An Upgrade Product Design Method for Satisfying Performance Criteria, Environmental Load, and Cost

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Abstract

To reduce the environmental load attributed to mass production, mass consumption, and mass disposal, an environmentally conscious upgrade product design method is required. Recently, technologically innovative products such as personal computers and smartphones are typically discarded because of the deterioration of their value even though these products have a fully functional and durable life. This paper proposes an upgrade product design method developed to increase the product value and extend the value lifespan by exchanging components closely related to its deterioration in value. This method predicts the required future product performance and functions. Therefore it designs products in advance to be compatible with anticipated future performance and product function upgrades. Because future product performance and functions include uncertain design information: An accurate prediction is very difficult. This paper defines uncertain design information as ranged sets. Moreover, the authors propose an upgrade product design method that considers product performance and functions, production costs, and environmental load concurrently by applying a preference set-based design method that can obtain ranged sets of design solutions that optimally satisfy multiobjective requirements. In addition, the authors propose a method that can specify future product performance and functions, effective upgradable product components, and the side effects of upgrade on other product components. Finally, this paper discusses the applicability of our proposed upgrade product design method by applying the method to an electric vacuum cleaner design problem.

Keywords: upgrade design, set-based design, preference, early phase of design, product performance, environmental loads, cost

1 Introduction

To achieve a sustainable society, the change of traditional paradigm of mass production and consumption is needed. In addition, companies and nations are required to reduce their environmental loads [1]. Therefore, environmentally conscious product design is essential. Some of these design methods such as the reuse, recycle, and upgrade product design method have been studied [2]. The upgrade product design method is intrinsically executed prior to the disposal of products. Shimomura et al. [3], [4] proposed a method for upgrade planning based on the prediction of customer demands. However, the method nearly addresses only physical product performance without quantitative considerations of requirements such as cost and environmental load. Thus, this paper focuses on an upgrade product design method, which can treat physical product performance, functions, environmental loads and product cost. This method also considers uncertain product requirements and design information needed in the future at the upgrade point of time. In this case, the assumption is that customers discard their products when the perceived value of their present product has deteriorated with time below a certain level relative to the perceived value of new products in the market. In addition, the authors propose a method that defines product performance and functions and identifies the components, which mostly affect product obsolescence and perceived product value as well as other components, which are affected by the anticipated upgrade.

2 Upgrade product design method

2.1 Purpose and procedure of the method

An upgrade product design method seeks to design products that are capable of being adapted to future enhancements of product performance and functions at the early phase of design by predicting those product performance and functions that will be required at the time of upgrade. There are two basic classes of this method: (a) upgrade by exchanging components and (b) upgrade by adding components or modifying the structure of the product. This study focuses on the former class of the method (a). Because future enhancements of product performance and functions eligible for upgrade are to be predicted, the proposed method must include uncertain design information. Here, the authors represent uncertain design information as a range value, and apply a preference set-based design (PSD) method [5], [6] to estimate future enhancements of product performance and features eligible for upgrade. The PSD method is based on the concept of set-based concurrent engineering [7] that can obtain a ranged set of design solutions. **Figure 1** shows the procedure of the proposed method.

This paper defines two product lifetimes: durable life and value life [5]. The durable life is a measure of the duration over which the failure rate of a product or component remains below a defined threshold. Conversely, the value life is a measure of the duration that the product value perceived by the consumer remains above a defined threshold, as illustrated in **Figure 2**. Products such as personal computers (PCs) and smartphones are usually discarded even though they are fully functioning. This situation derives from the condition where the value life is shorter than the durable life. Therefore, the primary purpose of our method is to reduce the extent of product disposal and the resulting environmental load by increasing the value life of products by exchanging components that have a relatively short value life or by adding new components in accordance with the description given in **Figure 2**.

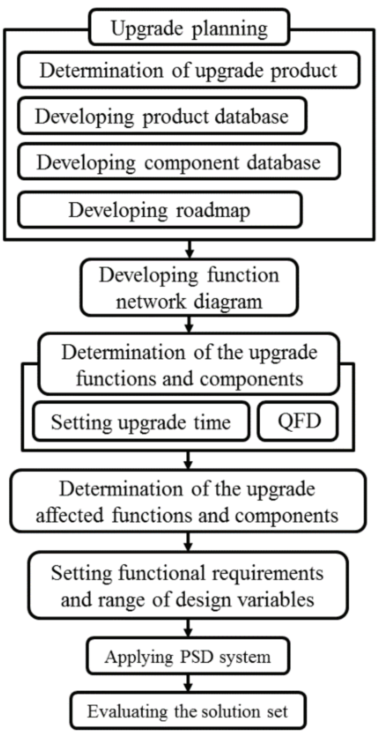

Fig. 1 Proposed procedure for the upgrade product design method

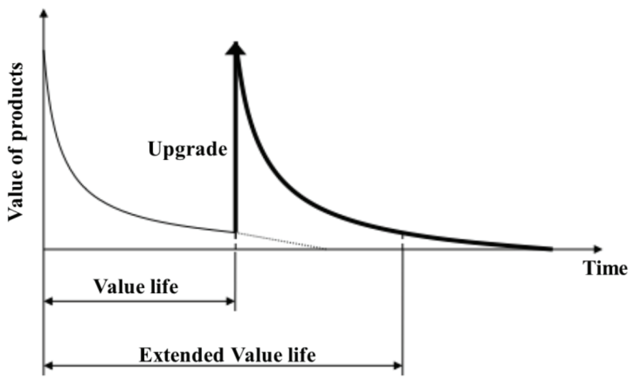

Fig. 2 Schematic illustration of the change in the product value with time [8]

2.2 Upgrade planning

Here, the authors establish the criterion of the upgrade time. Definition of the upgrade time is based upon several factors such as product upgrade cycle, disposal cycle, or administrative strategy. In addition, the authors create the product and component databases. These databases contain manufacturers, model numbers, launch times, and product and component performance and/or design variables such as the capacity of storage, weight, and dimension. Based on these databases, the authors create product and component roadmaps that evaluate the temporal distributions of performance criteria and/or design variable values. The upgrade time and the product and component roadmaps are used for configuring the performance requirements of the products and components. Under conditions where a product has not yet been launched, roadmaps of similar products can be used for market prediction and for configuring performance requirements.

2.3 Developing the function network

A function network diagram illustrates the input and output relationships between performance criteria and product components. This diagram is used for the analysis of upgrade components. **Figure 3** provides an example of a function network diagram for a laptop PC. In this diagram, performance criteria and product components are represented by the individual graphics, as shown in **Figure 4**. The positive parameters are indicative of a condition where a higher or larger value represents better performance. Conversely, negative parameters are indicative of a condition where lower or smaller values represent better performance. The input–output relations between performance criteria and product components are connected by straight lines, and relevant design variables are described on these lines. Therefore, designers can easily search for components that are related to upgrade performance by following the input–output lines.

In case of a laptop PC (cf. **Figure 3)**, for example, the characteristic battery life is the chosen target for upgrade performance. The pertinent components affecting that performance are Display, VGA, Memory, Storage, Chipset, CPU or Battery. They represent candidates with regard to an upgrade possibility.

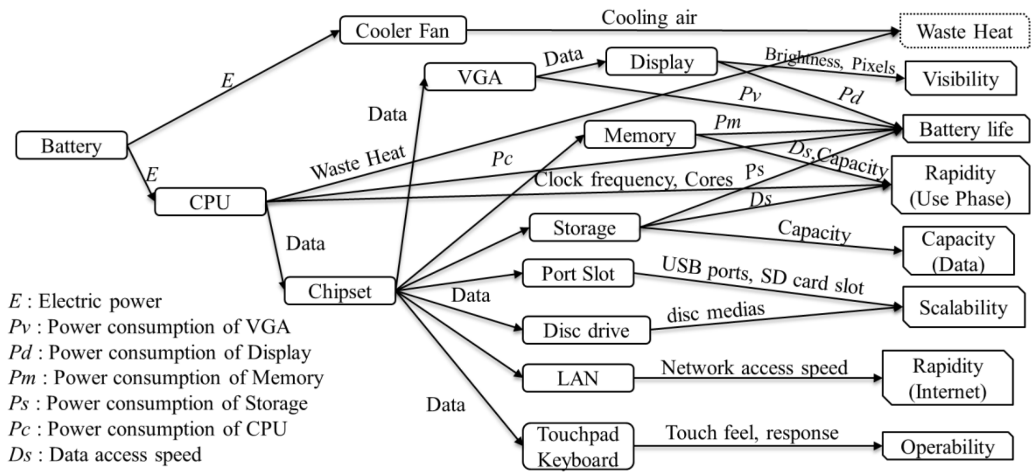

Fig. 3 Function network diagram of a laptop PC

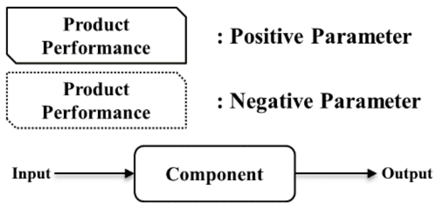

Fig. 4 Graphical representation of performance criteria (positive and negative) and product components in a function network diagram

2.4 Consideration of upgradable performance criteria and components

Upgradable performance criteria are defined as a product performance upon which consumer emphasis is placed, as evaluated by application of quality function deployment (QFD) or, alternatively, those performance criteria, which have a short value life. Using the function network diagram, the authors search for components that have close relationships with the chosen upgrade performance criterion and define those as potential upgrade components. When a plurality of upgrade components are identified, the candidates should be narrowed down by considering the balance between upgrade performance criteria and possible upgrade affected performance criteria and components as described below.

2.5 Consideration of upgrade affected performance criteria and components

Upgrade affected performance criteria indicate that the value of performance is changed by exchanging upgrade components. In addition, the authors define a component that has a close relationship with an upgrade affected performance criterion as an upgrade affected component. Upgrade affected performance criteria and components are identified in the same way as upgrade components by using the function network diagram. For example, a designer defines the performance of the Visibility as the upgrade performance criterion and the Display component as the upgrade component for the laptop PC system described in **Figure 3**. In this case, the Battery life is defined as an upgrade affected performance criterion because the upgrade causes the power consumption of the display P_d to increase. Therefore, VGA, Memory, Storage, and CPU emerge as upgrade affected components. Possible approaches for mitigating this condition can be developed: Building a low-power consumption VGA or CPU into the 1st generation PC, simultaneously upgrading the VGA or CPU with the Display, or developing and upgrading a Display that has low power consumption and a high visibility level. These approaches are narrowed down in the same way as that of the upgrade components.

2.6 Application of the PSD method and the evaluation of the solution set

In this study, the authors apply the PSD method to our method to obtain the range of required product performance and functions, and the range of the component design variables that can realize this performance and function range. To obtain these ranged design solutions, the equations and the range of the required product performance and functions and the design variables of the components are needed. The equations show the relationships between product performance, functions and component design variables. In the absence of equations, the designer should define approximate equations based on the performance parameters and design variables in the product and component databases.

Range of the required product performance and functions and the designer configurable range of design variables are configured in accordance with the distributions in the product and component roadmaps. A conclusive point-based design proposal is selected from the ranged set of design solutions and a preference number. Under conditions where the design proposal must be modified, the designer should search for the design proposal that satisfies the modified requirements from the ranged set of design solutions. However, in the absence of a design proposal in the ranged set of design solutions, the designer should define the required performance and design variables again and apply them to the PSD system.

3 PSD method

In this study, the goal of the application of the PSD method to the author's method is to obtain a ranged set of design solutions that satisfies multiple requirements concurrently with the designer's intention. The PSD method consists of a set-based design method and a preference number. A set-based design method can collectively and simultaneously treat several product performance requirements, representing performance trade-offs, as a ranged set. The preference number represents the designer's intentions for the design. The PSD method consists of four steps: set representation, set propagation, set modification and set narrowing.

3.1 Set representation

In this step, all the performance requirements and design variables are represented as ranged sets with a preference number. The preference number, defined as a number between 0 and 1, is given for the ranged set of required product performance criteria, functions, and component design variables. The preference number is based on the designer's knowledge and experience. A preference number "0" is indicative of the least preferable interval (allowable interval) and a number "1" is indicative of the most preferable interval.

3.2 Set propagation and modification

Here, the performance set, which is called the possible distribution, is calculated with the equations expressing the relationship between product performance requirements and component design variables. If all the ranged performance sets have sets in common between the space spanned by the performance requirements and the possible distribution, then a feasible subset exists within the initial design set. Otherwise, the ranged performance requirement sets or the ranged design variable sets should be modified.

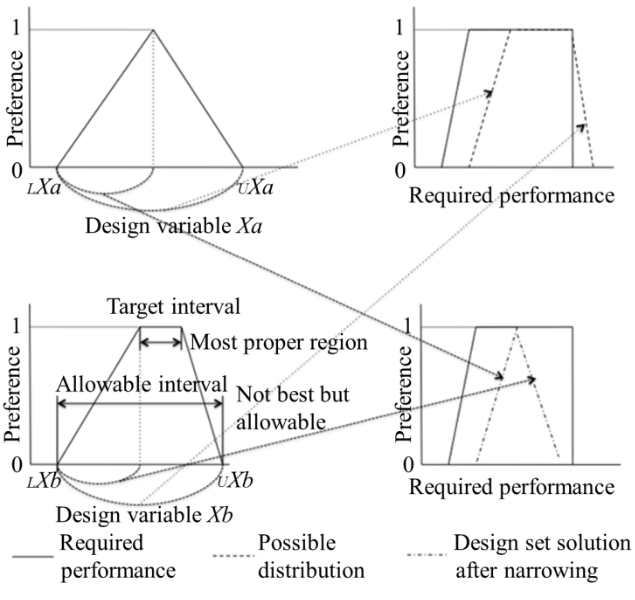

Fig. 5 Schematic illustration of the procedure of the PSD method [5]

3.3 Set narrowing

In cases where the possible distribution calculated over the entire range of each design variable does not completely satisfy each ranged set of the product performance requirements given by the designer, the ranged set of each design variable is divided into smaller regions. The combinations of the divided region of the design variables are propagated to the performance requirements. This division is repeated until the combinations meet every ranged set of the performance requirements. In the process, as evaluation criteria of the compatibility between the ranged sets of the possible distribution calculated from ranged design variable sets and the performance required by the designer, the degree of satisfaction and robustness of the ranged set solution are introduced. **Figure 5** shows these processes

4 Case study: application to the design of an electric vacuum cleaner

4.1 Setting the design problem

This paper shows an application of the proposed method to an electric vacuum cleaner. According to the cycle of trade up to a new model, the authors hypothesize an upgrade time equivalent to approximately five years (for a consumer trade up proportion of 60%) from launch time of the 1st generation product. To understand the trend of performance requirements and design variables, a creation of databases with regard to launched products and components is done. The product database include vacuum cleaners manufactured by three companies (Company A, B, and C) from 2005 to 2013. The component database includes motors manufactured by a single company in 2013 because there is no data for motors manufactured before 2012. **Figure 6** shows the temporal distribution of the suction power of a vacuum cleaner that is considered.

Figure 7 shows the function network diagram of a vacuum cleaner. Using the QFD method, the authors define Suction Power F (W) as an upgrade performance that has a high level of value degradation. Using the information in **Figure 7**, the Motor is configured as an upgrade component. In addition, the Energy Consumption E (W), Operation Noise S (dB), the amount of CO_2 Emission D (g), and total production cost C_T (¥) as the performance criteria affected by the upgrade are defined. The product performance requirements and the range of design variables based on the product database and roadmap are configured. Finally, the ranged set of design solutions is calculated using the equations between product performance and design variables from the PSD system.

The range of the design variables can increase and decrease relative to the reference values that are assumed to be the design variables of the 1st generation product. The total production cost of the upgraded product has multiple relations with the costs of the upgrade components and the affected components (i.e., Motor and Turbine Fan). The assumption is that the cost of the components increases relative to the difference

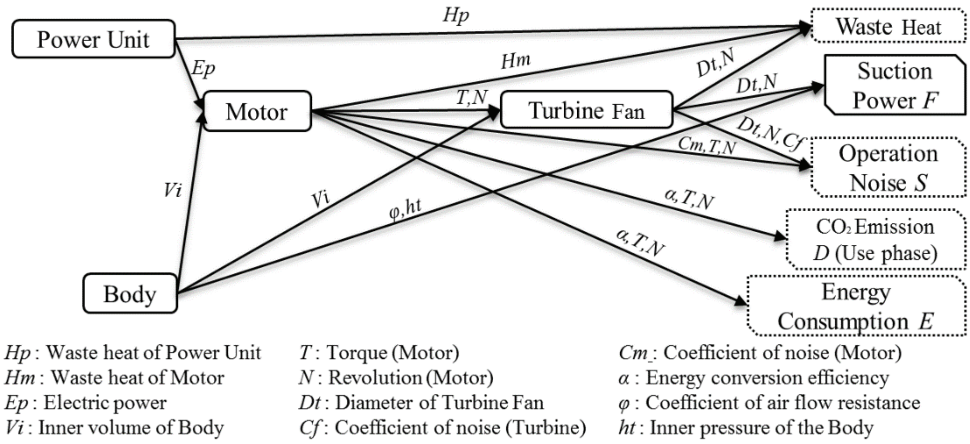

Fig. 7 Function network diagram of a vacuum cleaner

between the design variables of the 1st generation (reference value) and those of the 2nd generation. Therefore, the cost of components (not including the Motor and Turbine Fan) is higher than components without the upgrade. In this study, the authors assume that if the range of the design variables decreases, then total production cost increases moderately than is the case for an increase in the range of the design variables. **Figure 8** shows the relationship of the production cost of the product with and without the upgrade.

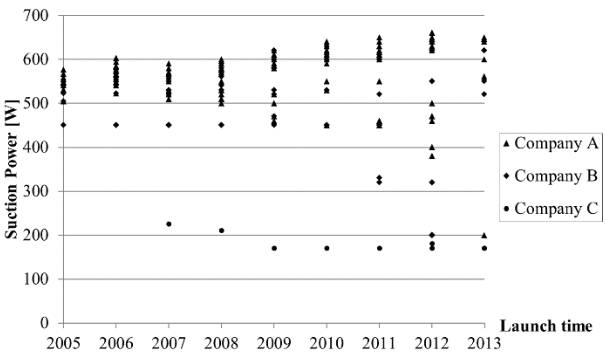

Fig. 6 Performance roadmap of the Suction Power *F*

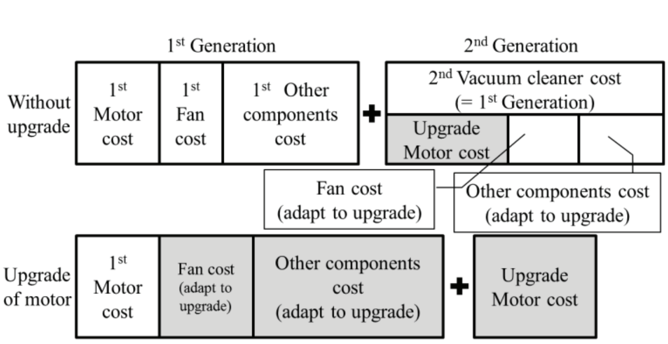

Fig. 8 Comparison of the product costs with and without the upgrade

Table 1 shows the ranged sets of required performances and design variables, and **Table 2** shows the ranged set of design solutions. In these tables, C_1 as the cost of the 1st generation product, and C_2 as the cost of the upgraded motor or the 2nd generation product without an upgrade is defined. Equation (1) shows the relationship among C_T, C_1, and C_2.

$$C_T = C_1 + C_2 \qquad (1)$$

In this application, the authors assume that the product performance and design variables of the components of the 2nd generation product without an upgrade are equal to the upgraded product's parameter. In addition, the authors assume that the cost of the 2nd generation without a product upgrade is equal to the 1st generation without a product upgrade.

4.2 Discussion

In this study, a ranged set of product design solutions that include various performance criteria, cost, and environmental loads in use concurrently with the consideration of future uncertain design information are obtained. **Table 2** shows that although the total production cost of the upgraded product C_T is reduced from 19.6% to 14.8% and CO_2 Emission D of the upgraded product is reduced from 13.9% to 4.5% compared to the product without the upgrade, the Suction Power F (upgraded performance) satisfies the required range. Therefore, the authors conclude that the PSD method can obtain a ranged set of product design solutions in consideration of performance criteria, cost, and environmental load. However, the authors should define the increasing rate of 1st generation production costs of the upgraded product that customers allow to consume because the 1st generation production cost of the upgraded product increases from 34.9% to 42.4%. Also the application of this increasing rate to the requirements of the upgraded product should be done.

In this paper, the ranged set of requirements that include future uncertainty is predicted arbitrarily based on the distribution of the product roadmap. Moreover, this prediction needs the designer's knowledge and experience. Therefore, predicting the ranged set of requirements logically is one of the subjects of future study. This application upgrades the Motor to upgrade

Table 1 Required ranged set for each generation

<table>
<tr><td colspan="5">Product performances</td></tr>
<tr><td rowspan="2"></td><td>F (W)</td><td>E (W)</td><td>S (dB)</td><td>D (g)</td></tr>
<tr><td colspan="4">Parameters</td></tr>
<tr><td>1st</td><td>599</td><td>922</td><td>54.0</td><td>511</td></tr>
<tr><td>2nd</td><td>[630, 680]</td><td>[0, 1100]</td><td>[55.0, 65.0]</td><td>[0, 550]</td></tr>
<tr><td colspan="5">Design parameters</td></tr>
<tr><td rowspan="2"></td><td>N (rpm)</td><td>α</td><td>T (Nm)</td><td>Dt (mm)</td></tr>
<tr><td colspan="4">Parameters</td></tr>
<tr><td>1st</td><td>33000</td><td>0.3</td><td>0.08</td><td>150</td></tr>
<tr><td>2nd</td><td>[30000, 40000]</td><td>[0.1, 0.5]</td><td>[0.05, 0.10]</td><td>[125, 150]</td></tr>
</table>

Table 2 Comparison of the solution ranges with and without the upgrade (UG)

<table>
<tr><td></td><td colspan="2">1st Generation</td><td colspan="2">2nd Generation</td></tr>
<tr><td></td><td>without UG</td><td>UG of motor</td><td>without UG</td><td>UG of motor</td></tr>
<tr><td colspan="5">Product performances</td></tr>
<tr><td>F (W)</td><td>599</td><td>[587, 611]</td><td colspan="2">[640, 674]</td></tr>
<tr><td>E (W)</td><td>922</td><td>922</td><td colspan="2">[792, 880]</td></tr>
<tr><td>S (dB)</td><td>54.0</td><td>[53.5, 54.4]</td><td colspan="2">[58.7, 60.3]</td></tr>
<tr><td>D (g)</td><td>511</td><td>511</td><td colspan="2">[440, 488]</td></tr>
<tr><td colspan="5">Cost</td></tr>
<tr><td>C_1 (¥)</td><td>25591</td><td>[34513, 36443]</td><td colspan="2"></td></tr>
<tr><td>C_2 (¥)</td><td colspan="2"></td><td>25591 (=C_1)</td><td>[6627, 7172]</td></tr>
<tr><td colspan="5">Total cost</td></tr>
<tr><td></td><td colspan="2">Without UG</td><td colspan="2">UG of motor</td></tr>
<tr><td>C_T (¥)</td><td colspan="2">51182</td><td colspan="2">[41140, 43615]</td></tr>
<tr><td colspan="5">Design parameters</td></tr>
<tr><td>N (rpm)</td><td>33000</td><td>33000</td><td colspan="2">[36000, 36400]</td></tr>
<tr><td>α</td><td>0.3</td><td>0.3</td><td colspan="2">[0.260, 0.276]</td></tr>
<tr><td>T (Nm)</td><td>0.08</td><td>0.08</td><td colspan="2">[0.058, 0.060]</td></tr>
<tr><td>Dt (mm)</td><td>150</td><td>[149, 151]</td><td colspan="2">[149, 151]</td></tr>
</table>

the Suction Power. However, the designer can upgrade that performance even by just upgrading the Turbine Fan. Therefore, the authors need to propose a method that can obtain the most suitable quantitative procedure for exchanging components by understanding the effect of exchanging components.

5 Conclusions

Base of operations is the assumption, that consumers discard their products because of the deterioration of product values. Therefore, a design method is proposed, that can obtain a ranged set of solutions that satisfies multiple product performance criteria, cost, and environmental load by considering uncertain design information. To obtain the ranged set of solutions, PSD method is applied to the author's method that proposes to increase product value and extend product life by exchanging components whose value has diminished below a threshold value. In addition, the authors proposed the function network diagram to define the product performance criteria and components that possess a short value life. This paper showed the usefulness of this diagram by an application. Therefore, it is essential to calculate the product manufacturing environmental load, but the authors have not treated the product manufacturing environmental load in this study but, rather, simply the product environmental load in use.

In general, the durable life is longer than the value life. Therefore, upgrade components are exchanged at the time when that value is exhausted leaving some durable life remaining. However, a method is required that can define the optimal balance between the value life and durable life, and a design method for components that have a necessary and sufficient durable life.

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