity consumption for clean use/operation is a technology know-how. It can be applied for other product. On the other hands, material change for material use optimization is not a technology know-how while the strategy is easier to apply.

- **Customer perception**

Effective DfE strategy might provide benefits with not only company but also customer. DfE strategy, clean use/operation usually focus on electricity consumption, water consumption and hazardous substance emission in use stage. All of focusing area is able to make consumer recognize the effect of DfE strategy with cost down and health & safety.

- **Preparatory to Future regulation**

Environmental regulations are getting more strict and harder to meet. A specific DfE strategy that is related to the predictable future regulation will be assigned to higher preference to others although the strategy strives to environmental burden that is not current problem.

3. Determine relative significance for criteria (STEP3)

Strategic factors and criteria defined in STEP 1 and 2

The strategic factors and criteria defined in STEP 1 and 2 were summarized in Table 12. All of them are used to formulate appropriate AHP model in order to determine relative weights of criteria. Theoretically, all the criteria in prior study can be included in the AHP based model, as the AHP methodology will enable us to compare and prioritize them. However, it is not practical to include all criteria as they increase the number of pair-wise comparisons and the related computational effort. It is also possible that assessment biases will occur in obtaining the pair-wise comparison judgements from evaluators. Fig. 20 shows the hierarchy scheme for determining relative significance among criteria.

Table 12. Evaluation criteria for environmental and business aspects.

	Environmental Aspects	Business Aspects	
Strategic Factors	Environmental Significance	Investment Requirement	Added Benefit
Criteria	Impact from Material use Manufacturing Use/Operation Distribution End of life	Level of technology R&D time required Hardware Installation required Personnel training required Cost required	Technology know-how Quality improvement Consumer perception Future regulation Cost reduction effect

The hierarchy scheme for determine weights for criteria

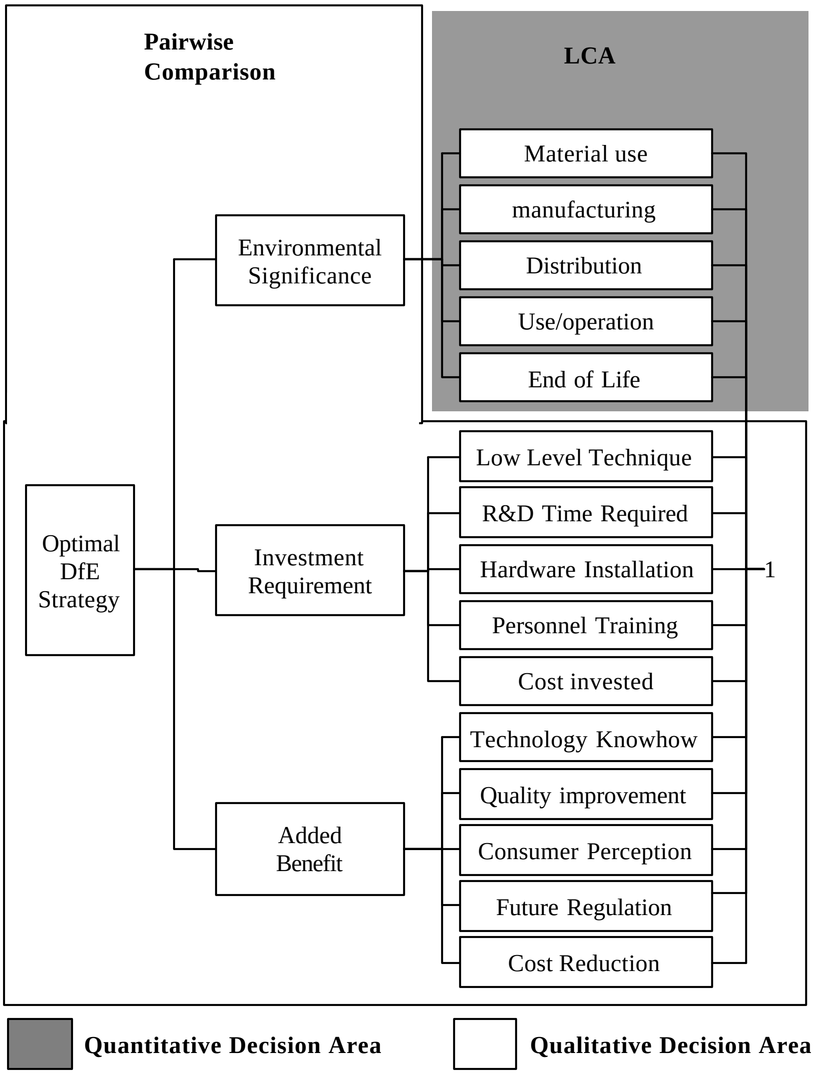

Figure 20. Hierarchy scheme for determining relative weights of criteria

The hierarchy of AHP model is composed of the goal, strategic factors, and criteria. The goal is to select best DfE strategy that minimize environmental burden from product system, bring benefits not only environmental one but also other business one. This goal is placed on the first level of the hierarchy as shown in Fig. 20. Three strategic factors, namely "environmental significance", "investment required", "added value" are identified to achieve this goal, which form the second level of the hierarchy.

The third level of the hierarchy occupies the criteria defining the three strategic factors of the second level. There are 5 criteria related "environmental significance", which are composed of 5 life cycle stages of product system; impact from material use, manufacturing, use/operation, distribution, end of life. On the other hand, the criteria associated with "investment required" are level of technology, R&D time required, hardware installation, personnel training needed, cost required. Finally, benefits related to DfE strategy are divided into technology know-how, product quality improvement, consumer perception, preparatory to future regulation and cost reduction effect.

Determination of relative weights of criteria

This STEP 3 includes assigning pair-wise comparisons to the strategic factors and criteria. The relative importance among criteria in terms of environmental significance is calculated by LCA study. For that of other criteria, nine-point scale is used to assign pair-wise comparisons of elements in each level of the hierarchy. For this AHP analysis, a set of questionnaire was prepared in appendix A.

The questionnaire consisting of strategic factors and criteria of the two levels of AHP model is used to collect the pair-wise comparison judgements from all participants. The pair-wise comparison judgements are made with respect to attributes of one level of hierarchy given the attribute of the next higher level of hierarchy, starting from the level of strategic factors down to the level of criteria. The results collected from the questionnaire are used to form the corresponding pair-wise comparison judgment matrices for determining the local weights for each level. Table 13 and 14 shows a fictional example of pair-wise comparison judgement matrix for each level

Table 13. A fictional example of pair-wise comparison judgement matrix among strategic factors (second level of hierarchy)

	ES	IR	AB	local weights for strategic factors (Lw_i)
ES	1	2	3	0.54
IR	1/2	1	2	0.30
AB	1/3	1/2	1	0.16

CR = 0.067 (less than 0.1)

ES: Environmental Significance; IR: Investment Required; AB: Added Benefit

Table 14. A fictional example of pair-wise comparison judgement matrix among criteria for strategic factor, "Added Benefit". (third level of hierarchy)

	A	B	C	D	E	local weights for criteria (Lw_j)
A	1	1/5	1/5	3	1/5	0.079
B	5	1	1	5	1	0.290
C	5	1	1	5	1	0.290
D	1/3	1/5	1/5	1	1/5	0.050
E	5	1	1	5	1	0.290

CR = 0.040 (less than 0.1)

A: Technology know-how; B: Product quality improvement; C: Consumer perception; D: Preparatory to future regulation; E: Cost reduction effect

Each of matrices is then translated into the corresponding largest eigenvalue problem and is solved to find the normalized weights for each criterion. The consistency ratio (CR) of each matrix is also calculated in order to check consistency of the answer. The matrix is accepted to be reasonable when CR of the matrix is less than 0.1 that is rule of thumb value. The normalized local weights of strategic factors and criteria obtained are combined together with respect to all successive hierarchical levels to obtain the global weights of criteria as shown in equation (1).

$$GW_j = Lw_i \times Lw_j \qquad \text{Equation (1)}$$

GW_j : global weights for j^{th} criteria

Lw_i : local weights of i^{th} strategic factor

Lw_j : local weights of j^{th} criteria with respect to i^{th} strategic factor

An example of calculation for global weight of criteria was showed in Table 15. Bold type figures represent relative significance of normalized contribution scores of fictional LCA results. Others were from fictional pair-wise comparison judgement matrix. A set of global weights was determined for each of criteria by multiplying local weights of the criteria with weights of the parent nodes above it.

Table 15. An example of calculation for global weights of criteria

strategic factors (I)	local weight (Lw_j)	Criteria (j)	local weight (Lw_I)	Global Weight (GW_j)
Environmental Significance	0.54	Impact from Material use	**0.310**	0.167
		Impact from Manufacturing	**0.240**	0.130
		Impact from Distribution	**0.150**	0.081
		Impact from Use/operation	**0.220**	0.119
		Impact from End of life	**0.080**	0.043
Investment Required	0.30	low level of technique required	0.180	0.054
		Less R&D time required	0.260	0.078
		Less Hardware installation	0.110	0.033
		Less personnel training required	0.070	0.021
		Less cost required	0.380	0.114
Added Benefit	0.16	Technology know-how	0.079	0.013
		product quality improvement	0.290	0.046
		Consumer perception	0.290	0.046
		Future regulation	0.050	0.008
		Cost reduction effect	0.290	0.046

4. Determine rating scale and assign to DfE strategy (STEP4)

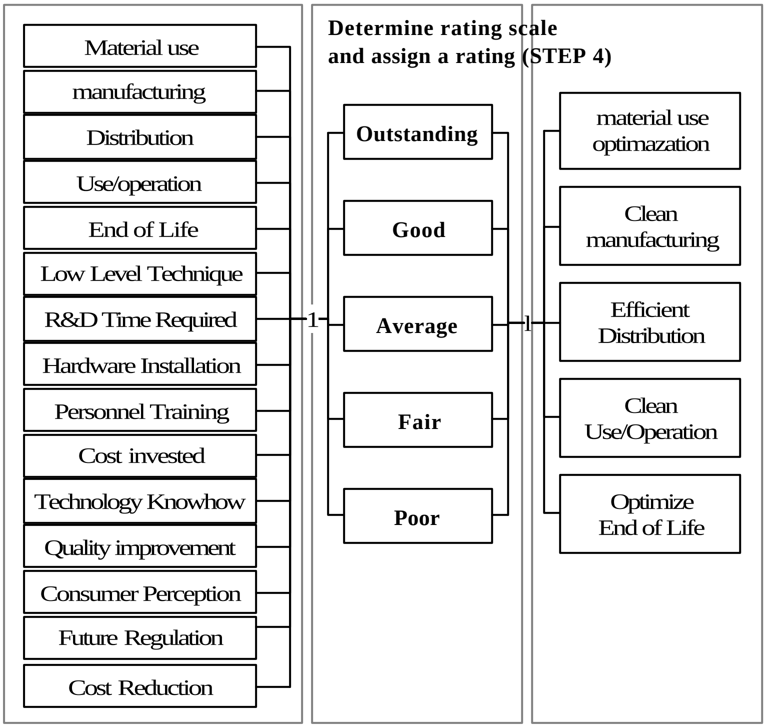

Figure 21. Hierarchy scheme for determination of rating scale and assignation of a rating to DfE strategy

The fourth level of the hierarchy contains the rating scale as shown in Fig. 21. In this step 4, rating scale is determined by pair-wise comparison. Furthermore, the DfE strategy is scored by the rating scale based on individual subjectivity. This level is different from the usual AHP approach in that a rating scale will be assigned to each DfE strategy with respect to each criterion, instead of assessing pair-wise comparisons among the strategies in the usual fashion. The use of a rating scale instead of direct pair-wise comparisons among alternatives (DfE strategy in this study) can be found in Maggie et. al (2001)[85].

The major advantage of this method is to overcome the explosion in the number of required comparisons when the number of required comparisons when the number of alternatives in large. However, this is not the reason for rating method in this study. The alternative DfE strategy is only five. The main reason for adopting this method is that the DfE strategies of this study involves many specific strategies such as design for disassembly (DfD), design for recycling (DfR) and even including specific technology as described in chapter 3. It may be practically too difficult to make pair-wise comparisons among the DfE strategies adopted in this study. Objective of this study is to propose general frame of

[85] Maggie C. Y. (2001).

procedure prioritizing DfE strategy using AHP methodology and therefore how to prepare a set of DfE strategy is beyond of the study. In addition, it is a time consuming process. The use of a rating scale can eliminate these difficulties as each evaluator can assign a rating to a DfE strategy without making direct comparison.

A five-point rating scale of outstanding (O), good (G), average (A), fair (F), and poor (P) is adopted and the weights of these five scales can be determined using pair-wise comparisons. A potential complication might arise when assigning the rating scales by using the five-point rating system. For example, the relative rating of an "out standing" VS. a "good" rating may differ for different criteria. However, such fine discriminations in judgement would be very difficult. Furthermore, prioritizing DfE strategy is not needed detail evaluation that is like selection of design alternative. Rating system makes the assessment process as simple as possible. A simple example of pair-wise comparison among rating scale in Table 16. Rating score is determined based on the weights of a rating scale.

Table 16. An example of pair-wise comparison judgement matrix for five-point rating scale

	O	G	A	F	P	rating score (weights of each rating scale)
O	1	3	5	7	9	0.51
G	1/3	1	3	5	7	0.26
A	1/5	1/3	1	3	5	0.13
F	1/7	1/5	1/3	1	3	0.06
P	1/9	1/7	1/5	1/3	1	0.03

CR = 0.067 (less than 0.1)

After rating sores are determined, managers and designers are asked to assign a rating to a DfE strategy with respect to each criterion in questionnaire as shown in Table 17. This work replaces direct pair-wise comparison among DfE strategies as mentioned earlier.

Table 17. An example of assigning a rating to DfE strategy for each criteria

Decision Criteria \ DfE Strategy	Material use optimization	Clean Manufacturing	Efficient Distribution	Clean Use/ operation	End of Life Optimization
…..	…..	…..	…..	…..	…..
Low level Technology Required	O	F	O	F	G
less R & D Time Required	A	G	G	F	A
Less Hardware Installation	O	P	G	G	F
Less Personnel Training Required	G	P	F	F	G
Less cost invested	G	F	O	A	F
…..	…..	…..	…..	…..	…..

O: outstanding; G: good; A: average; F: fair; P: poor

5. Assigning priority score to each DfE strategy (STEP 5)

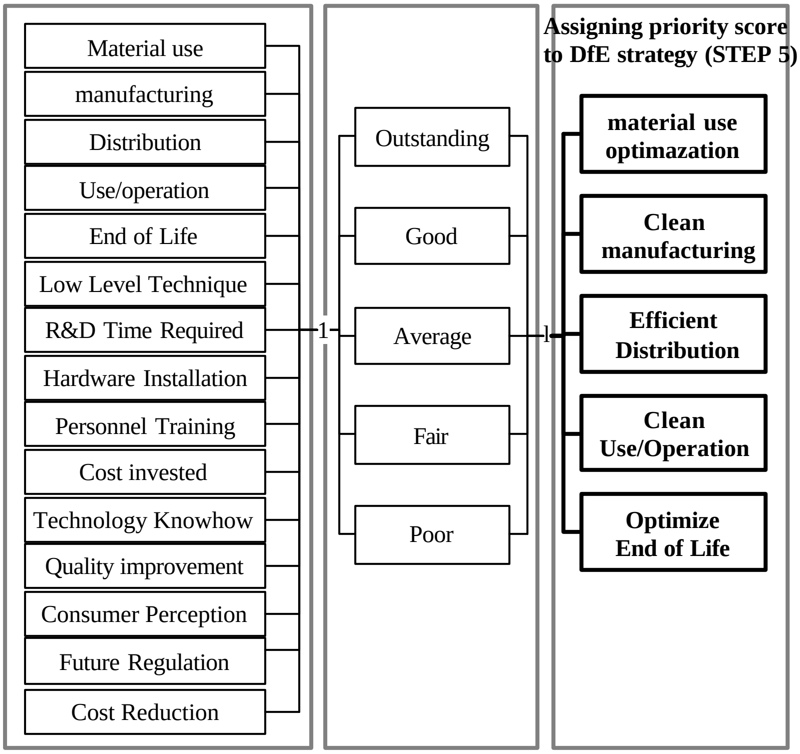

Figure 22. Hierarchy scheme for assigning global priority score to a DfE strategy

The lowest level of the hierarchy consists of the DfE strategy to be evaluated as shown in Fig. 22. After rating scale is determined and a rating is assigned to each DfE strategy with respect to each criterion, a spreadsheet format can be used to calculate the global priority score of DfE strategy. Global priority score can be calculated by multiplying the global weight of criteria with the rating score of DfE strategy with respect to each criterion, and adding the resulting values as shown in Equation (2).

$$G.P.S_k = \sum_j (GW_j \times RS_{j,k}) \qquad \text{Equation (2)}$$

$G.P.S_k$: global priority score of k^{th} DfE strategy

GW_j : global weight of j^{th} criteria

$RS_{j,k}$: rating score of k^{th} DfE strategy with respect to j^{th} criteria

Table 18 shows an example of calculation sheet for global priority weights of DfE strategies. The Table 18 included only two DfE strategies; material use optimization, clean manufacturing and renormalized priority score was calculated based on these two DfE strategies in order to give an example. The example shows that the strategy of material use optimization is more appropriate than clean manufacturing with higher GPS (0.59)

The proposed methodology is generally applicable to any set of DfE strategy that designers wish to evaluate, as it covers the critical strategic factors and related criteria for DfE strategy selection. In other words, the model provides the flexibility to include any specific criteria and DfE strategy to be evaluated.

Table 18. An example of global priority weight of DfE strategy

Criteria (j)	GW for Criteria	Material use optimization (k)			Clean Manufacturing (k)		
		Rating	RS	G.P.S	Rating	RS	G.P.S
	STEP 3	STEP 4		STEP 5	STEP 4		STEP 5
Environmental Significance							
Material use	0.167	O	0.510	0.085	G	0.260	0.043
Manufacturing	0.130	F	0.060	0.008	O	0.510	0.066
Impact from use	0.081	G	0.260	0.021	P	0.030	0.002
Distribution	0.119	P	0.030	0.004	P	0.030	0.004
End of Life	0.043	G	0.260	0.011	F	0.060	0.003
Investment Requirement							
Low level technique	0.054	O	0.510	0.028	F	0.060	0.003
Time required	0.078	A	0.230	0.018	G	0.260	0.020
Hardware installation	0.033	O	0.510	0.017	P	0.030	0.001
Personal training	0.021	G	0.260	0.005	P	0.030	0.001
Software needed	0.114	G	0.260	0.030	F	0.060	0.007
Added Benefit							
Technology know-how	0.013	F	0.060	0.001	A	0.230	0.003
Quality improvement	0.046	G	0.260	0.012	A	0.230	0.011
Consumer perception	0.046	G	0.260	0.012	F	0.060	0.003
Future regulation	0.008	A	0.230	0.002	O	0.510	0.004
Cost reduction	0.046	A	0.230	0.011	F	0.060	0.003
Global priority scores				**0.263**			**0.173**
Renormalized scores				**0.603**			**0.397**

Ⅴ. Summary and conclusion

This research proposes a systematic methodology for setting priority of DfE strategy in designing an environmentally friendly product by considering both environmental and business aspects of a product. Brezet (1997), Keoleian&Menerey (1993) and ISO TR 14062 were investigated prior to the description of methodology. Three general steps for establishing DfE strategy were identified from the literatures. They included identification of the environmental aspects, identification of internal/external design drivers and integration those aspects into establishing DfE strategy.

Checklist method, MET matrix methods and quantitative Life Cycle Assessment (LCA) are compared as tools for identification of environmental aspects. Qualitative methods including checklist and MET matrix were effective in terms of time and cost while loose results are obtained. On the other hand, quantitative LCA was the best in objectivity and accuracy. Environmental aspects of product are decisive criteria in DfE. Accordingly, quantitative tool would be necessary. As for identification of internal/external design drivers, No formal method was found in the literatures because design drivers vary with company business strategies and products developed.

Integrating methods founded were checklists, matrix (QFD or modified QFD), Ecodesign wheel method and knowledge based system. Those tools were compared with decision-making characteristics, criteria considered, pros. and cons. Checklist was the easiest and cheapest while results are so loose that it has a possibility of misleading the decision. As for decision-making characteristics, EOD, the modified type of QFD matrix, was the quantitative making trade off easily. Ecodesign wheel was also quantitative but strategies are prioritized by individual subjectivity through expert group discussion in the methods.

The proposed methodology is based on LCA and Analytic Hierarchy Process (AHP) , and consists of five steps. They include identification of the environmental design factors (1^{st} step), identification of the business design factors (2^{nd} step), determination of the relative significance of both environmental and business design factors (3^{rd} step), rating DfE strategies per design factor (4^{th} step), and derivation of global priority score (GPS) of each DfE strategy from 3^{rd} and 4^{th} steps (5^{th} step). A total of five DfE strategies were used including material use optimization, clean manufacturing, efficient distribution, clean use and operation, and end-of-life optimization.

Environmental design factors are identified in the 1^{st} step. Normalized environmental impacts of a product system have been allocated into material use, product manufacturing, distribution and packaging, use, and disposal stages of a product life cycle. This results in a total of five environmental design factors.

Business design factors have been divided into two aspects in the 2^{nd} step; investment requirement and added benefit. Level of technology required, R & D time required, hardware required, personnel training required, and cost invested are considered as design factors in the investment requirement aspect. Technology know-how, product quality improvement, customer perception, cost reduction effect, preparation to future regulations are considered as design factors in the added benefit aspect. This results in a total of ten business design factors.

Relative weights of three strategic factors and fifteen design factors are determined based on AHP analysis in the 3rd step. Environmental significance, investment requirement, and added benefit are three strategic factors. Relative weights of the strategic factors, higher level in the AHP analysis, are determined by pair-wise comparison. Relative weights of the design factors or criteria belonging to each strategic factor, lower level in the AHP analysis, are determined by pair-wise comparison. Instead of a pair-wise comparison, LCA results are applied to the relative weights of the environmental design factors. Global weight of a criterion is a product of the relative weights of criterion and strategic factor.

DfE strategies belonging to each criterion are rated in the 4th step. Prior to the rating, however, rating scale of five rating yardsticks including outstanding, good, average, fair, and poor, is determined through pair-wise comparison. This pair-wise comparison is the same in concept as that used in determining relative weights. Relative weights of the rating yardsticks or rating scores are obtained in this process. Then scores to DfE strategies per criterion are assigned using the five rating scores.

Finally GPS value is computed per each DfE strategy in the 5th step. GPS value is a product between relative weight of a criterion and rating score of a DfE strategy, followed by summation for all criteria. This is shown in the equation below.

$$GPS_k = \sum_j (GW_j \times RS_{j,k})$$

GPS_k : global priority score of k^th DfE strategy

GW_j : global weight of j^th criteria

$RS_{j,k}$: rating score of k^th DfE strategy with respect to j^th criteria

The outcome of this research is the proposition of a DfE strategy prioritization methodology applicable to an environmentally friendly product design. Application of the design factors and DfE strategies evaluated in the proposed methodology should be modified relevant to a specific situation of a product design.

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국 문 요 약

최근 환경문제와 자원고갈문제가 국제적 문제가 되면서 이들 문제의 주 원인 제공자인 기업은 환경 친화적으로 제품을 생산해야 할 책임을 지게 되었다. 이러한 이유에서 환경을 고려한 제품설계 (Design for Environment: DfE) 는 제품의 환경측면을 개선 하는 것 뿐만 아니라 동시에 제품경쟁력을 높이기 위한 사업 전략으로 인식되고 있다.

환경을 고려한 제품설계 시 환경 친화적 제품설계 전략 (DfE 전략)의 올바른 수립은 제품의 환경 친화성을 결정하는 요인이 된다. 또한 DfE 전략의 수립은 그 과정이 복잡하고, 또한 난해한 의사결정이 요구 된다. 그러나 아직까지 체계적인 DfE 전략 수립 방법론에 대한 연구는 부족한 실정이다.

이 연구에서는 환경을 고려한 설계 시 DfE 전략 수립단계에 환경측면과 시장측면을 동시에 고려하여 DfE 전략의 우선순위를 도출하는 체계적인 방법론을 제안하였다. DfE 전략은 환경측면의 설계 고려사항, 시장측면의 설계 고려사항, 이 둘을 통합한 DfE 전략 도출의 순으로 수립된다.

제안된 방법론은 전과정평가 (Life Cycle Assessment: LCA) 와 계층분석법 (Analytic Hierarchy Process: AHP) 을 기본골격으로 하고 있으며 전체 5 단계로 구성되어 있다. 각 단계는 환경측면의 설계고려사항 파악 (1 단계), 시장측면의 설계고려사항 파악 (2 단계), 환경측면 및 시장 측면 설계 고려 사항들의 상대적 중요도 결정 (3 단계), 각 설계고려사항 별 DfE 전략의 등급 평가 (4 단계), 3,4 단계 결과로부터 각 DfE 전략의 우선순위 점수 (global priority score: GPS) 도출 (5 단계) 등이다. 사용된 DfE 전략은 총 5 개로서 재료사용 최적화, 청정생산, 효율적 유통, 청정사용 및 폐기단계 최적화 등이다.

1 단계에서 환경측면의 제품 설계 고려사항은 LCA 를 이용하여 규명하였다. 제품 시스템에서 기인된 환경영향은 재료사용, 제품 생산, 유통 및 포장, 사용 및 폐기단계에서의 환경영향으로 나타내었다. 이는 환경측면에서 총 5 개의 환경측면 설계 고려사항이 된다.

2 단계에서 시장측면의 제품 설계 고려사항은 크게 투자필요성 부분과 부가적 이득 부분으로 나누었다. 투자 필요성 측면에서 기술 적용의 난이도, 연구개발 시간의 소요정도, 설비 투자의 필요성, 전문교육의 필요성, 비용 소모 정도를 고려하였다. 부가적 이득 측면에서 기술노하우의 축적효과, 제품 품질개선 효과, 소비자 인지도 개선효과, 비용절감효과, 예측 가능한 법규에 대한 선행조치로 구분하였다. 이는 총 10 개의 시장측면 제품 설계 고려사항이 된다.

3 단계에서는 AHP 를 통한 분석계층 구조를 따라 3 개의 전략적 요소(strategic factor)와 15 개의 설계 고려사항(criteria)에 대한 상대적인 중요도를 결정한다. 여기서 환경측면, 투자필요성 부분, 및 부가적 이득 부분이 전략적 요소가 된다. 이때 상위 계층에 속한 전략적 요소들을 쌍대비교하여 각각 중요도를 구하고 그 하위 계층인 설계 고려 사항들도 해당 전략적 요소별로 쌍대비교를 통하여 중요도를 결정한다. 이때 환경측면 설계 고려사항의 경우는 쌍대비교를 하지 않고 LCA 결과값을 적용한다. 설계고려사항의 전체 가중치는 설계고려사항 사이의 상대적인 중요도와 해당되는 전략적 요소의 상대적인 중요도의 곱으로 산출한다.

4 단계는 각각의 설계고려사항에 대해 DfE 전략의 등급점수를 부여하는 단계이다. 이를 위해서 5 가지 등급- outstanding, good, average, fair, poor 를 쌍대비교 하여 등급척도를 먼저 결정한다. 등급 척도의 결정은 상대적인 중요도를 결정하는 것과 같은 과정이다. 이 과정에서 얻어지는 상대적인 중요도 즉, 등급 척도가 해당등급이 가지는 등급 점수가 된다. 결정된 5 가지의 등급의 점수를 이용하여 각각의 설계고려사항 별로 DfE 전략에 점수를 부여한다.

5 단계에서는 각각의 DfE 전략에 대해서 최종적인 GPS 를 계산한다. GPS 는 15 가지설계 고려 사항의 상대적인 중요도에 해당 설계고려사항 별 DfE 전략의 점수 즉, 등급점수를 곱한 뒤 이것을 모두 취합하여 DfE 전략의 GPS 로 아래 식과 같이 계산한다.

$$GPS_k = \sum_j (GW_j \times RS_{j,k})$$

GPS_k : global priority score of kth DfE strategy

GW_j : global weight of jth criteria

$RS_{j,k}$: rating score of kth DfE strategy with respect to jth criteria

이 연구의 성과는 환경을 고려한 제품설계 시 DfE 전략 수립에 적용 가능한 다 기준 의사결정기법의 활용방안을 제시하였다는데 있다. 제안된 방법론에서 적용된 설계고려사항이나 평가되는 DfE 전략의 종류는 상황에 맞게 적용되어야 한다.

APPENDIX A

QUESTIONNAIRE FOR AHP APPLICATION

Dear Participants,

Thank you for your favor to accept this inquiry. This inquiry will be used only for the research purpose, and no individual viewpoints will be exposed to the public. This inquiry is sent to both managers and designers in business. The results will be used to prioritizing Design for Environment (DfE) strategy for a product that is being carried out as a part of DfE activities.

The scope of this inquiry

DfE activities and DfE strategies are wide well known concepts used in product development processes, but the prioritizing procedures of DfE strategy has not been fully examined, even though nobody doubts the importance of product development strategy for design process. This inquiry is prepared to quantify relative significance of some criteria related to DfE strategy selection in DfE process. (Note: the results can not be used for all of product. With respect to product feature or company environmental vision, the result might be different.)

All participants of this inquiry will be asked to decide the relative importance of each parameters affecting DfE strategy selection based on their experiences and subjectivity (pair-wise comparison). Then, estimation of rating scale of different levels within a criterion will be asked. Finally, DfE strategy will be rated with the given rating score based on subjectivity. All questions have no correct or incorrect answers, so please chose the best answer based on your individual subjective judgement. The answers will be aggregated by method of Analytic Hierarchy Process (AHP), and the DfE strategies for a specific product will be prioritized as a result.

How to reply this inquiry

In replying this inquiry, you can use e-mail attaching this MS Word file with answers, or you can ask a return envelope. The return envelope will be mailed on demand. If you received a return envelope, you can send me the answer sheet by exchanging the enveloped coupons into your country's stamps at the post office.

If you need some help or there is something illegible, please don't hesitate to contact me (hyc408@madang.ajou.ac.kr). And any kind of comments on this inquiry will be welcomed. I again greatly appreciate your kindness.

Best Regards,

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Descriptions about Decision Criteria

For prioritizing DfE strategy, three strategic factors were chosen and divided into 5 criteria for each strategic factor in order to be able to systematically. Three strategic factors include "Environmental significance", "Investment requirement" and finally "Added benefit" in the first level. The second levels covered 15 criteria for a decision; environmental impact from material use, manufacturing, use/operation, distribution and end of life for environmental significance; "low level technology required", "R&D time requirement", "hardware installation needed", "personnel training requirement", "Cost requirement" for investment requirement; "technology know-how", "product quality improvement", "consumer perception", "preparatory to future regulation", "cost reduction" for added benefit. Those evaluation criteria are illustrated in decision tree shown in Fig.A1

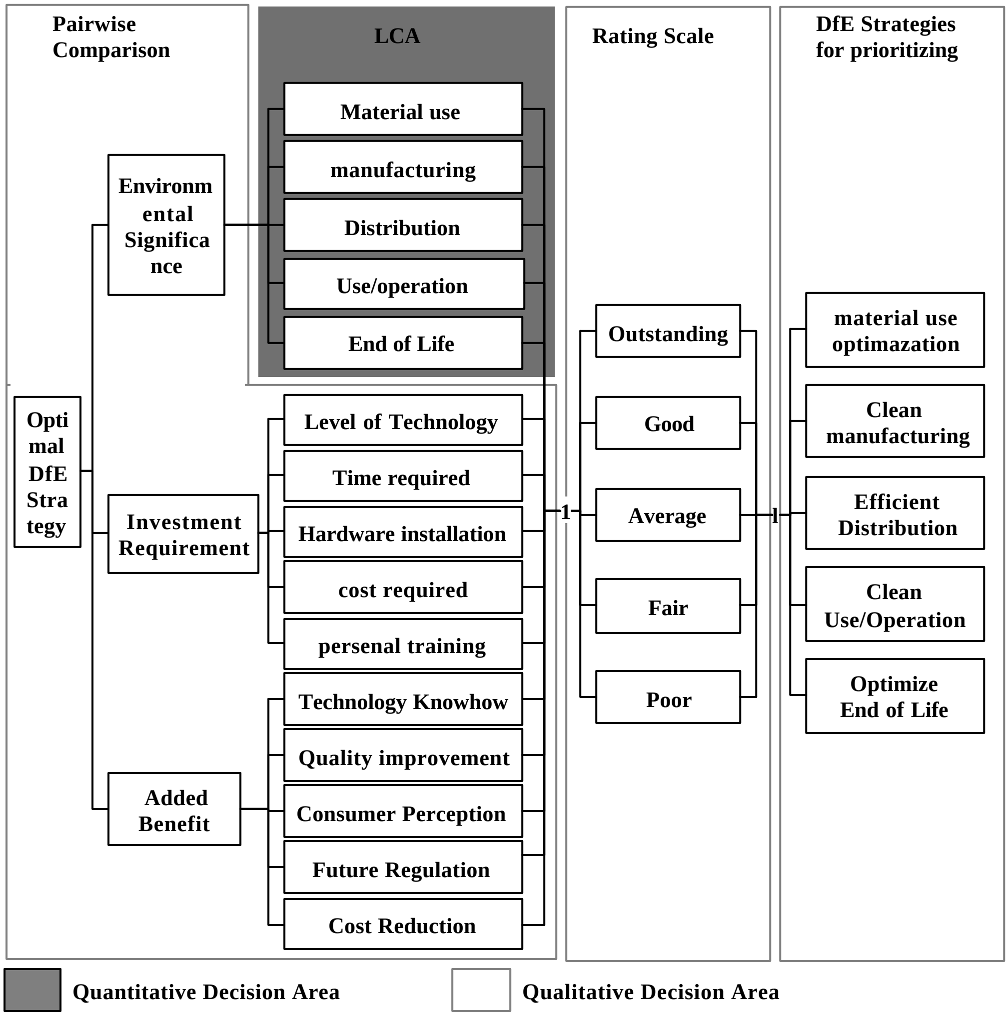

Figure A1. Decision Tree for Prioritizing DfE Strategy

You will be asked how much those criteria are related relatively to the upper level strategic factors comparing them in pair. (pair-wise comparison) Below is the explanation of those criteria.

Note: relative significance of environmental criteria for strategic factor, environmental significance, is calculated quantitatively by LCA study of existing product so that pair-wise comparison is not required in this inquiry.

Level 1. Strategic factors

In DfE practice improving of environmental aspects of product is the most important elements affecting selection of DfE strategy, however, business aspects including investment and benefit of DfE strategy can not be ignored.

1. Environmental Significance

Environmental burden from product and product system is one of key elements when prioritizing DfE strategy. 'Environmental significance', is a strategic factor for designing a product. Probably DfE strategy can be affected by decision how environmentally significant product is and how much effort will be given to improve the environmental aspect of product. Managers and designers must make a decision on how much environmental significance of product will be considered in design strategy selection.

2. Investment Requirement.

'Investment Requirement' represents that how much effort should be made when you take a specific DfE strategy. In business perspective less cost needed and less time to market to realize a specific strategy are preferred while selecting DfE strategy. In the first level, you will be asked to decide how much investment required affect your selection of DfE strategy.

3. Added Benefit

DfE strategy basically aimed at improving environmental aspects of product but it is well known fact that application of DfE strategy for product development process is likely to achieve another benefit such as cost reduction, quality improvement, technology know-how etc.

Level 2. Decision Criteria

1. For the Environmental Significance

For improving environmental aspects of product, DfE practitioner must identify environmental bottlenecks of a product because effectiveness of DfE strategy will be differed with respect to types and sources of environmental problem. Environmental problems vary with their types such as wastes, process emission, material use or to their sources such as material and component manufacturing stage, product manufacturing stage, use/operation stage, distribution stage, finally end of life stage. In this inquiry, environmental bottlenecks are classified by their sources that are composed of product life cycle stages. Which life cycle stages are more significant will affect to decision on prioritizing DfE strategy. Each of life cycle stages as criteria are described below but as mentioned at the beginning of this inquiry, relative significance of each life cycle stages is based on LCA result, not pairewise comparison of participants.

- **Material use**

Environmental impact from material extraction to material use for a product including material processing

- **Manufacturing**

Environmental impact from product manufacturing – may be air and water emission, solid wastes.

- **Use/operation**

Environmental impact from product use and operation – may be energy consumption

- **Distribution**

Environmental impact from product distribution

- **End of life**

Environmental impact from product end of life stage, which is may be from recycling process and disposal process.

2. For the Investment Requirement

For the investment requirement factor, five criteria are taken into account: level of technology needed, R&D time requirement, hardware installation and cost invested and personnel training required.

- **Level of Technology required**

Level of Technology required represents which kind of technology there are and how easy to access the technology in order to apply a specific DfE strategy. If there are many common technologies for a DfE strategy, the strategy will be preferred to others.

- **R&D time required**

R&D time also could be critical decision criteria relating to cost need and time to market launch. Common technology availability for a specific DfE strategy can also affect to R&D time need. A DfE strategy witch requires less R&D must be preferred to others.

- **Hardware installation requirement.**

Hardware installation might be required to realize a specific DfE strategy. For instance, recycling process for optimizing end of life, wastes treatment process for clean manufacturing etc. hardware installation must be cost driver so that company probably does not want to take.

- **Personnel training requirement**

Personnel training might be required for a specific strategy. In manufacturing, distribution, use/operation and end of life, individual usually treat sources of environmental burden so that personnel training are required for a most DfE strategies.

- **Cost Invested**

Product development projects always need expenditure while project budget is limited. With respect to the strategy, cost needed to apply for a specific strategy will be different and cost-effective strategy will be preferred to others.

3. For the Added Benefit

For the added benefit factor, company benefit and customer benefit criteria are taken account. Furthermore, company benefit divided into two sub criteria: cost reduction and product quality improvement.

- **Cost reduction effect**

Effective DfE strategy is able to reduce manufacturing cost or distribution cost. It is usually originated from reduction of material purchased, hazardous material must be treated, weight of product distributed etc. If application of a specific strategy is able to reduce those cost, the strategy will have higher preference.

- **Product quality improvement**

Product quality can be improved by effective DfE strategy as well as cost reduction. Design for disassembly or design for maintenance is usually applied to optimize end of life stage but those strategies make product life longer. Those benefits might make DfE practitioner inspire to select a specific strategy.

- **Technology Know-how**

While DfE strategy is realized through development process, some strategies would be set as company's own know-how but others would not. For example, Design for disassembly for optimizing end of life stage or reduction of electricity consumption for clean use/operation is a technology know-how. It can be applied for other product. On the other hands, material change for material use optimization is not a technology while the strategy is easier to apply.

- **Customer perception**

Effective DfE strategy might provide some benefit with not only company but also customer. DfE strategy, clean use/operation usually focus on electricity consumption, water consumption, hazardous substance emission etc. All of focusing area is able to make consumer recognize the effect of DfE strategy with cost down and health & safety.

- **Preparatory to Future regulation**

Environmental regulations are getting more strict and harder to meet. Although some of environmental burden is not current problem, a specific DfE strategy that is related to the predictable future regulation will be assigned to higher preference to others.

- Limitations of this approach:

The choice of criteria and DfE strategies are somewhat subjectively defined. And it is notable that the relative importance between each parameter varies with the product category and business strategy of a company, which means results of this approach are different from case by case.

The rating scale applied in this approach is identical for every different criterion. From the reason, a potential complication might be arisen when assigning the rating scales by using five-point rating system; outstanding (O), good (G), average (A), fair (F) and poor (P). For example, the relative rating of an "outstanding" vs. a "good" rating may different for each criterion. But such fine discrimination in judgement would be very difficult. Furthermore, this rating system is able to keep the prioritizing process as simple as possible. Therefore, one set of rating system was taken in this approach.

Instruction for preparing answer sheet

Only two parameters are compared at a time, and the relative importance between the two will be asked. The answer will have the form such as **"I think A is moderately important compared to B with respect to the selection of optimal DfE strategy so that I give a point 3 to B"** Sometimes the relative importance is hard to be expressed as a absolute measurement. But this study employs the quantitative judgment rather than qualitative one such as "very important" or "strongly important." When you judge the relative importance between two, the use of discrete 9 point scales suggested by Saaty will be helpful. First, judge in verbal expression, then translates into a score with table below.

Judgement	Score	Explanation
Equally	1	Two attribute equally to the upper level criteria
	2	
Moderately	3	Experience and judgement slightly favor one attribute over another
	4	
Strongly	5	Experience and judgement strongly favor one attribute over another
	6	
Very strongly	7	An attribute is strongly favored and its dominance demonstrated in practice
	8	
Extremely	9	The evidence favoring one attribute over another is of the highest possible order of affirmation

● *Example*

Below is the blank answer sheet in which the relative importance between parameter A and B is compared.

----

1. Compare A and B

A : environmental significance
B : added benefit

	Extr m		Vry strng		strng		Mod		Eual		Mod		strng		Vry strng		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A																		B

And if you think the strategic factor A is very strongly important than B in terms of the selection of optimal DfE strategy, then you will mark the answer sheet as shown below.

----

1. Compare A and B

A : environmental significance
B : added benefit

	Extrm		Vry strng		strng		Mod		Eual		Mod		strng		Vry strng		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A					○													B

This judgment **is made only on the basis of individual experience and subjectivity and there is not any correct or incorrect answer.**

Answer Sheet

Information of Participant

Name :
Country :
E-mail :
Contact Address(office) :

This Answer sheet is composed of three parts:

Ⅰ. pair-wise comparison analysis for decision criteria
Ⅱ. Pair-wise comparison analysis for five point rating scale
Ⅲ. Rating DfE strategies with respect to each criteria

Ⅰ. Pair-wise Comparison Analysis for Decision Criteria

A. You will be asked about relative importance of two strategic factors in terms of selection of optimal DfE strategy.

A : Environmental significance
B : Investment required **in terms of "selection of optimal DfE strategy"**
C : Added benefit

	Extrm		vry stg		str ng		mod		Eqal		Mod		str ng		vry stg		Ext rm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A																		B
A																		C
B																		C

B. You will be asked about relative importance of two parameters in terms of Investment Requirement.

A : Low level technique required
B : Less R&D time required
C : Less hardware installation
D : Less personnel training
E : Less cost invested

in terms of "Investment Requirement"

	Extrm		vry stg		strng		mod		Eqal		Mod		strng		vry stg		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A																		B
A																		C
A																		D
A																		E
B																		C
B																		D
B																		E
C																		D
C																		E
D																		E

C. You will be asked about relative importance of two criteria in terms of Added Benefit.

A : Technology know-how
B : Product quality improvement
C : Consumer perception **in terms of “Added Benefit”**
D : Preparatory to future regulation
E : cost reduction

	Extrm		vry stg		strng		mod		Eqal		Mod		strng		vry stg		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A																		B
A																		C
A																		D
A																		E
B																		C
B																		D
B																		E
C																		D
C																		E
D																		E

Ⅱ. Pair-wise comparison analysis for five point rating scale

In this section, you will be asked to answer relative degree of rating score; outstanding (O), Good (G), Average (A), Fair (F), Poor (P)

And if you think the score, Good, is very strongly higher than Average, then give a mark in the answer sheet as shown below.

	Extrm		vry stg		strng		mod		Eqal		Mod		strng		vry stg		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Good			○															Average

A. You will be asked about relative degree of two rating score for five point rating scale.

A : Outstanding
B : Good
C : Average
D : Fair
E : Poor

in terms of "Added Benefit"

	Extrm		vry stg		strng		mod		Eqal		Mod		strng		vry stg		Extrm	
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
A																		B
A																		C
A																		D
A																		E
B																		C
B																		D
B																		E
C																		D
C																		E
D																		E

Ⅲ. Rating DfE strategies with respect to each criterion

In this section, give a rating score for each DfE strategy in column with respect to criteria in row using five point rating scale; Outstanding(O), Good (G), Average (A), Fair (F) and Poor (P)

For example,

If you think the DfE strategy, material use optimization is Outstanding strategy for a environmental significance of material use then give a "O" score in the corresponding matrix. And if you think the DfE strategy, Efficient Distribution have nothing to do with environmental significance of the end of life stage then give a "P" score in the corresponding matrix shown in below. Note that all of matrices have to be filled your score.

Decision Criteria \ DfE Strategy	Material use optimization	Clean Manufacturing	Efficient Distribution	Clean Use/ operation	End of Life optimization
For Environmental significance of Material use	O				
For Environmental Significance of Manufacturing phase					
For Environmental Significance of Distribution Stage					
For Environmental Significance of Use Stage			P		
For Environmental Significance of End of life Stage					

A. You will be asked to rate all of DfE strategy with respect to each criterion in this section.

Use Five point rating scale; Outstanding (O), Good (G), Average (A), Fair (F) and Poor (P)

1. In terms of "Environmental significance"

Decision Criteria \ DfE Strategy	Material use optimization	Clean Manufacturing	Efficient Distribution	Clean Use/ operation	End of Life optimization
For Environmental significance of Material use					
For Environmental Significance of Manufacturing phase					
For Environmental Significance of Distribution Stage					
For Environmental Significance of Use Stage					
For Environmental Significance of End of life Stage					

2. In terms of "investment required"

Decision Criteria \ DfE Strategy	Material use optimization	Clean Manufacturing	Efficient Distribution	Clean Use/ operation	End of Life Optimization
Low level Technology Required					
R & D Time Required					
Less Hardware Installation					
Less Personnel Training Required					
Less cost invested					

3. In terms of "Added benefit"

Decision Criteria \ DfE Strategy	Material use optimization	Clean Manufacturing	Efficient Distribution	Clean Use/ operation	End of Life Optimization
Technology Know-how					
Product Quality Improvement					
Consumer Perception					
Preparatory to Future Regulation					
Cost Reduction					

Thank you very much !

The results will be reported to all participants

- The End of Inquiries -