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ORIGINAL PAPER

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Strategic evolution of eco-products: a product life cycle planning methodology

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Abstract This paper presents a methodology and a software tool to establish an eco-design concept of a product and its life cycle by assigning appropriate life cycle options to the components of the product. The product life cycle planning (LCP) methodology provides the following systematic procedures. First, the medium- or long-term production and collection plan for the product family is clarified. Next, target values for the product and its life cycle are set in the process of determination of customer-oriented specification and eco-specification. Then, eco-solution ideas to realize reasonable resource circulation are generated by using various life cycle option analysis charts. Finally, an eco-design concept which involves eco-solution ideas is evaluated for decision-making at early stages of product development. A design support tool was made for efficiently planning product life cycles by using quality function deployment and life cycle assessment data. Based on case studies, it was verified that the proposed methodology and tool are useful for developing multi-generational eco-products.

Keywords Environmentally conscious design (eco-design) · Design for environment (DfE) · Life cycle planning (LCP) · Quality function deployment (QFD) · Life cycle assessment (LCA) · Environmentally conscious product (eco-product).

1 Introduction

Environmental problems have become crucial issues for current generations and will be so for future generations as well. The problems are extensive, complex, and have a wide spectrum. Today, the consideration of environmental aspects is an essential step in planning, in industrial companies (Graedel and Allenby 1995). In order to realize a sustainable manufacturing industry, new manufacturing paradigms inspired by a natural circulation system have been proposed, such as “inverse manufacturing” (Kimura and Suzuki 1996) and “zero-emission” (Capra and Pauli 1995).

To achieve sustainable industry, environmentally conscious design (eco-design) or design for environment (DfE) is becoming an increasingly important topic (Brezet and Van Hemel 1997). In many cases, the product development process can be modeled as a product evolution process based on the representation and understanding of a current product. Hence, systematic methodologies for product evolution are necessary from a practical viewpoint (Otto and Wood 1998; Martin and Ishii 2000). In the same way, it is important to systematize a design methodology for evolution of eco-products based on modeling and analyzing current products (Coulter and Bras 1997, 1999).

In the practice of eco-design, life cycle assessment (LCA) provides the basic modeling framework for evaluating the environmental load and impact throughout the entire product life cycle from material acquisition to disposal (Wenzel et al. 1997). LCA tools will be playing an increasingly important role in communication between manufacturing companies and their stakeholders, such as in the case of eco-labeling or green procurement. However, it is difficult to integrate the environmental, quality, and cost aspects of a product simultaneously when only LCA results are applied to the improvement of a product.

On the other hand, the importance of eco-design in earlier phases has been emphasized, because decisions made in these phases greatly affect the environmental impact throughout the product life cycle (Frei and Züst 1997). Conventional approaches in the early design phases, such as quality function deployment (QFD) (Clausing 1993), consider the usage phase of the product. In order to consider the entire life cycle and fulfill customer satisfaction, an eco-design methodology must

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be incorporated into the conventional methods in the early phases of design.

In this study, product life cycle planning (LCP) aims to set target specifications for the product and its life cycle, and to establish eco-design concepts (Kobayashi 2000, 2001). A design concept here is defined as a set consisting of solution ideas. Solution ideas are to be expressed using natural language. In eco-design, it is essential to consider the resource-circulation path for components in the product system. Each such path is hereafter referred to as a life cycle option, and a selection of life cycle options for components is also regarded as a solution idea.

There are many life cycle options for products and components, such as maintenance service with or without upgrade to extend the use period of a product, reuse or recycling of a component or a product for resource-saving, disposal by landfill or incineration with or without energy recovery, and dematerialization by replacing the functions of products with services (Umeda and Life Cycle Design Committee 2001). This study focuses on particular life cycle options, namely "upgrade of products," "maintenance of products," "extension of useful lifetime," "product or component reuse," and "material recycling" (Fig. 1). This is because concern with regard to these options has increased in importance due to consumer interest and market forces. It is here assumed that "maintenance of products" includes preventive maintenance and breakdown maintenance. The latter is also referred to as repair. Also, "product or component reuse" here implies remanufacturing, product installation reuse, spare parts reuse, and global reuse (Umeda and Life Cycle Design Committee 2001).

In a previous study, an LCP methodology for a single product was developed (Kobayashi and Haruki 2003). The objective of this study was to extend the LCP methodology and implement a software tool for strategic, continuous eco-evolution of products. In the LCP process, comprehensive environmental requirements are considered from the life cycle perspective, and the environmental aspect is integrated with the quality and cost aspects in the early phases of design. A number of new techniques are also developed to analyze applicability of various life cycle options at the product and component levels.

2 Related work and research approach

2.1 Related work

In this section, related studies such as checklist methods, matrix-based methods, concept generation and evaluation methods and tools, and simulation-based approaches, are introduced and reviewed. There are some excellent eco-design guidelines and checklists available (e.g. Brezet and Van Hemel 1997). These guidelines are easy to use, well organized, and time-efficient. However, they do not provide a mechanism to prioritize the environmental requirements and to deploy them into the product development process.

In QFD, customer requirements are incorporated throughout the product development process (Clausing 1993). In order to reflect the customer requirements in the product specifications, QFD matrices are utilized. QFD clarifies the relationship between customer requirements and quality characteristics, and the relationship between quality characteristics and components is clarified. Applications to describe environmental requirements in a QFD matrix have been proposed (Dannheim et al. 1998; Masui et al. 2000; Zhang et al. 1998a). Customer requirements are not obligatory issues for manufacturing companies; however, environmental requirements do include obligatory aspects, such as compliance with regulations. Environmental requirements are different from customer requirements and are better treated, based on risk management.

The environmental failure mode and effect analysis (E-FMEA) is also useful for prioritizing environmental requirements (Lindahl 1999). In a customer-oriented DfE method, customer needs, competitor information, and environmental issues are described and prioritized in the life cycle matrix (Johnson and Gay 1995). Al-

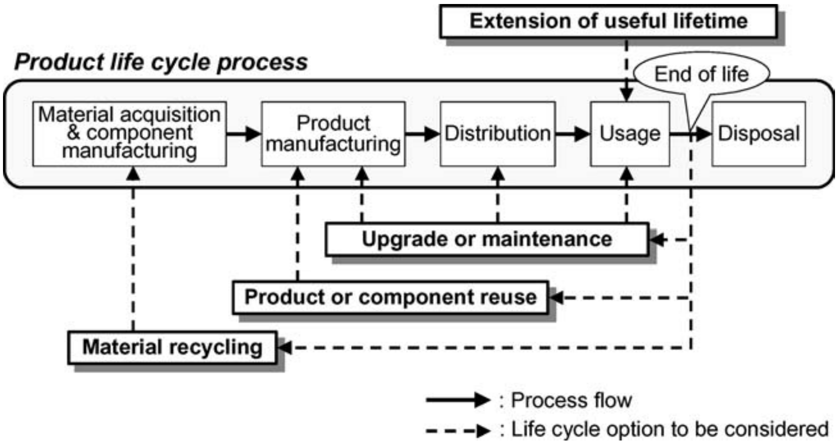


Fig. 1 Product life cycle process and life cycle options

though these matrix-based approaches are useful in the early design phases, they do not support creation of eco-solution ideas.

Product idea tree diagrams help structure eco-idea generation activities and their outcomes (Jones et al. 2001). However, since they are based on an intuitive approach, they cannot make good use of the quantitative product data. Design support tools applicable in the early phases of design have been developed based on systematized eco-design knowledge or cases (Kobayashi 2000; Brink et al. 1998; Rombouts 1998). Although these tools can suggest eco-solution ideas corresponding to product characteristics, it is difficult to update and reorganize the eco-design knowledge or cases. An end-of-life (EOL) design support tool, which suggests appropriate EOL options at product level based on technical product characteristics, has been developed (Rose et al. 2000). Because this tool uses a decision tree generated by statistical analysis, the validity of this tool depends strongly on its database of collected engineering cases.

In order to evaluate or select a solution idea or a design concept, weighted rating methods are generally utilized (Pahl and Beitz 1988). In these methods, weighting of the evaluation criteria greatly affects the evaluation result. Total evaluations of eco-products have been reported (Williams et al. 1996; Zhang et al. 1998b). In these evaluations, the weighting factors of the evaluation criteria were calculated using the analytic hierarchy process (AHP) (Satty 1980). On the other hand, a method that evaluates an eco-product from the cost and environmental aspects independently has been reported (Biswas et al. 1997). In addition, a methodology based on the formulation of compromise decision support problems has been reported (Coulter and Bras 1999). However, this method requires a great amount of detailed information, making it inapplicable to the early phases of design.

Product life cycle simulation (LCS) techniques have been proposed to evaluate the environmental burden and revenue of a company caused by single or multiple product life cycles from a medium-term or long-term viewpoint (Hoshino et al. 1995; Murayama et al. 2001; Umeda et al. 2000). LCS is useful for evaluating the business strategies or modular architecture for an eco-product. However, if the number of components or materials constituting the product is too large, calculations cannot be executed in a practically feasible time, because the number of possible combinations of life cycle options increases exponentially. Hence, the feasible life cycle options need to be selected before LCS calculation.

2.2 Research approach

As mentioned in the previous section, related works lack a mechanism to deal with environmental requirements properly and to support generating an eco-solution idea without a database including many eco-design cases. To accomplish an easy-to-use and practical solution for a real problem, our research approach was based on the following concepts:

- systematically incorporating environmental aspects into the conventional product development process and
- determination of the best mixture of life cycle options at the component level using analytic support.

It is necessary to incorporate environmental aspects appropriately into existing product development processes, because many manufacturing companies have their own product development frameworks (Kobayashi et al. 1999). In this study, QFD, which is a popular method for the early phases of product development, is integrated into an LCP methodology. From a practical viewpoint, it is desirable that life cycle options are assigned appropriately at the component level. For this purpose, a number of new analytic techniques were developed. In these techniques, the QFD data of the target product and the cost and environmental load of the components constituting the baseline product are utilized.

In this paper, the environmental load data are calculated using "Easy-LCA" (Kobayashi et al. 2002), which is based on input–output analysis (IOA). The method enables calculation of life cycle inventories, such as for CO_2, SO_x, NO_x, or BOD, and characterization of factors for impact categories, such as global warming potential (GWP), using the input data for the bill of materials (BOM) and the amount of energy use. We would have preferred using an integrated impact assessment index, such as Eco-indicator 99 (Goodkoop and Spriensma 2000), but the available eco-indicators have not been developed for use in Asian countries (an integrated impact assessment index for Asian countries is, however, currently being developed (Itsubo and Inaba 2001). Hence, like many Japanese companies, we use CO_2 emission as the main index for LCA for the present.

3 Methodology and software tool

3.1 Methodology

The LCP methodology provides a systematic procedure consisting of the following stages to establish an eco-design concept (Fig. 2). At the first stage, a plan for medium- or long-term production and a collection plan for products are clarified based on the business requirements and product lifetime. The designer creates a rough image of the material flow cycle of the target product in the product family. At the next stage, the specifications of a product and its life cycle are set. The product specifications for fulfilling customer requirements are defined using a QFD-I matrix; the customer

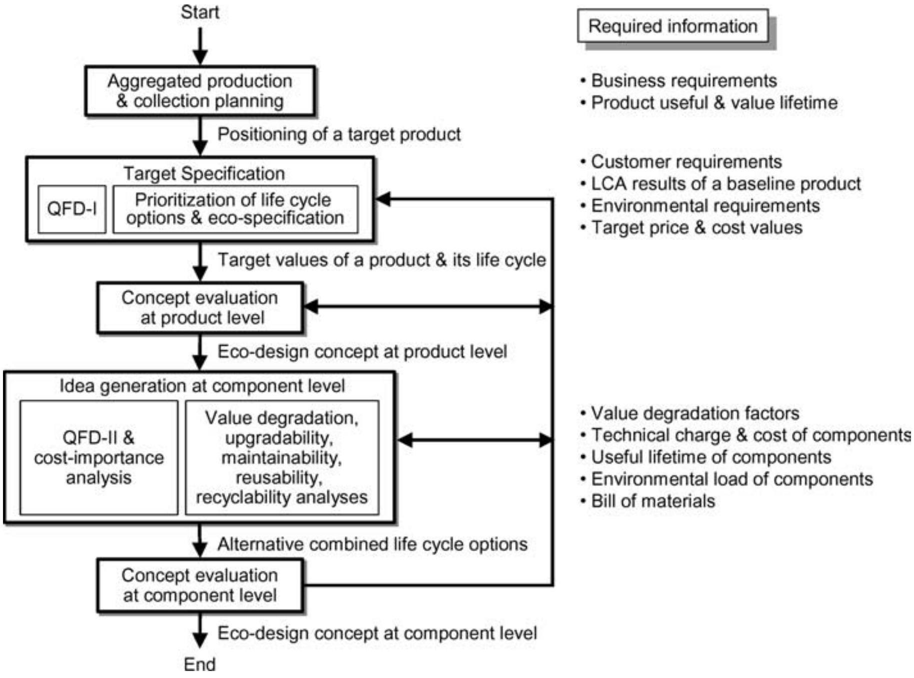


Fig. 2 Flowchart of the product LCP process

requirements are connected to the quality characteristics, including factors related to functions and performance. Meanwhile, environmental requirements are described in a specific matrix that is explained in Section 4.2.4 in detail. Reconciliation of the differences between customer requirements and environmental requirements lead to adjustment of the target values for the quality and environmental characteristics. The target price and cost values are given based on the company's methods for marketing and target costing. Then, a new eco-design concept at the product level is created and the created new product concept is evaluated from the environmental, quality, and cost aspects. Next, solution ideas at the component level are generated which is supported by various analytical methods. For example, the QFD-II matrix and cost-important analysis support customer-oriented solution ideas. Meanwhile, some new analysis methods for considering specific life cycle options, including value degradation analysis, upgradability analysis, maintainability analysis, reusability analysis, and recyclability analysis, help generate eco-solution ideas. As a result of the idea, generation process mentioned above, an eco-design concept for the target product is established at component level, and the created concept is evaluated in the same manner at product level.

3.2 Software tool

To support LCP based on the proposed methodology, a software tool "LCPlanner" was implemented as a macro program in Microsoft Excel. LCPlanner efficiently supports the processes in LCP, because it can use imported data generated by LCA software such as "Easy-LCA" (Kobayashi et al. 2002) and "QFDNavi" (Nakano et al. 2001), which supports the QFD process and cost-importance analysis.

The LCPlanner makes various matrices and analysis charts automatically using data input by a designer and imported data from LCA and QFD. Table 1 shows the features of LCPlanner. Since the designer may have access to only the data available at the product development site, this software tool is practical. In the case of novel designs in the field (not the evolution of already existing products), it is necessary to estimate the data of a baseline product based on a similar product.

Figure 3 illustrates the process and information flows for eco-design using design support tools. In the planning and conceptual design phases, the eco-design concept is determined by using LCPlanner, which utilizes the QFD data of the target product and the LCA data of the baseline product because LCA of the target product is not executed at this point yet. Here, for instance, the

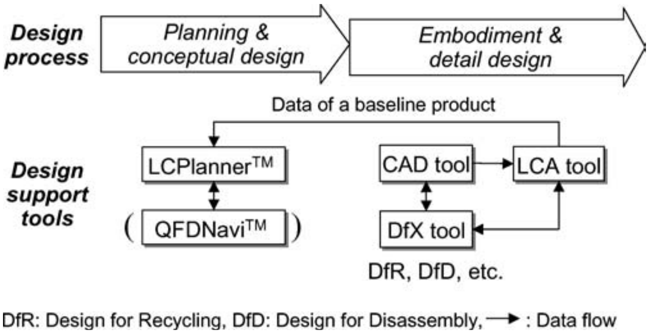


Fig. 3 Design process and design support tools

Table 1 Features of LCPlanner

Feature
Positioning of a target product by making aggregated production and collection chart
Target setting for quality aspects of a product based on QFD-I matrix
Prioritization of life cycle options at product level
Target setting for environmental aspects of a product life cycle based on eco-specification matrix
Calculation of importance of a component based on QFD-II matrix
Calculation of the influence of value degradation of a component based on value degradation analysis matrix
Analysis of the upgradability of a product
Analysis of the maintainability of a product
Analysis of the reusability of a product
Analysis of the recyclability of a product
Concept evaluation at the product or component level

QFD data include the data of quantitative quality characteristics of the target product (e.g. product weight), components composing the product, and their importance. Although the QFD data can be made by QFDNavi, it is not necessary to use this software tool because LCPlanner provides basic functions to make QFD matrixes based on a traditional method (e.g. Clausing 1993). Also, the LCA data include the data of environmental load, such as emissions to the air, water, and soil, at each life cycle phase or environmental load of each component using BOM data. The LCA process is executed by using Easy-LCA based on a framework of ISO 14040 (ISO 14040 1997). Subject to the assumption that the environmental profile of the target product is similar to that of the baseline product, various analysis techniques are applied to create a new concept for the target product using LCA and cost data of the baseline product. In these phases, design alternatives are evaluated by semiquantitative methods because detailed data are not available in the early phases of design. Next, the detailed product structure is designed using a CAD tool, and in some cases, DfX tools, such as for the design for recycle or disassembly, are applied simultaneously. Then, the environmental burden is evaluated quantitatively by an LCA tool, which utilizes data from the CAD or DfX tools. With regard to application of design support tools to the eco-design process, reusability of the design data is increased, and continuous improvement of eco-design can be supported effectively and efficiently.

4 Application example

In this section, an application example of the generational design of virtual laptop personal computers (PCs) using LCPlanner, QFDNavi and Easy-LCA is demonstrated.

4.1 Aggregated production and collection planning

Figure 4 illustrates the production and collection plan for four generations of PCs, namely, a baseline product and from version 1 to 3. It was assumed that the baseline product was already commercialized at that point. Time to market and production period of products were set based on business requirements. In this example, the product collection period was simply forecasted by shifting the production period using the smaller of the useful lifetime and the value lifetime of the baseline product. Here, the useful lifetime LU is the lifetime in the traditional sense, based on internal factors such as "product failure" and "physical degradation." It has also been referred to as the physical lifetime (Umeda and Life Cycle Design Committee 2001) or as the absolute lifetime (Kobayashi 2000). The value lifetime LV is based on external factors, such as technology infrastructure changes and attractiveness compared with competing products. Although a product itself might be

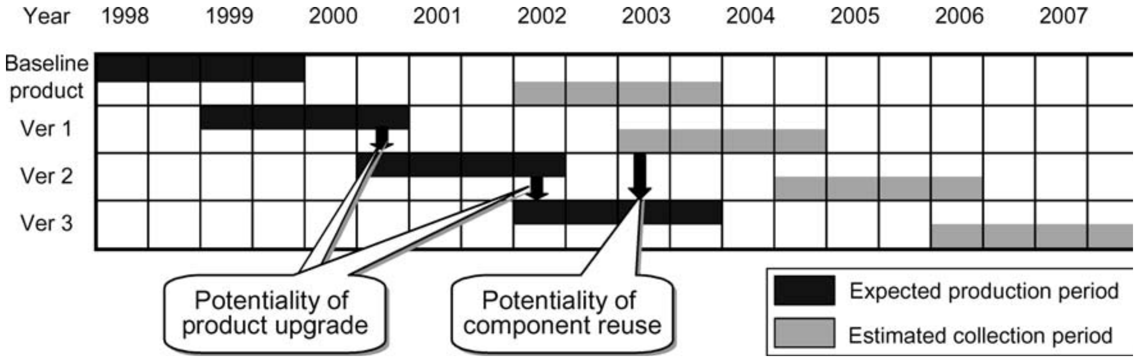


Fig. 4 Aggregate plan for production and collection of the product

working perfectly well at the end of its value lifetime, the product is thrown away because its performance, function, or appearance does not satisfy the changed customer preferences. Value lifetime is also referred to as relative lifetime in the literature (Kobayashi 2000). The product usage period is defined as the smaller of these lifetimes. In this example, LU = 7 years and LV = 4 years which were estimated based on the baseline product, and therefore the product usage period is regarded as 4 years.

4.2 Target specification

For eco-design in manufacturing companies it is essential to integrate the environmental, quality, and cost aspects. Even if a company improves the environmental aspects of a product, its competitiveness cannot be increased without sufficient attention to the quality and cost aspects.

In this study, the design requirements are treated so that the customer requirements and environmental requirements are not merged in the initial stages of the design. This is because the customer and environmental requirements come from different information sources; namely, from customers and from the company's strategy. Here, environmental requirements are determined based on information such as a corporate voluntary plan, an in-house eco-design checklist or environmental regulations. Customer requirements and environmental requirements are respectively managed using a QFD-I matrix and an eco-specification matrix described later. When developing products for green consumers, the environmental requirements desired by green consumers should also be managed using the QFD-I matrix. Furthermore, the target price and cost values, such as sales price and manufacturing cost, are given in this study. Therefore, these target values are not set by the QFD-I and eco-specification matrices.

4.2.1 QFD-I

Although it is generally important and difficult to set the customer requirements and their importance vis-à-vis the target products appropriately, well-known market research techniques such as the questionnaire method were applied and they were set as shown in Table 2. Then, the customer requirements i (= 1, ..., I), their importance p_i, the quality characteristics j (= 1, ..., J), and the relationship between i and j, α_{ij}, were described in the QFD-I matrix (Table 2). The relative importance values p^*_j were computed by the equation

$$p_j^* = \sum_{i=1}^{I} p_i \alpha_{ij} \bigg/ \sum_{i=1}^{I} \sum_{j=1}^{J} p_i \alpha_{ij} \tag{1}$$

The computed values p^*_j are utilized at the concept evaluation stage explained in Section 4.5. The target values for the quality characteristics were set, as initial values, based on the relative importance p^*_j and by comparison with a competitor's product (refer to the middle portion of Table 2).

4.2.2 Referring to the LCA result for a baseline product

By referring to the LCA result for a baseline product, it was clarified that the material acquisition, component manufacture, and product usage phases were the main causes of the environmental load (Fig. 5). Thus, it is important to reduce energy consumption in the usage phase and to select suitable life cycle options for the components and materials. Here, the environmental load was evaluated based on CO_2 emission by using Easy-LCA and was calculated under the assumption that the product usage period was 4 years and that all products collected were incinerated or put in landfills.

4.2.3 Prioritization of life cycle options

Before eco-specification, the life cycle options at the product level are prioritized based on the useful lifetime LU and value lifetime LV of the target product (Kobayashi 2000). Primary life cycle options to be mentioned for the target products can be focused on here. In the case of PCs, it was found that the focus should be on the upgrade and reuse of product or components (Fig. 6). Figure 6 shows the ideal state when the useful and value lifetimes are equal. In order to achieve the ideal state, life cycle options for extending the usage period of the product, namely, maintenance, extension of useful lifetime or upgrade, are selected. On the other hand, if the useful lifetime is longer than the value lifetime, then reuse of components might be possible under particular conditions. Moreover, if useful lifetime is more than twice as long as the value lifetime, then product reuse might also be a candidate to be considered. Whether or not a product or component is upgraded, maintained, or reused, it should ultimately be processed for material recycling, recovering energy, or final disposal. Therefore, these final life cycle options are omitted in Fig. 6.

4.2.4 Eco-specification

On the basis of the preliminary studies, eco-specification was clarified using a matrix similar to an FMEA matrix, in which environmental requirements throughout the product life cycle were described comprehensively and classified into MUST or WANT requirements. MUST requirements are obligatory, such as legal restriction or a company's commitment, while WANT requirements are the issues that it is desirable to address based on the environmental evaluation such as LCA. This classification of environmental requirements affects the concept evaluation stage described later. Because MUST

Table 2 Example of QFD-I matrix

Customer requirements/	Importance p_i	Quality characteristics j							
		Size of display (in.)	CPU clock frequency (MHz)	Average energy consumption (W)	Memory capcity (MB)	Thickness (mm)	Product wight (kg)	Hard disk drive capcity (GB)	Vertical range of key movement (mm)
Screen quality	9	9							
Processing speed	9		9	3					
Portability	3	3				3	3		
Long value	3		3		9			3	
Comfortable operation	1	3	1	1		1			3
Sum		93	91	28	27	10	9	9	3
Relative importance p^*j		34%	34%	10%	10%	4%	3%	3%	1%
Spec of baseline product		14	700	52	128	45	3	4	2.7
Target values (initial)	Ver 1	14	800	55	128	43	3	6	2.7
	Ver 2	14	900	60	256	43	3	20	2.7
	Ver 3	15	1000	65	512	43	3.3	40	2.7
Related env. WANT req.				+			+		
Target values after compromise	Ver 1			50			2.7		
	Ver 2			55			2.7		
	Ver 3			60			3		

Relationship: strong concern, 9; concern, 3; weak concern, 1

requirements are not reflected in the weight of concept evaluation characteristics, but only WANT requirements are reflected in that, the designer has to classify the environmental requirements into the MUST or WANT category according to whether or not a particular requirement is to be taken into account at the concept evaluation stage. In the example of PCs, the MUST requirements were “material recycling,” etc. based on Japanese domestic recycling law. The WANT issues included “use of recycled materials,” “weight-saving,” “power management,” and “upgradability” based on the company’s eco-design checklist. The environmental characteristics were set for each environmental requirement. WANT characteristics were prioritized using the environmental priority number (EPN) (Lindahl 1999; Kobayashi 2001). In this study, the EPN r_m of environmental WANT characteristics m ($=1, \ldots, M$) is defined as follows:

$$r_m = \prod_{t=1}^{3} r_{mt}, \tag{2}$$

where $t=1$ is the company policy, $t=2$ is the market impact, and $t=3$ is the environmental impact.

Each of these factors was assigned a discrete number between one and three in this case. Based on the EPN values and benchmarking between the company’s own baseline product and the competitor’s product, the tar-

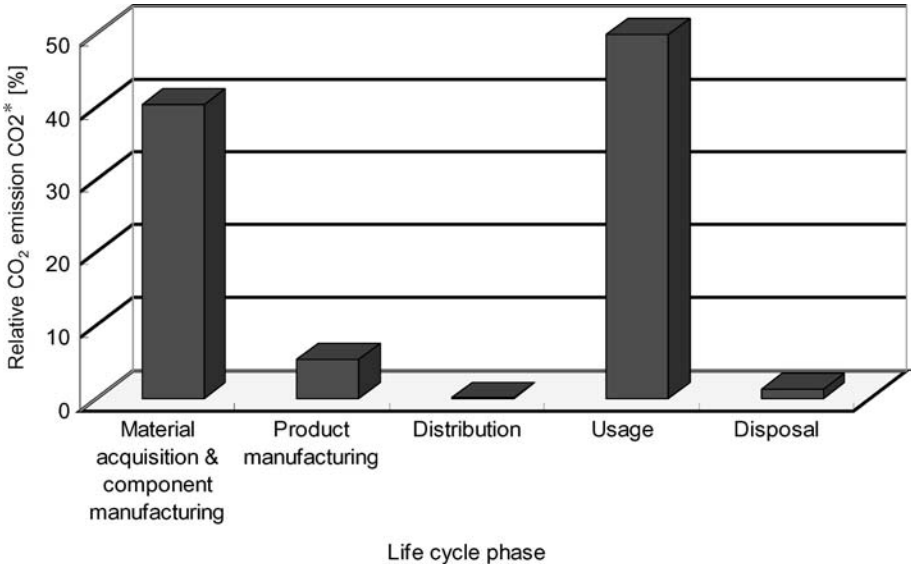


Fig. 5 Life cycle inventory of baseline product

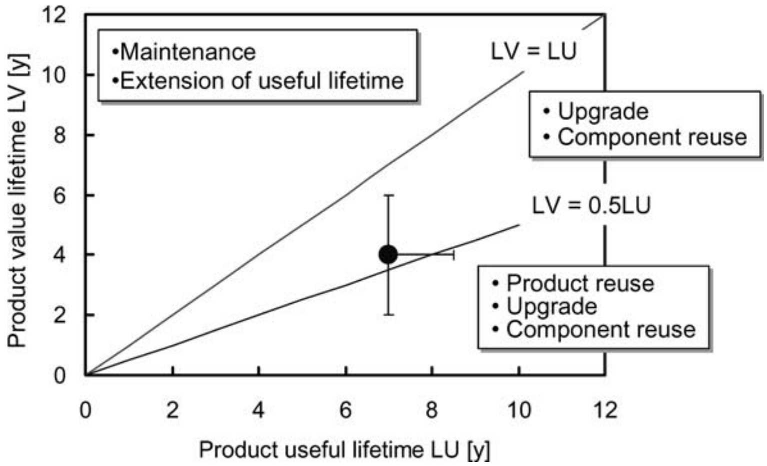


Fig. 6 Prioritization of life cycle options at the product level

get value of each environmental characteristic was set. If the EPN value of an environmental characteristic is relatively higher, then it is desirable to improve its spec compared with the baseline product. Here, a general target setting method based on benchmarking (e.g. Clausing 1993) can also be applied. Of course, target values of MUST requirement have to satisfy regulation or a commitment value. Table 3 shows a portion of the eco-specification matrix.

4.2.5 *Re-evaluation of the target value*

At this stage, quality characteristics related to the environmental WANT requirements were marked (in the bottom part of Table 2). As a result, the target values of the quality or environmental characteristics might be modified as necessary. In Table 2, the target values for maximum energy consumption and product weight were modified due to the effects of the environmental WANT requirements.

4.3 Concept evaluation at the product level

At this point, a design concept at the product level is to be evaluated. A design concept at the product level implies one solution idea or a combination of solution ideas expressing a basic concept of the target product. In the design of laptop PCs, it can, for example, be expressed as "the slimmest PC in the world by using titanium." The application of TRIZ is sometimes useful for creation of a novel product concept (Leon-Rovira and Aguayo 1998). In the case of design for improvement of the baseline product, the design concept at the product level might be almost the same as that for the baseline

Table 3 Portion of eco-specification matrix

Life cycle phase	Inventory category	Environmental requirements	MUST / WANT	Envronmental characteristics	Prioritizing				Spec of baseline product	Target values		
					Company policy (t=1)	Market impact (t=2)	Environmental impact (t=3)	EPN r_m		Ver1	Ver2	Ver3
Material acquisition	Material	Use of recycled materials	W	Ratio of used recycled plastics [%]	3	1	2	6	0	30	30	50
		Weight saving	W	Product weight [kg]	3	3	2	18	3.0	2.7	2.7	3.0
	Energy											
	Hazardous substance	Use of lead-free solder	W	Quantity of lead [g]	3	2	3	18	15	15	0	0
	…	…	…	…	…	…	…	…		…	…	…
	…	…	…	…	…	…	…	…		…	…	…
	…	…	…	…	…	…	…	…		…	…	…
End of life	Solid waste	Upgrade	W	Upgradability ratio under the acceptable charge [%]	2	3	3	18	0	10	10	10
		Component reuse	W	Reusability ratio [%]	3	2	3	18	0	10	20	20
		Material recycling	M	Recyclable ratio [%]	-	-	-	-	50	50	60	70
	Emission to air											
	Emission to water											

product, and thus this concept evaluation process can be omitted. Since the example in this paper also concerns the improvement design of PC, concept creation and concept evaluation at the product level were omitted. Here, the way in which the concept evaluation method is applied at product level is the same as that at component level described in Section 4.5.

4.4 Idea generation at the component level

In this section, various charts to consider relevancy between components and life cycle options, such as upgrade, maintenance, reuse and recycle, are generated by LCPlanner. For generating the analysis charts, it is necessary to prepare component data of the baseline and the target products. The former implies such items as manufacturing and service cost, useful lifetime, BOM and CO_2 emission until the component manufacturing stage. Here, data of BOM and CO_2 emission are available from LCA data of the baseline product. On the other hand, the latter implies such items as importance of quality characteristics, influence of product value degradation factor that is described in Section 4.4.2, and recyclability of composed materials. Here, data of importance of quality characteristics are taken over from the QFD-I matrix described in Section 4.2.1. In LCPlanner, input data are converted to an appropriate format automatically if necessary, and then each component is plotted in various life cycle option analysis charts consisting of two specific axes that indicate environmental, quality, or cost viewpoint. Each chart, which is described in the following sections, is divided into some areas that are associated with specific design strategies. Hence, a designer can be inspired to generate an eco-solution idea at the component level by looking at those charts.

4.4.1 QFD-II and cost-importance analysis

A QFD-II matrix, which maps the quality characteristics j against the components k $(=1, ..., K)$ constituting the product, is constructed. As in the case of the QFD-I matrix, the relationship α_{jk} was described in the QFD-II matrix and then the relative importance values p^*_k of the target product were computed by

$$p_k^* = \sum_{j=1}^{J} p_j^* \alpha_{jk} \bigg/ \sum_{j=1}^{J} \sum_{k=1}^{K} p_j^* \alpha_{jk} \tag{3}$$

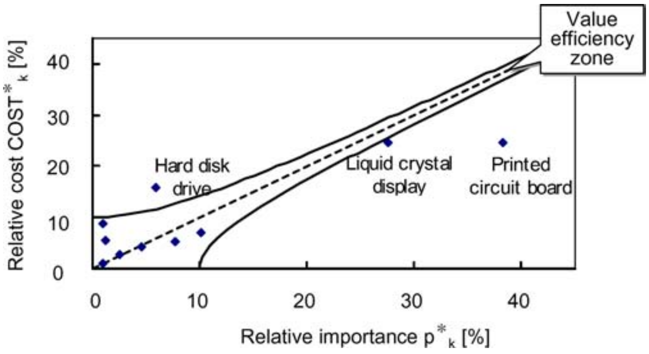


Fig. 7 Example of cost-importance analysis

In order to generate customer-oriented solution ideas, cost-importance analysis (Beiter and Ishii 1999), which is a value engineering technique, was applied. In cost-importance analysis, it is desirable that there is close correlation between the relative cost and relative importance of every component; that is, every component should fall within the value efficiency zone. Here, the relative cost COST^*_k of the baseline product was calculated by

$$\mathrm{COST}_k^* = \mathrm{COST}_k \bigg/ \sum_{k=1}^{K} \mathrm{COST}_k \tag{4}$$

Components that represent small percentages of the total cost or importance are not critical as redesign targets compared with components that have a large cost or are important contributors. For this reason, the two parabolic boundaries allow wider distribution from the diagonal at low cost and low importance magnitudes. Components that are above the boundary should be examined for potential cost reduction. Based on Fig. 7, the solution idea "use of hard disk drive designed for desktop PC" was generated for cost reduction.

4.4.2 Value degradation analysis

Table 4 demonstrates an example of the matrix for value degradation analysis. Influences of value degradation of components are calculated, based on the factors shortening the product value lifetime such as appearance and trendiness, at the component level using a disposal cause analysis matrix (Umeda and Tomiyama 2000). Here, the relative value degradation influence p^*_k of the target product is expressed as

$$q_k^* = \sum_{x=1}^{X} \sum_{j=1}^{J} q_x \alpha_{xj} \alpha_{jk} \bigg/ \sum_{x=1}^{X} \sum_{j=1}^{J} \sum_{k=1}^{K} q_x \alpha_{xj} \alpha_{jk}, \tag{5}$$

where x $(=1, ..., X)$ is value degradation factor, q_x is their influence, and α_{xj} is the relationship between x and j. The results shown in Table 4 indicate that the printed circuit board, the liquid crystal display, and the hard disk drive have a large relative value degradation influence.

4.4.3 Upgradability analysis

Figure 8 illustrates an example of the upgradability analysis of components using the relative importance based on QFD-II and the relative value degradation

Table 4 Example of value degradation analysis

Value degradation factors x	Influence q_x	Quality characteristics j								
		Size of display [inch]	CPU clock frequency [MHz]	Average energy consumption [W]	Memory capacity [M]	Thickness (mm)	Product weight (g)	Hard disk drive capacity (GB)	Vertical range of key movement (mm)	
Capacity or size	3	9						9		
Appearance or trendiness	1					3	9			
Function or performance progress	9		9	1	3					
	Sum	27	81	9	27	3	9	27	0	
	Relative influence q_j^*	14.8%	44.3%	4.9%	14.8%	1.6%	4.9%	14.8%	0.0%	
	Components k									Relative influence q_k^*
	Printed circuit board		9	9	9	9	3			49.7%
	Liquid crystal display	9		3		3	9			16.2%
	AC adapter			3			1			1.6%
	Base cover	3			3	1	1			7.8%
	Keyboard cover	3				1				3.8%
	Hard disk drive			3		3	3	9		13.7%
	Battery module					9	9			4.8%
	Keyboard					1	1		9	0.5%
	Speaker			1		1				0.5%
	CD-ROM drive					1	3			1.3%

Relationship: strong concern, 9; concern, 3;weak convern, 1

influence based on value degradation analysis. This chart shows components whose exchange as part of an upgrade is not feasible because of the upgrading costs or functional reasons. If a component is a large relative value degradation influence contributor, then it should be designed as an upgradable component for extension of the product value lifetime. Here, note that customers may not accept upgrading service for a component that has a large relative value degradation influence but small relative importance, because their willingness to pay for upgrading services is based on the improvement level relative to their initial requirements. The boundary lines are drawn based on the experience. Figure 8 shows that the solution idea "upgradable design for printed circuit

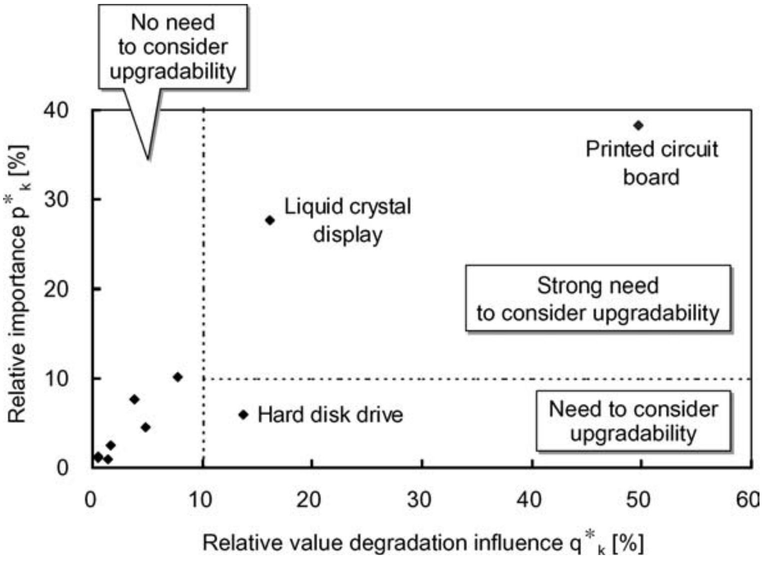


Fig. 8 Example of upgradability analysis

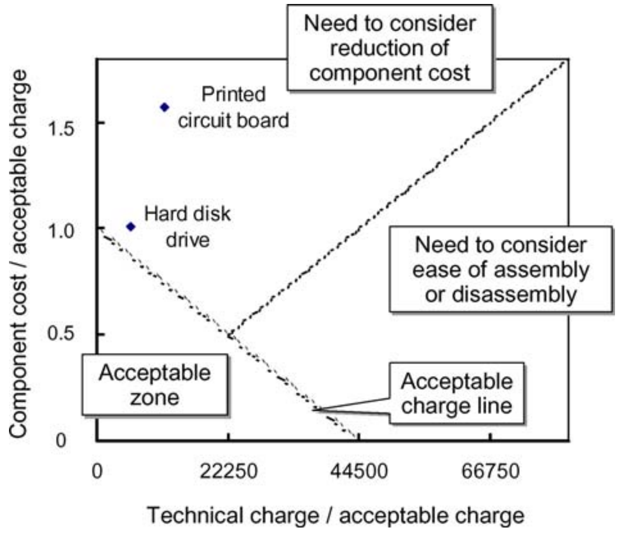


Fig. 9 Example of cost analysis for component upgrade

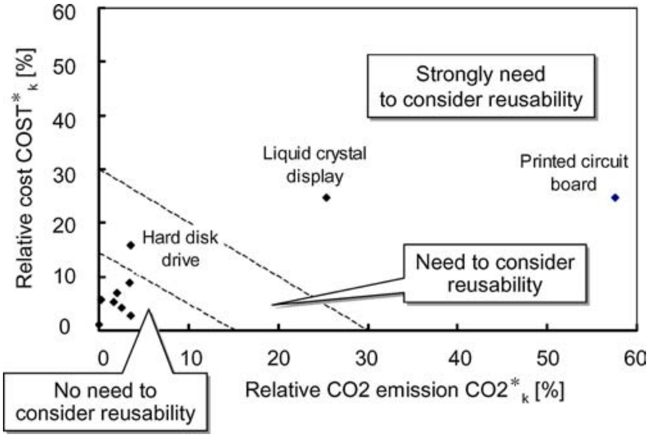


Fig. 10 Example of cost-CO_2 emission analysis

board and liquid crystal display" should be positively considered in order to extend the value lifetime of the product. Although "upgradable design of hard disk drive" is moderately important, there is a functional relation between the hard disk drive and printed circuit board, suggesting this solution idea.

An example of cost analysis for functionally upgradable components that cannot be upgraded only for cost reasons is shown in Fig. 9. Here, an acceptable charge implies the upper limit of the amount the customer is willing to pay to upgrade the product in use and not replace the whole product. The acceptable charge was set based on the result of marketing research. Although the chart indicates that the printed circuit board should be improved, its manufacturing cost is fixed. Then this component was considered at a smaller part level, such as the CPU, AC/DC converter, memory chips, and I/O circuit. Consequently, the idea for upgrading only the CPU and the memories, which are the critical parts on the printed circuit board, was generated. The component cost of the hard disk drive would be reduced by the solution idea in Section 4.4.2, and therefore other solution ideas were not generated here.

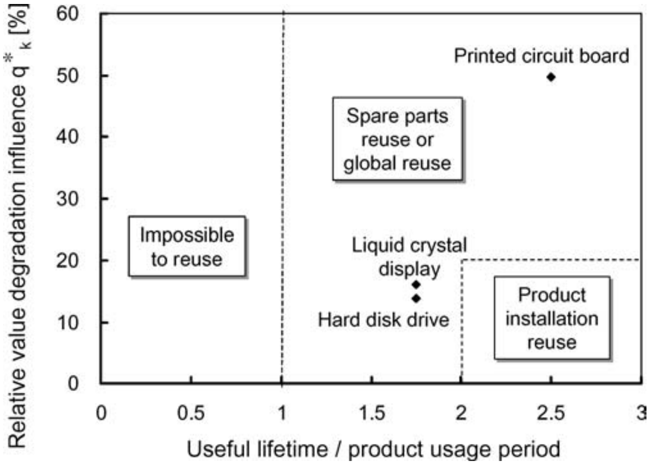


Fig. 11 Example of reusability analysis

4.4.4 *Reusability analysis*

The reusability of a component is considered from viewpoints of cost, environmental merit, and remaining value, and useful lifetime of a component. In Fig. 10, it is pointed out that the liquid crystal display and the printed circuit board should be considered for component reuse, because they have a large influence both on the cost and the environmental load for manufacturing. Here, the relative CO_2 emission CO^{*}_{2k} of the baseline product is given by

$$\mathrm{CO}^{*}_{2k} = \mathrm{CO}_{2k} \bigg/ \sum_{k=1}^{K} \mathrm{CO}_{2k}, \tag{6}$$

where CO_{2k} is the amount of CO_2 emission of component k from raw material extraction to component manufacturing. Since this analysis is based on the assumption that the environmental load during the cleaning or testing processes for component reuse can be ignored, it is necessary to consider the environmental load when the assumption does not hold. In addition, another environmental index may be adopted as an alternative to CO_2 emission if possible.

After clarifying the candidates for component reuse, they were evaluated from the value degradation and durability perspectives. Here, component reuse is classified into product installation reuse, spare parts reuse, and global reuse (Umeda and Life Cycle Design > Committee 2001). Product installation reuse implies that reused components are utilized in a new or a remanufactured product. For product installation reuse, the component's remaining useful lifetime must correspond to more than one product usage period. Spare parts reuse means that reused components are

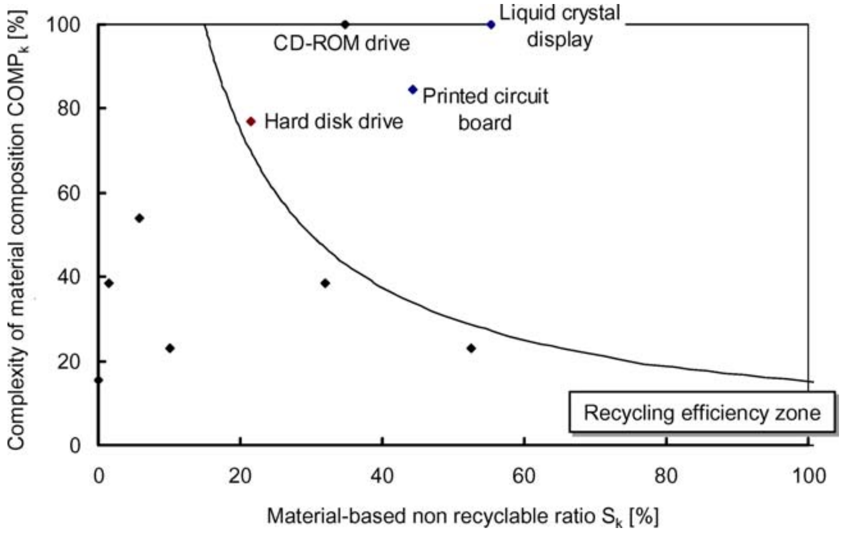


Fig. 12 Example of recyclability analysis

utilized as spare parts in the maintenance process. Global reuse implies the reuse of a component in another type of product, or reuse of a product in another market. There is a potential for spare parts reuse and global reuse when the useful lifetime of a component is longer than the product usage period. Here, the product usage period is estimated as the smaller of the useful lifetime and value lifetime of the product as described in Section 4.1.

Figure 11 shows that the printed circuit board, the liquid crystal display, and the hard disk drive are applicable for reuse as spare parts or global reuse parts. In this example, the idea of "reusing these components as spare parts" was selected.

4.4.5 Recyclability analysis

Using the BOM data of the baseline product and the recyclable material data of the current recycle treatment plant, a recyclability analysis chart was drawn. The concept of the chart is based on the ideas of Lee and Ishii (1997) and Kobayashi et al. (1999). Here, the complexity of material composition COMX_k and the material-based non-recyclable ratio S_k are defined by

$$\mathrm{COMX}_k = \mathrm{NUM}_k / \max_{k=1}^{K}\{\mathrm{NUM}_k\}, \tag{7}$$

$$S_k = 1 - \sum_{y=1}^{Y} MASS_{ky}/MASS_k \tag{8}$$

where NUM_k is the number of materials of component k, and MASS_{ky} is mass of recyclable material y included in component k.

Figure 12 indicates that the liquid crystal display, CD-ROM drive, printed circuit board, and hard disk drive do not fall into the recycling efficiency zone. This means that sufficient material recycling cannot be expected even by making efforts to separate components into individual materials. In this case, the solution ideas "design for easy to separate of liquid crystal display, CD-ROM drive, and hard disk drive" and "use of halogen-free and stibium-free printed circuit board" were generated.

4.5 Concept evaluation at component level

A design concept at the component level implies an appropriate combination of solution ideas at component

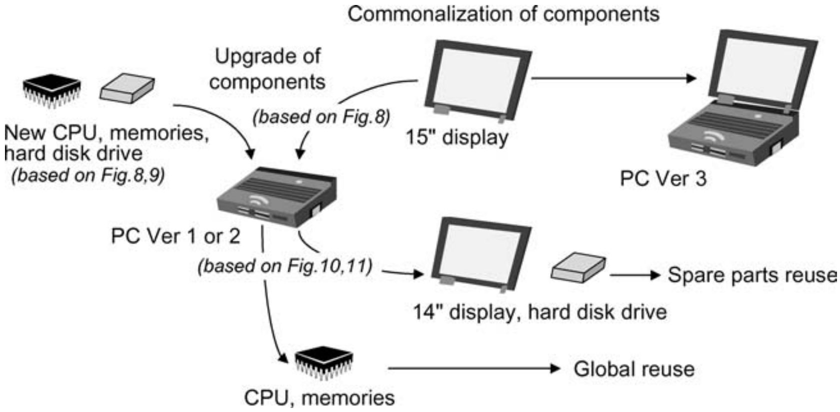


Fig. 13 Generated key eco-solution ideas

Table 5 An Example of concept evaluation matrix

Evaluation of Solution ideas (Cost evaluation)
+2 Strong improvement (Cost reduction exceeding 10% of product price)
+1 Improvement (Cost Reduction of 5-10% of product price)
Almost same as the baseline product
-1 Degradation (Cost increase of 5-10% of product price)
-2 Strong degradation (Cost increase exceeding 10% of product price)

				Solution ideas *n*																			
				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
				Use of hard disk drive designed for desktop PC	Utilization of recycled plastics in base cover	Use of plastics including halogen-free incombustible materials	Use of lead-free solder	Adoption of new energy saving utility system	Introduction of on-line manual	Upgradable design of liquid crystal display by commonalization	Use of 15-inch liquid crystal display	Upgradable design of CPU	Upgradable design of memories	Upgradable design of hard disk drive	Use of high-performance CPU	Spare parts reuse of liquid crystal display	Spare parts reuse of CPU	Spare parts reuse of memories	Spare parts reuse of hard disk drive	Use of halogen-free & stibium-free printed circuit boards	Design of easy-to-separate liquid crystal display	Design of easy-to-separate CD-ROM drive	Design of easy-to-separate hard disk drive
Deisgn concepts			Ver 1 (Variant 1)			X		X	X	X		X	X	X				X					
			Ver 1 (Variant 2)	X				X							X								
			Ver 2 (Variant 1)			X		X	X	X		X	X	X		X	X	X	X	X		X	X
			Ver 2 (Variant 2)	X				X			X				X			X	X				
			Ver 3	X	X	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X
Aspect	WANT/ MUST	Evaluation characteristics	Weight[%]																				
Quality	WANT	Size of display [inch]	34.4							+2	+2												
Quality	WANT	CPU clock frequency [MHz]	33.7									+2			+2								
Quality	WANT	Ave. energy consumption [W]	10.4					+2		-1		-1			-1								
Quality	WANT	Memory capacity [M]	10.0										+2										
Quality	WANT	Thickness [mm]	3.7																				
Quality	WANT	Product weight [g]	3.3							-1	-1												
Quality	WANT	Hard disk drive capacity [GB]	3.3											+2									
Quality	WANT	Vertical range of key movement [mm]	1.1																				
Environment	WANT	Ratio of used recyclable plastics [%]	4.7		+2																		
Environment	WANT	Product weight [g]	14.0	-1																			
Environment	WANT	Quantity of lead [g]	14.0				+2																
Environment	MUST	Quantity of cadmium [g]																					
Environment	MUST	Quantity of plastics including particular bromic incombustible materials [g]				+2																	
Environment	WANT	Weight of manual [g]	9.3						+2														
Environment	WANT	Weight of product package [g]	9.3																				
Environment	MUST	Quantity of chromium in ink [g]																					
Environment	WANT	Energy consumption efficiency [-]	20.9					+2		-1		-1											
Environment	WANT	Upgradability ratio under the acceptable charge [%]	14.0							+2		+2	+1	+1									
Environment	WANT	Reusability ratio [%]	14.0													+2	+1	+1	+1				
Environment	MUST	Recyclability ratio [%]																		+1			
Cost (Company)	WANT	Material procurement cost [yen]	20.0	+1	-1	-1					-1				-1								
Cost (Company)	WANT	Manufacturing cost [yen]	20.0																				
Cost (Company)	WANT	Distribution/Sales cost [yen]	20.0																				
Cost (Company)	WANT	Upgrade/Maintainance cost [yen]	20.0							-1		-1	-1	-1									
Cost (Company)	WANT	Collection/Recycling/Disposal cost [yen]	20.0																	+1	+1	+1	+1
Cost (Customer)	WANT	Product price [yen]	25.0																				
Cost (Customer)	WANT	Operational cost [yen]	25.0					+1															
Cost (Customer)	WANT	Upgrade/Maintainance charge [yen]	25.0							-1		-1	-1	-1		+1	+1	+1	+1				
Cost (Customer)	WANT	Recycling charge [yen]	25.0																				

level. Here, an eco-design concept was constructed by aggregating the solution ideas generated in the previous steps. An overview of the ideas for upgrade and reuse, which are the keys in this example, is illustrated in Fig. 13.

All the solution ideas were described in a concept evaluation matrix (Table 5). In this step, the solution idea including the life cycle options of a component was assessed using the evaluation score e, which takes integral values from -2 (strongly degraded) to $+2$ (strongly improved) based on a baseline product.

The total evaluation score E of quality, environment, company cost, and customer cost aspects was calculated by

$$E_{\text{Quality}} = \sum_{j=1}^{J} \sum_{n=1}^{N} p_j^* e_{jn}, \tag{9}$$

$$E_{\text{Environment}} = \sum_{m=1}^{M} \sum_{n=1}^{N} r_m^* e_{mn}, \tag{10}$$

$$E_{\text{Company\_cost}} = \frac{1}{A} \sum_{a=1}^{A} \sum_{n=1}^{N} e_{an}, \tag{11}$$

$$E_{\text{Customer\_cost}} = \frac{1}{B} \sum_{b=1}^{B} \sum_{n=1}^{N} e_{bn}, \tag{12}$$

where n is a solution idea for a design concept ($n=1$, ..., N), $r_m^* = \prod_{t=1}^{3} r_{mt} / \sum_{m=1}^{M} \prod_{t=1}^{3} r_{mt}$, a represents the company cost characteristics ($a=1$, ..., A), and b represents the customer cost characteristics ($b=1$, ..., B). Because MUST characteristics are design constraints, a solution idea is not evaluated based on the MUST characteristics. However, whether the idea satisfies the MUST characteristics or not is checked. Equations 9, 10, 11, and 12 are useful when it is assumed that the positive or negative effects of conflicting solution ideas offset each other.

By combining appropriate solution ideas, it is possible to establish a design concept, which is balanced with respect to the quality, cost, and environmental aspects. Figure 14 shows three types of product evolution strat-

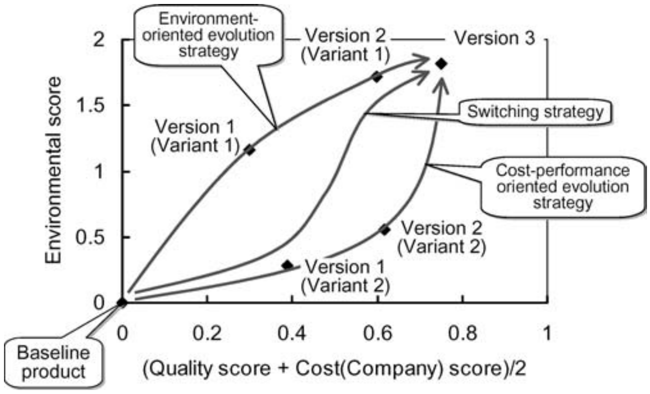


Fig. 14 Result of concept evaluation at the component level

egies, namely an environment-oriented evolution strategy, a cost-performance-oriented evolution strategy, and a switching strategy, using different combinations of solution ideas. Finally, the eco-design concepts according to product version 1–3 were determined on the basis of the preferences of decision-makers. Consequently, a strategic evolution plan of eco-design concepts was efficiently established.

5 Discussion

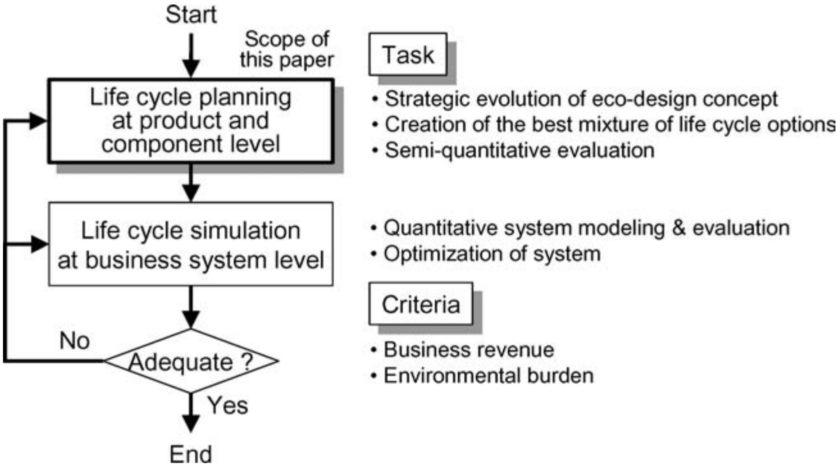
The presented LCP methodology is a new approach compared with the other design methodologies for multigenerational product planning (e.g. Martin and Ishii 2000), because LCP supports plan design options based on life cycle options for eco-design as opposed to the other methodologies, which support design a product platform for minimizing the cost of product development while fulfilling customer needs.

The presented LCP methodology is applicable to most generic assembly products that can be supported by QFD. In the conventional product development process, QFD and LCA have been utilized independently from each other. On the other hand, this work makes good use of both QFD and LCA data including BOM, enabling life cycle options at the component level to be considered. However, only a portion of the LCA data is utilized currently; namely, the data for the raw material and component manufacturing phases. In fact, the primary contributor to a consumer product's environmental burden is the usage phase (e.g. see Fig. 5). On the basis of this tendency, an interdisciplinary approach focused on the product usage phase has been reported (Oberender et al. 2001). However, a systematic methodology to support eco-usage has not yet been developed. Thus, future LCP research will include the development of a method of design for the usage phase using LCA data and incorporation of the method into the LCP process.

This study is focused on the evaluation of the eco-design concept from the quality, cost, and environmental viewpoints. In the evaluation step, the evaluation is executed based only on the WANT requirements in order to consider the company's market strategy. Since the presented concept evaluation method is semiquantitative, it can easily be applied to real projects. However, the actual environmental burden and revenue from a business system depends on the production/collection quantities and timelines for the product. Moreover, in an environmentally conscious business system, such as the Inverse Manufacturing business system, it is important to implement effective life cycle options, such as closed-loop recycling, component reuse, and upgrading of products. These life cycle options make sense under the product family concept and were illustrated in the application example (see Fig. 13).

To overcome the above issues, a framework of LCP at the business system level is proposed as shown in Fig. 15. The model uses recursive cycles in which eco-design concepts are planned at the product and component levels, and their validities are evaluated quantitatively by LCS techniques at the business system level. If the evaluation result is not adequate, then the production/collection plans or eco-design concepts includ-

Fig. 15 Framework of LCP at business system level



ing life cycle options at the product/component level are modified. This paper focuses on the LCP at the product and component levels. It is considered that the LCP at the product and component levels is valuable for executing the LCS efficiently under feasible conditions. One of the future topics for research is the systematization of a methodology for establishing an Inverse Manufacturing system based on the proposed framework.

6 Conclusions

In this paper, a product LCP methodology for incorporating environmental aspects into early phases of the design process was presented. The LCP methodology is a new approach for planning eco-product evolution based on life cycle options. The major accomplishments of this study are summarized below:

- A systematic process to set target specifications for the product and its life cycle and to establish an eco-design concept was proposed.
- The eco-specification matrix was found to be useful for comprehensively integrating the environmental and life cycle viewpoints.
- New analysis charts were useful for selecting the effective life cycle options at the component level.
- Trade-offs between environment, quality, and cost could be analyzed by a semi-quantitative concept evaluation method.
- The usefulness of the LCP methodology was demonstrated through the application examples adopted by the design support tool.

The presented methodology and tool are being applied to real product development projects in Toshiba Group companies. Based on the experiences in real projects, the presented approach is considered to be one of the most promising and practical approaches for manufacturing industry, because of its comprehensive perspective, usability, time efficiency, and strategic framework.

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