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Paper:

Decision Support Method for Upgrade Cycle Planning and Product Architecture Design of an Upgradable Product

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An upgradable product is a product in which the valuable life is extended by exchanging or adding components. An upgradable product is both environmentally and economically advantageous compared with products requiring replacement because its functions can be improved by adding only a few components. Therefore, the design and sale of upgradable products represent effective methods for attaining a sustainable society. Previous studies of upgradable product design methods have assumed that products have a modular architecture, in which all components are functionally independent. However, actual products have both integral architectures and modular architectures. Achieving high-performance products through component optimization is easier with an integral architecture than with a modular architecture. However, the integral architecture makes it difficult to disassemble and replace individual components. It is difficult to achieve high levels of performance in products with modular architecture, but it is easy to disassemble and replace components. Therefore, upgradable product design must determine the most appropriate product architecture. Hence, this paper focuses on the product architecture of upgradable products and proposes a decision support method that yields the appropriate combination of product architecture and upgrade cycle. In addition, the authors propose evaluation models for the environmental load, cost, and customer dissatisfaction, as well as a comprehensive evaluation index based on these models. The overall model, which gives the evaluation index, considers the differences in the evaluated values resulting from differences in the product architecture and the number of upgrades. The proposed method was applied to a motherboard module design problem for a laptop computer. The results of this case study confirm that the proposed method successfully supports the designer during upgradable product design by deriving the most suitable combination from a set of product architectures and upgrade cycle candidates.

Keywords: product architecture, upgradable product, upgrade planning, upgradable product design, customer dissatisfaction

1. Introduction

To realize a sustainable society, a single product must continue to be used for a long time [1]. However, because products become obsolete over time, even if they are durable and long-lived, consumers may dispose of or replace them before they break down. Therefore, it is necessary to develop products for which periodic upgrades of selected components can prevent obsolescence, delay the increase in dissatisfaction accumulated by the product, and suppress consumer disposal behavior. However, proper maintenance and management of a realized upgradable product are required to ensure that the upgradability does not go to waste. Therefore, an upgradable product service system (Up-PSS) [2] that integrates upgradable products and their maintenance services is necessary.

Furthermore, to generalize upgradable products, such products must be designed with a structure that allows easy upgrading. This study proposes a method to derive an appropriate architecture for upgradable products from an upgrade planning perspective. The proposed method evaluates the architecture and upgrade cycle of upgradable products in terms of environmental load, cost, and customer dissatisfaction. Furthermore, the overall evaluation model considers the differences between integral and modular architectures. The proposed method derives all combinations of architectures and upgrade cycles from the set of product architecture candidates and upgrade cycle candidates. Subsequently, this method assigns a preference to each combination based on the three aforementioned viewpoints. The designer then selects an appropriate combination of architecture and upgrade cycle from the results, with consideration of the business strategy of the company.

This paper outlines the design process for a method to support upgradable product design that uses an evaluation model to determine the most suitable product architec-

Table 1. Details of the variables in this paper.

Detailed variable descriptions		
c	:	Subscript of component
CD_c	:	Disposal or recycling cost for a component
CDS_{RSP}	:	Cumulative dissatisfaction function of RSP
CI_c	:	Production cost of an interface component
Cn_c	:	Contribution of component to the RSP (receiver state parameter)
Co_c	:	Component
CP_c	:	Production cost of a component
CPD_V	:	Cumulative disposal distribution by value cause
$CPD_{V,c}$	:	Cumulative disposal distribution by value cause of a component
C_{Total}	:	Life cycle cost
CU_c	:	Cost in the component usage stage
$C_{Uth\,gen.}$	:	Cost in U-th generation
d	:	Subscript of customer demand
De_d	:	Customer demand
DS_c	:	Dissatisfaction function of component
DS_{RSP}	:	Dissatisfaction function of RSP
ED_c	:	Environmental load of component disposal
EI_c	:	Environmental load of interface component production
EP_c	:	Environmental load of component production
E_{Total}	:	Life cycle environmental load
EU_c	:	Environmental load in the component usage stage
$E_{Uth\,gen.}$	:	Environmental load in U-th generation ($U \geq 2$)
f	:	Subscript of production function
Fu_f	:	Production function
Nc	:	Number of components
Nd	:	Number of demands
Nf	:	Number of functions
Nu	:	Number of upgrades
Nuc	:	Number of upgraded components
PD_F	:	Product disposal distribution by failure cause
PD_P	:	Product disposal distribution
PD_V	:	Product disposal distribution by value cause
RaC_c	:	Reduction rate of cost due to product architecture
RaE_c	:	Reduction rate of environmental load due to product architecture
$RtC_{c,U}$	:	Reduction rate of cost due to technical improvement in U-th generation
$RtE_{c,U}$	:	Reduction rate of environmental load due to technical improvement in U-th generation
UAI	:	Upgradable architecture index
UC	:	Upgrade cycle (i.e., usage time per generation)
w_{Dd}	:	Importance of demand d
w_{DdFf}	:	Importance of function f to demand d
w_{FfCc}	:	Importance of component c to function f

ture and upgrade cycle. The applicability of the proposed method is confirmed by applying it to the design problem of a laptop computer motherboard module. **Table 1** lists the variables and symbols used in this paper.

2. Related Works

2.1. Product Architecture (Modular) Design

Product architecture includes both integral architecture and modular architecture. The actual product is a complex combination of integral and modular architectures. In products with an integral architecture, one functional element is composed of multiple components, and one component is related to multiple functional elements. Thus, maximum optimization between components and high levels of performance can be achieved. However, the interaction between components is poorly defined, and individual components influence each other in a complicated manner [3]. As a result, it is very difficult to remove, replace, or upgrade some components. In contrast, in products with a modular architecture, component integration is limited, and it is difficult to design a high-performance product. However, the relationships among the components are well-defined; thus, each component is functionally independent and can be easily replaced.

In previous studies on product architecture design, many methods have been proposed that aim to reduce the development lead time and to share modules in product family design [4, 5]. In addition, the design structure matrix (DSM) [6] tool has been widely utilized to realize these methods [7]. Zheng et al. [8] proposed a modular design method that considers the product life cycle based on maintenance. This method evaluates the module design from the viewpoint of maintenance cost, maintenance cycle, and system availability. Shoval et al. [9] proposed a model that determines the change and additional cost of system clustering through the life cycle of the system using a 3D-DSM, which is a combination of a function DSM and an ility DSM. Tseng et al. [10] modularized components from the perspective of component pollution and evaluated the design using a material cost analysis. Kim et al. [11] proposed a modularization method from the viewpoint of product recovery and evaluated the design considering the complexity of the interfaces between components and the similarities among both the materials and physical lifespans. Inoue et al. [12] proposed a modularization concept from the viewpoint of supply chain management (SCM) [13].

These studies have thoroughly explored the concept of modular design based on product life cycle, wherein the design is evaluated mostly from a cost perspective. However, these methods have not sufficiently taken into account the upgrade cycle and the number of upgrades.

2.2. Upgradable Product and Service Design

An upgradable product is a product in which the valuable life is extended by renewing the value of the product, by replacing or adding certain components when they become obsolete over time. Among the previous studies on design methods for upgradable products, a method [14] has been proposed for designing products that can simultaneously achieve low environmental impact, low price, and high profit compared with conventional replacement-type products. In addition, the study confirmed that the product created through this method contributed positively to a sustainable social system.

Watanabe et al. [15] proposed a design method for upgrade planning based on a database of components predicted to be available in the future. This method derives an upgrade plan (including renewal time and replacement components) by predicting the specifications that consumers will require in the future and the time when products currently owned by customers will become obsolete.

Pialot et al. [2] conducted a survey on the reasons for disposal of certain home appliances (vacuum cleaners and espresso machines) to identify potential upgrade needs. The results revealed that more than 50% of the products had been replaced, even though they were still functional. The reason for disposal was an accumulation of dissatisfaction, and it was confirmed that functional improvements can effectively eliminate such dissatisfaction.

Michaud et al. [16] conducted a discrete choice experiment based on focus group interviews to identify the factors that affect consumer willingness to purchase upgradable products. The results confirmed that consumers are interested and willing to purchase upgradable products. In addition, the study reported a preference for upgrade costs. Furthermore, they confirmed a preference for a longer upgrade cycle and determined that the upgrade means depend on the product. In a related survey by Lobasenko et al. [17], the preferred content and means of upgrade were found to differ based on gender.

Focusing on identifying components for upgrades, Umeda et al. [18] proposed a decision support method for upgrade, maintenance, and reuse selections from the viewpoints of physical life and valuable life. Kobayashi [19] also proposed a life cycle planning method to support environmentally conscious design. This method supports decision-making regarding the upgrade, maintenance, lengthened life, reuse, and recycling of components from environmental, cost, and quality viewpoints during the early design stage.

The abovementioned studies include proposals for a method to determine the components to be upgraded [18, 19], a support method for planning an upgrade cycle [20], and a design support method for the over-specification given to non-upgraded components for adapting functional improvement [14]. However, there are almost no design support methods for the product architecture of the upgradable product itself.

3. Proposed Method and Evaluation Models

3.1. Outline and Procedure

This paper focuses on the architectural design of the upgradable product itself, which has not been considered in previous studies on upgradable design. The proposed method aims to support the derivation of an appropriate upgradable product architecture, considering its upgrade cycle. Here, the product architecture designed by the proposed method refers to the degree of modularity. In addition, this paper proposes evaluation models based on the sustainability-related viewpoints of environmental load, cost, and customer dissatisfaction and applies them to the evaluation of the design architecture. Furthermore, the overall evaluation model considers the differences in product architecture and the number of upgrades. In this study, the authors assume that consumers purchase new products because of accumulated dissatisfaction with their own products. Therefore, the level of customer satisfaction is evaluated by customer dissatisfaction. **Fig. 1** illustrates the procedure followed in the proposed method.

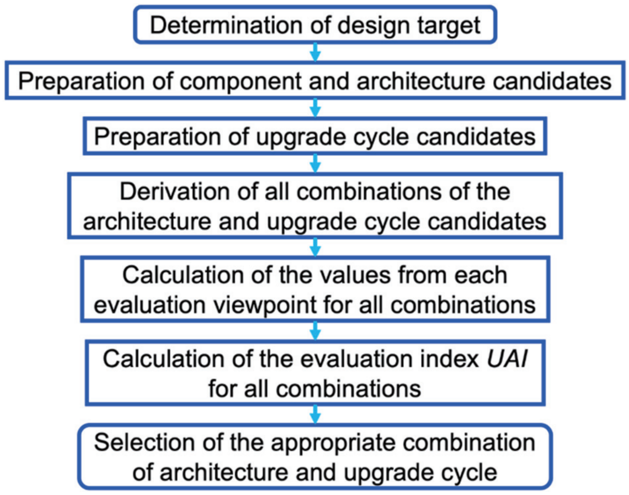

Fig. 1. Design procedure of the proposed method.

First, the design target product is determined, and the designer prepares its components and candidates for the product architecture as well as the business strategy of the company and candidates for the upgrade cycle. Subsequently, the combinations of product architecture and upgrade cycle are derived, and each value of the evaluation viewpoints for each of these combinations is calculated. Furthermore, the evaluation index *UAI* is calculated using these evaluation viewpoint values; finally, the appropriate combination of architecture and upgrade cycle is selected by referring to the value of the index.

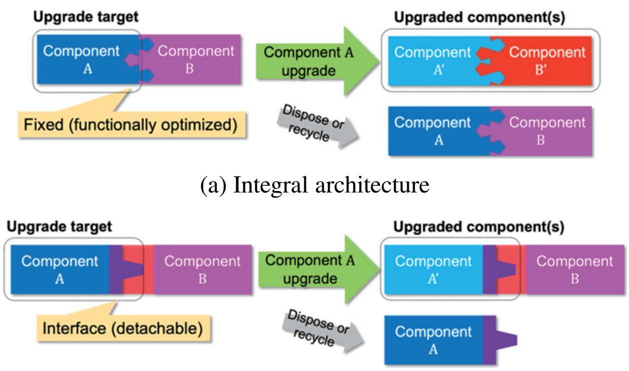

Fig. 2. Difference in product architectures and upgrading.

3.2. Cost and Environmental Load Models

Figure 2 shows a schematic diagram of component upgrades for each product architecture, in which **Figs. 2(a)** and **(b)** illustrate the integral and modular architecture cases, respectively. In the integral architecture case, com-

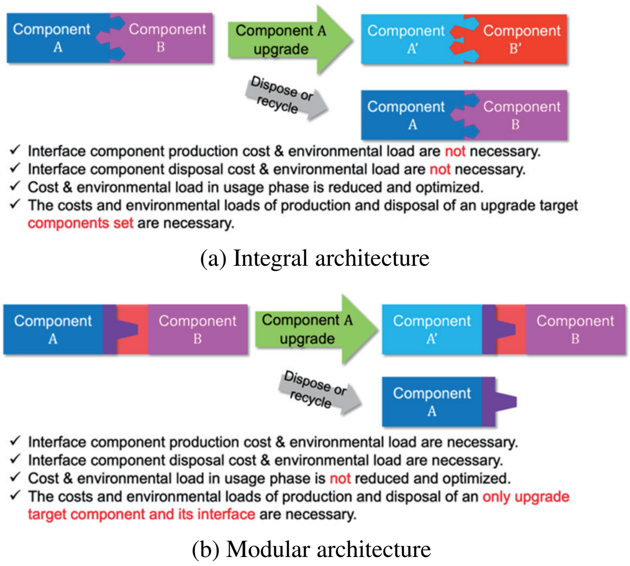

Fig. 3. Schematic of the environmental load and cost derivation.

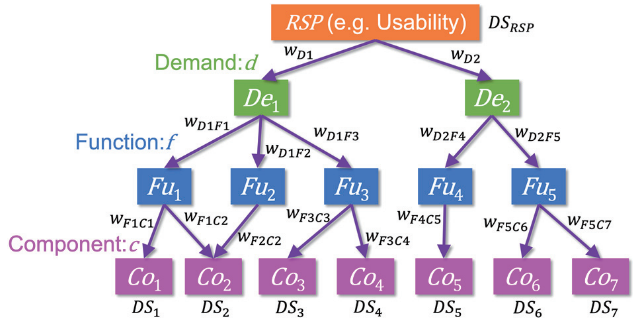

Fig. 4. RSP structure used in this study.

ponents are directly connected to each other and cannot be removed. Conversely, in the modular architecture case, the components are connected via an interface and can thus be attached and detached. An upgrade to component A in the integral architecture requires replacing components A and B. Conversely, in the modular architecture case, it is possible to upgrade component A alone, along with the section of the interface accompanying component A.

As **Fig. 2** demonstrates, a modular architecture requires removable interface components, and when upgrading, both the target component and its interface components are replaced. Therefore, the environmental load and cost are based on the upgraded component and its interface. Conversely, in the integral architecture, the entire set of integrated components is upgraded. Therefore, at the time of upgrade, environmental loads and costs must be calculated for all integrated components. **Fig. 3** shows the models used for each product architecture at the time of upgrade to determine the environmental loads and costs generated.

In the evaluation models, a higher degree of component integration is correlated with a higher product performance and efficiency. Therefore, the environmental loads and costs at the usage stage are subsequently multiplied by a coefficient that expresses the performance and efficiency improvements associated with component integration. Considering the upgrade and architecture differences proposed in this study, the environmental load evaluation model is presented in Eqs. (1)–(3), and the cost evaluation model is given by Eqs. (4)–(6).

$$E_{Total} = E_{1st\,gen.} + \sum_{U}^{Nu} E_{Uth\,gen.}, \quad \ldots \ldots \quad (1)$$

$$E_{1st\,gen.} = \sum_{c}^{Nc} (EP_c + EI_c + RaE_c \times EU_c + ED_c), \quad . \quad (2)$$

$$E_{Uth\,gen.} = \sum_{c}^{Nuc} RtE_{c,U}\,(EP_c + EI_c + RaE_c \times EU_c + ED_c) + \sum_{c}^{Nc-Nuc} (RaE_c \times EU_c), \quad \ldots \ldots \quad (3)$$

$$C_{Total} = C_{1st\,gen.} + \sum_{U}^{Nu} C_{Uth\,gen.}, \quad \ldots \ldots \quad (4)$$

$$C_{1st\,gen.} = \sum_{c}^{Nc} (CP_c + CI_c + RaC_c \times CU_c + CD_c), \quad . \quad (5)$$

$$C_{Uth\,gen.} = \sum_{c}^{Nuc} RtC_{c,U}\,(CP_c + CI_c + RaC_c \times CU_c + CD_c) + \sum_{c}^{Nc-Nuc} (RaC_c \times CU_c). \quad \ldots \ldots \quad (6)$$

3.3. Model of Customer Dissatisfaction

In this study, a customer dissatisfaction model was created by applying the concept of a receiver state parameter (RSP) [21], which is used in the field of service engineering to represent the state quantity of a service receiver. The RSP is represented by a tree structure, as shown in **Fig. 4**. In this study, the RSP is expressed in three layers: customer demands De_d, functions Fu_f, and components Co_c. The contribution Cn_c of component c to the RSP is given by Eq. (7).

Furthermore, a component dissatisfaction function DS_c was defined for a component c using the disposal distribution of existing products. **Fig. 5** shows a schematic diagram of the dissatisfaction function creation process, divided into the following steps. First, the disposal distribution was classified using disposal cause analysis into a distribution resulting from failure and another resulting from value degradation [22]. Second, the distribution resulting from value degradation was accumulated and subsequently allocated to components using the contributions Cn_c. Third, the value of the accumulated distribution when all value-deteriorated products have been disposed of was defined as the threshold, equal to 10. Finally, a formula approximating the accumulated distribution was defined, which represents the dissatisfaction function DS_c for component c. In this study, a dissatisfaction value above the threshold level of 10 indicates a strong user desire for replacement.

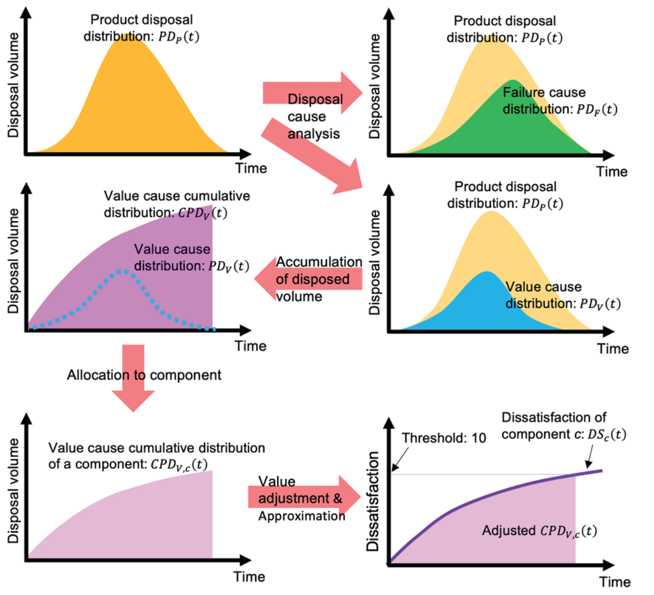

Fig. 5. Dissatisfaction function creation process.

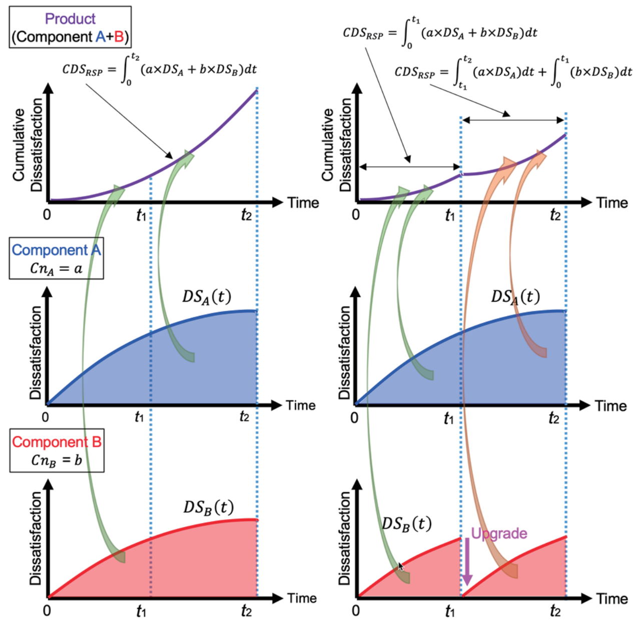

Fig. 6. Cumulative dissatisfaction increases with and without upgrade.

However, if dissatisfaction with individual parts can be directly observed, the dissatisfaction function of the individual parts can be obtained, instead of calculating from the number of discards associated with the value factor of the product.

As shown in Eq. (8), the temporal change model for dissatisfaction with RSP (e.g., usability) DS_{RSP} was derived by adding the product of the dissatisfaction function DS_c and the contribution Cn_c. In Eqs. (7) and (8), Nd, Nf, and Nc indicate the number of demands, functions, and components, respectively. In the derivation of the contribution, an analytic hierarchy process or a conjoint analysis was utilized to derive the importance of customer demand d, represented by w_{Dd}. Similarly, the importance of function f, termed w_{DdFf}, was derived from the importance of customer demand w_{Dd}, and the importance of component c, denoted w_{FfCc}, was derived from the importance of the function w_{DdFf}. These operations model the relationship between the RSP and the component.

$$Cn_c = \sum_f^{Nf} \sum_d^{Nd} w_{FfCc} w_{DdFf} w_{Dd}, \quad \text{(7)}$$

$$DS_{RSP} = \sum_c^{Nc} (Cn_c \times DS_c). \quad \text{(8)}$$

When dissatisfaction with RSP is used as an evaluation viewpoint, the cumulative dissatisfaction CDS_{RSP} that the user experiences during use of the product service is considered. Cumulative dissatisfaction was obtained by calculating the integral of the derived RSP dissatisfaction for a period in which services were provided. In this study, the cumulative dissatisfaction CDS_{RSP} throughout the entire service period was evaluated using the model given in Eq. (9). In Eq. (9), the cumulative dissatisfaction with first-generation product usage is added to the cumulative dissatisfaction with each upgrade. Hence, the first term on the right side of Eq. (9) represents the cumulative dissatisfaction received from the first generation of the product, and the second term represents the cumulative dissatisfaction received from the components being upgraded in the second and subsequent generations. Furthermore, the third term in Eq. (9) represents the cumulative dissatisfaction received from non-upgraded components in the second and subsequent generations. The variable UC represents the upgrade cycle, or the usage time per generation. **Fig. 6** graphically displays the increase in cumulative dissatisfaction in cases with and without upgrades. Because upgrading resets the value of the accumulated dissatisfaction with the component, the increase in cumulative dissatisfaction with RSP becomes more gradual in the upgrade case.

$$CDS_{RSP} = \int_0^{UC} DS_{RSP}\, dt + \sum_{U=1}^{Nu} \left\{ \int_0^{UC} \sum_c^{Nuc} (Cn_c \times DS_c)\, dt \right\} + \sum_{U=1}^{Nu} \left\{ \int_{UC \times U}^{UC \times (U+1)} \sum_c^{Nc-Nuc} (Cn_c \times DS_c)\, dt \right\}. \quad \text{(9)}$$

3.4. Evaluation of Architecture and Upgrade Cycle

The upgrade cycle and product architecture were evaluated using the outputs of each of the previously described evaluation models to determine the comprehensive evaluation index. This evaluation index, the upgradable architecture index (UAI), is given by Eq. (10).

$$UAI = CDS_{RSP} \times E_{Total} \times C_{Total}. \quad \text{(10)}$$

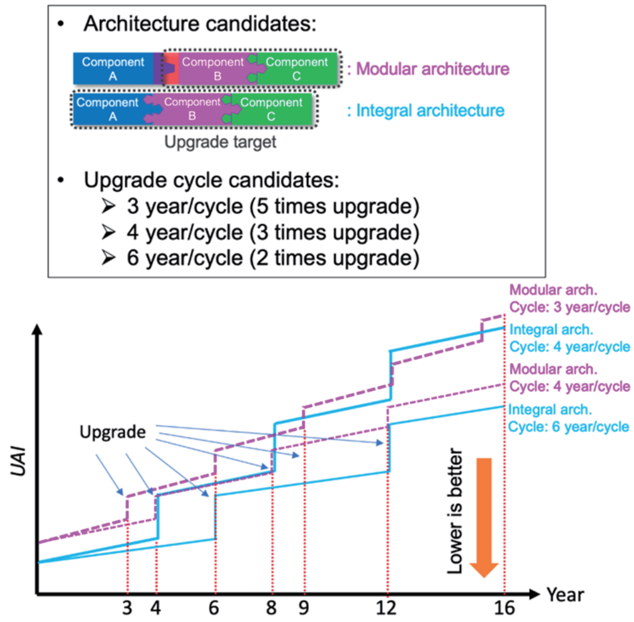

Fig. 7. Comparison of *UAI* for various combinations of architecture and upgrade cycle.

The proposed evaluation method favors the combination of architecture and cycle that achieves a low environmental load, low cost, and low dissatisfaction. Therefore, the combination with the smallest *UAI* value is selected as the appropriate architecture and upgrade cycle. **Fig. 7** shows a schematic diagram of a sample set of evaluation results. **Fig. 7** considers two candidates for the architecture and three candidates for the upgrade cycle, and a 16-year evaluation period was assumed. A designer can use this information to determine the combination with the lowest *UAI*. Based on the figure, the designer can conclude that an integral architecture and 6-year upgrade cycle are the most appropriate combinations. Alternatively, if an example company chooses a 4-year renewal lease as a business strategy, they may determine that a modular architecture is most suitable.

4. Case Study: Laptop Computer Motherboard Module Design

4.1. Purpose and Design Conditions

This case study demonstrates the evaluation of architecture and upgrade cycle combinations in terms of dissatisfaction, environmental load, and cost based on the input design information and provides designers with a ranking of the desirability of these combinations. In addition, it should be noted that the design variables used in the evaluation include assumed values because of the above purpose. This case study evaluates the architecture and upgrade cycle of the motherboard module of a laptop computer. The motherboard module consists of three components: the CPU, motherboard (circuit board), and memory. The CPU was defined as the component to be upgraded, and the four product architectures shown in **Table 2** were evaluated. In the modular architecture, the assumed interface components include the CPU connection pins required for assembly with the motherboard, the memory module board for mounting the memory elements and connecting to the motherboard, and the CPU and memory sockets on the motherboard for connecting the CPU and the memory module. The evaluation period was 10 years, and the upgrade cycle candidates used were 2-, 3-, 4-, and 5-year cycles.

Table 2. Candidates for product architecture.

Architecture	Product architecture detail
CBM	All components are integrated. CPU (C), motherboard (B), and memory (M) are to be upgraded.
CB&M	CPU and motherboard are integrated. Memory is individual. CPU and motherboard are to be upgraded.
C&BM	CPU is individual. Motherboard and memory are integrated. Only CPU is to be upgraded.
C&B&M	All components are individual. Only CPU is to be upgraded.

To evaluate customer dissatisfaction, the authors defined RSP as the usability of a laptop and developed the usability structure for a laptop computer, as shown in **Fig. 8**. Based on the assumptions for this case study, the dissatisfaction function for a laptop computer was assumed to be a function of the square root of time, and the authors calculated the contributions Cn_c and defined the dissatisfaction functions DS_c for each component. **Table 3** lists the contributions and dissatisfaction functions for the CPU, motherboard, and memory, along with the cumulative dissatisfaction function for the usability, CDS_{RSP}.

The environmental loads and costs generated in the manufacturing and usage stages were utilized to evaluate the environmental load and cost for each architecture. The environmental load during manufacturing was calculated by disassembling the actual product and subsequently determining information about the materials, weight, and intensity of converted CO_2 emissions. The manufacturing cost was based on the sales price of the components. The authors calculated the environmental load and cost during the usage phase using the power consumption information for each component, assuming that the usage time of the laptop computer was 8 h per day, 245 days per year. The power consumption was derived based on the power consumption information for each component and the measured values obtained by the Watt checker. The assumed performance change caused by the integration was defined as a 30% reduction (i.e., $RaC_c = RaE_c = 0.7$) in power consumption. In addition, the performance change resulting from future technological improvements was assumed to be a 0% reduction (i.e., $RtC_{c,U} = RtE_{c,U} = 1$) in the power consumption for all generations, as the power

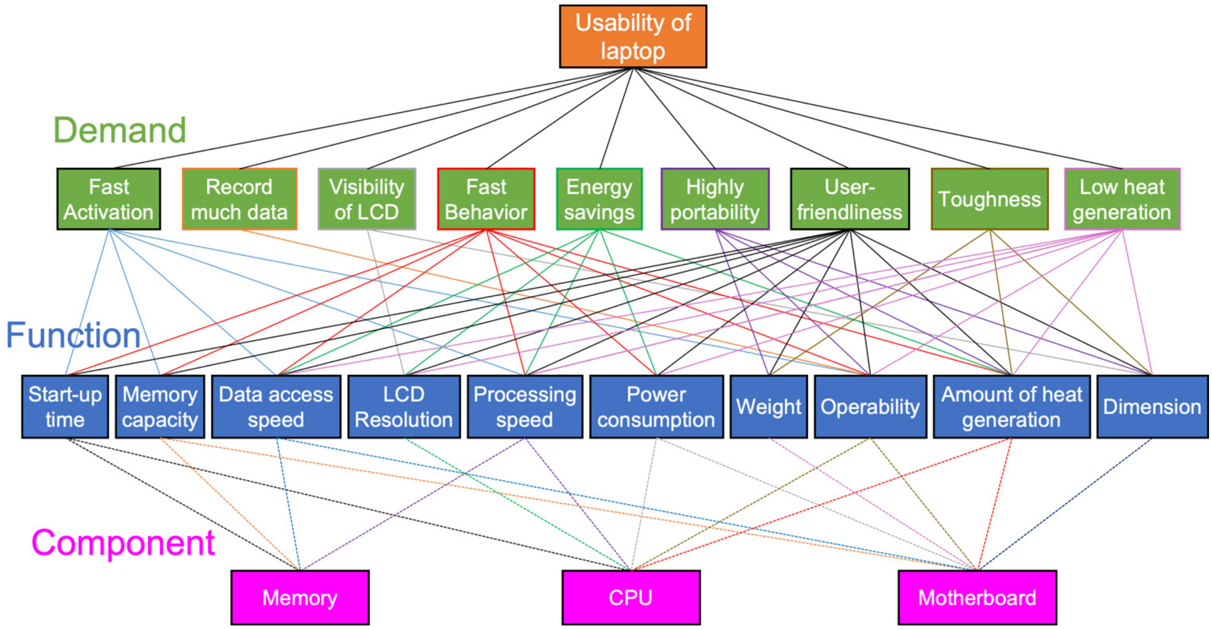

Fig. 8. Structure of the usability of a laptop's motherboard module.

Table 3. (Cumulative) dissatisfaction functions.

	Contribution	*DS* or *CDS* function (t: time)
CPU	$Cn_{CPU} = 0.281$	$DS_{CPU} = 1.25\sqrt{t}$
Motherboard	$Cn_{MB} = 0.092$	$DS_{MB} = 0.4\sqrt{t}$
Memory	$Cn_{Mem} = 0.074$	$DS_{Mem} = 1.25\sqrt{t}$
Usability		$CDS_{RSP} = 0.107t\sqrt{t}$

Table 4. Design information used for evaluation.

	Production stage		
Component	Env. Load [g-CO_2e]	Cost [Yen]	
CPU	551	18,000	
Motherboard	12.8×10^3	8,800	
Memory	1.35×10^3	4,600	
Interface	Env. Load [g-CO_2e]	Cost [Yen]	
Connecting pin	0.87	2,000	
CPU socket	34.4	1,000	
Memory socket	16.4	200	
Circuit board	23.2	400	
	Power consumption [W]		
Architecture	CPU	Motherboard	Memory
CBM	3.5	2.1	1.4
CB&M	3.5	2.1	2
C&BM	5	2.1	1.4
C&B&M	5	3	2
	Intensity in the usage stage		
Env. load	0.479 kg-CO_2e/kWh		
Cost	27 Yen/kWh		

consumption of the actual components will not significantly change. **Table 4** shows the design information used in the evaluation.

4.2. Results and Discussion

Based on the conditions described in Section 4.1, the authors calculated the environmental load, cost, and cumulative customer dissatisfaction for each combination of product architecture and upgrade cycle. **Table 5** shows the *UAI* rankings and the recommended combinations based on these calculations. The results of the evaluation indicate that integrating all three components and upgrading every five years is most suitable for the laptop computer motherboard module. Therefore, the CPU, motherboard, and memory must be designed with a physical lifespan of at least 5 years. For all the upgrade cycle candidates, the highest evaluation value was obtained for the architecture with all three components integrated. This means that integrating the CPU with the other components is more highly recommended than upgrading the CPU alone. This result is due to the greater influence of the usage stage environmental load value on the *UAI* compared with the manufacturing stage value. Clearly, the effect of the reduced environmental load in the usage stage resulting from component integration is greater than the effects caused by increasing the number of upgraded components in the manufacturing stage. Moreover, the results confirm that dissatisfaction with the integral architecture was lower because of the increase in the number of upgraded components in the component integration cases and the corresponding suppression of cumulative dissatisfaction accumulation.

Although this case study utilizes hypothetical values, the input information used in the evaluation is commonly used in all combinations of architectures and upgrade cycles. Therefore, the results demonstrate the success of the

Table 5. Results and evaluation rank.

Product arch.	Evaluation viewpoint	Upgrade cycle [year/cycle]			
		2	3	4	5
CBM	E_{Total} [kg-CO_2e]	194	180	165	150
	C_{Total} [Thou. Yen]	215	184	153	121
	CDS	410	481	546	649
	UAI [$\times 10^{10}$]	1.71	1.59	1.37	1.18
	Rank	8th	6th	2nd	1st
CB&M	E_{Total} [kg-CO_2e]	195	181	168	155
	C_{Total} [Thou. Yen]	199	172	145	118
	CDS	730	756	780	818
	UAI [$\times 10^{10}$]	2.83	2.35	1.90	1.50
	Rank	16th	15th	11th	4th
C&BM	E_{Total} [kg-CO_2e]	152	151	151	150
	C_{Total} [Thou. Yen]	174	154	134	114
	CDS	748	771	793	828
	UAI [$\times 10^{10}$]	1.98	1.79	1.60	1.41
	Rank	12th	10th	7th	3rd
C&B&M	E_{Total} [kg-CO_2e]	166	166	165	164
	C_{Total} [Thou. Yen]	175	155	135	115
	CDS	748	771	793	828
	UAI [$\times 10^{10}$]	2.18	1.99	1.77	1.56
	Rank	14th	13th	9th	5th

proposed method and the overall evaluation model in suggesting the recommended architecture and upgrade cycle to the designer by considering the differences in product architecture. In addition, the proposed method was confirmed to be useful for making design decisions about product architecture, upgrade cycle, and physical lifetime of individual components for an upgradable product.

However, the proposed method was based on the assumption that there is one component of the upgrade target and one integrated component group. Hence, improvements in the evaluation models and the computational system are needed to manage design problems with multiple upgrade targets and multiple integrated parts. In addition, although the proposed method uses point values to evaluate combinations, the cost and environmental load reduction rates are uncertain because the upgrades are performed later than the design stage. For this reason, it is preferable to use an assumed range of values for the evaluation, similar to conventional methods for upgradable product design. For this purpose, it is necessary to improve the evaluation model and computation system so that it is possible to evaluate a range of evaluation values.

5. Conclusions

This paper proposes a decision support method using evaluation models to derive an appropriate upgrade cycle and product architecture combination for an upgradable product. This method includes evaluation models for environmental load, cost, and customer dissatisfaction, which are utilized to assess the possible combinations of product architecture and upgrade cycle. The proposed method was applied to the motherboard module design challenge in a laptop computer, and the recommended combination of product architecture and upgrade cycle was derived. In addition, the method revealed the environmental load, cost, and cumulative dissatisfaction when implementing products with derived architectures. Furthermore, the method demonstrated the ability to determine the minimum physical life recommendation for each component based on the recommended combination of product architecture and upgrade cycle. The results of the case study confirmed that the proposed decision support method and evaluation model are useful for supporting designers in the upgrade cycle and product architecture design for upgradable products.

The future work indicated by this study includes an investigation of changes in reliability resulting from component integration, and development of a reliability evaluation model that considers the differences in product architecture and upgrades. In addition, the proposed method simply derives the customer dissatisfaction function based on the known product disposal distribution. However, users sometimes hoard products without disposing of them, even if usage has stopped because of value deterioration. Therefore, the model should also utilize technology to estimate the degree of value degradation of user-owned products. Hence, future work must examine estimation methods for the valuable life expectancy using the Internet of Things or other technologies, in addition to determining which data should be collected.

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