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# An Upgradable Product Design Method for Improving Performance, CO$_2$ Savings, and Production Cost Reduction: Vacuum Cleaner Case Study

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*Abstract*—**Customers often discard products without considering the environmental load, because of the deterioration of their value even though they are fully functional. An upgradable product design can enhance the product value and stop the entire product replacement and disposal by replacing only the components responsible for the decrease in value. This paper proposes an upgradable product design method for improving product performance, incurring CO$_2$ savings, and production cost reduction while increasing the product value and extending the value lifespan by exchanging components closely related to the deterioration in value. In addition, this paper proposes a method that can specify future product performance, effective upgradable product components, and the effect of the upgrade on other product components. Finally, this paper discusses the applicability of the proposed method by considering the designing of a vacuum cleaner and customer demands such as performance, noise, and energy savings.**

*Keywords*ー*Sustainability, upgradability, CO$_2$ savings, cost reduction, customer demand, set-based design*

## 1. Introduction

A sustainable society requires changes in the traditional paradigm of mass production and consumption. Companies and countries need to reduce their environmental loads [1]—especially at the product design phase, where at least 80% of the production cost of the supply chain and quality is established [2]. Therefore, an environmentally conscious product design is essential. Design methods such as the 3R, which refers to reuse, reduce, and recycle, and upgradable product design methods have been studied [3]. An upgradable product design method is inherent to the disposal of products. A sustainable society needs to consider product upgradability as a new sort of "evolution" [4] while harmonizing environmental and financial demands in designing the supply chain [5]. Ishigami et al. [6] proposed a method for upgrade planning based on the prediction of customer demands. They specified a line-up of candidate upgradable components for each generation. Furthermore, Fukushige et al. [7] developed a prototype system for product upgradability based on 3D-CAD. However, these methods focus on the physical product performance without quantitative consideration of requirements such as production cost and environmental load (CO$_2$ savings). Thus, this paper focuses on an upgradable product design method for improving product performance and CO$_2$ savings while reducing the production cost. This method also considers future unknown product requirements and design information. We assume that customers discard a product when its perceived value has decreased with time below the perceived market value of new products. In addition, this paper proposes a method for specifying future product performance and functions, effective upgradable product

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components, and the effect of the upgrade on other product components. Finally, this paper discusses the applicability of the proposed upgradable product design method by considering a vacuum cleaner and customer demands such as performance, noise, and energy savings.

## 2.    Upgradable Product Design Method

### 2.1    Purpose and methodology

An upgradable product design method seeks to design products that are capable of adaptation to future product performance enhancement and functions by predicting the product performance and functions that will be required at the time of the upgrade. There are two basic implementations of the method:

(a)  upgrade by exchanging components and
(b)  upgrade by adding components or modifying the product structure.

In this study, we focus on the first kind. Because future enhancements of product performance and functions need to be predicted, the proposed method must consider fuzzy design information. The traditional design practice often considers the engineering design as an iterative process; that is, it quickly develops a "point solution," evaluates it on the basis of multiobjective criteria, and then iteratively moves on until it reaches a satisfactory point solution. However, there is no theoretical guarantee that the process will ever converge and produce an optimal solution. In addition, the use of a point solution does not provide information about uncertainty. In this study, the uncertainty in the design information is represented as a range of values, and we use a preference set-based design (PSD) method [8], [9] to estimate future product performance enhancements and upgrade features. The PSD method results in a range of design solutions. Figure 1 shows the proposed methodology.

In this study, we define two product lifetimes: durable life and value life [10]. Durable life measures the duration over which the failure rate of a product or a component remains below a defined threshold. Conversely, value life represents the duration over which the product value as perceived by the customer remains above a defined threshold. Products such as personal computers and smartphones are discarded even though they are fully functional. In this case, value life is shorter than durable life. Therefore, the primary purpose of
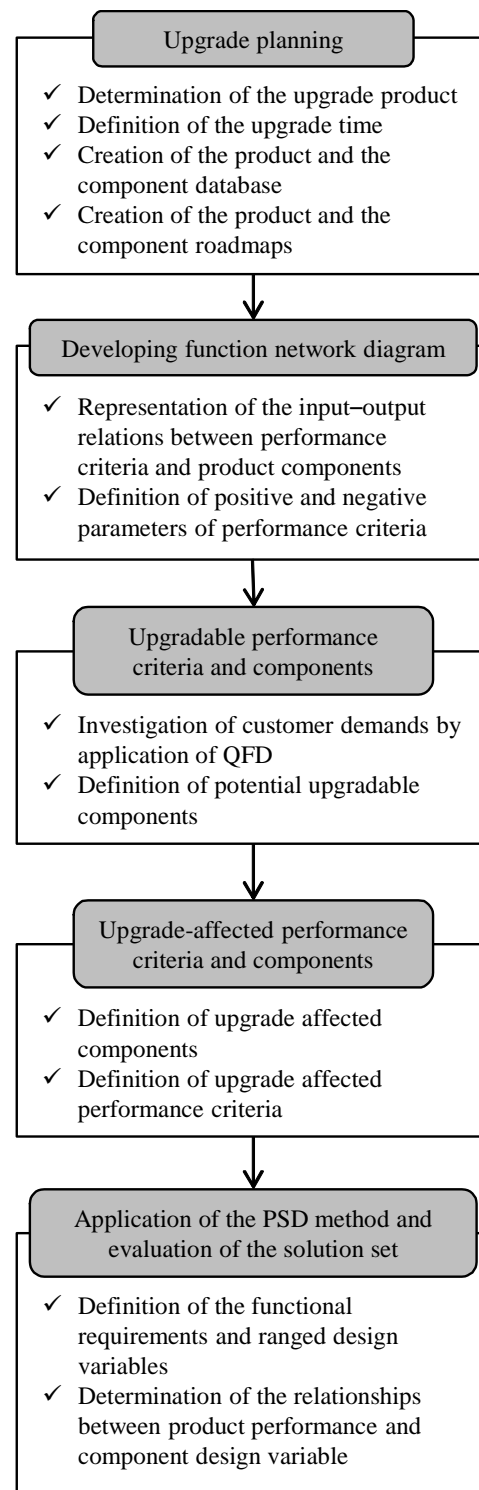


**Figure 1.** Procedure of the proposed upgradable product design method

our methodology is to reduce the extent of product disposal and the resulting environmental load by increasing the product value life by exchanging components with relatively short value life or by

adding new components in accordance with the above description.

## 2.2 Upgrade planning

We establish the criterion of the upgrade time. The definition of the upgrade time is based on several factors such as product upgrade cycle, disposal cycle, or administrative strategy. In addition, product and component databases are created. These databases contain manufacturers, model numbers, launch times, and product and component performance, or design variables such as storage capacity, weight, and dimensions. Based on these databases, we create product and component roadmaps to evaluate the temporal distribution of performance criteria and design variable values. The upgrade time and product and component roadmaps are used for configuring the performance requirements of the products and components. When a product has not yet been launched, roadmaps of similar products can be used for market predictions and for configuring the performance requirements.

## 2.3 Developing the function network

## diagram

A function network diagram shows the input and output relation between performance criteria and product components. This diagram is used to analyze the upgrade components. Figure 2 gives an example of a function network diagram for a vacuum cleaner. In this diagram, performance criteria and product components are represented by individual graphics. Positive parameters denote conditions where a higher or larger value represents better performance, while negative parameters denote conditions where a lower or smaller value represents better performance. The input–output relations between performance criteria and product components are connected by straight lines, and on these lines, the relevant design variables are described. Therefore, designers can easily search for components that are related to upgrade performance by following the input–output lines.

In the case of a vacuum cleaner (Figure 2), for example, suction power is the chosen target for upgrade performance. The components affecting the performance are the motor, turbine fan, body, power unit, and are candidates for upgrade.
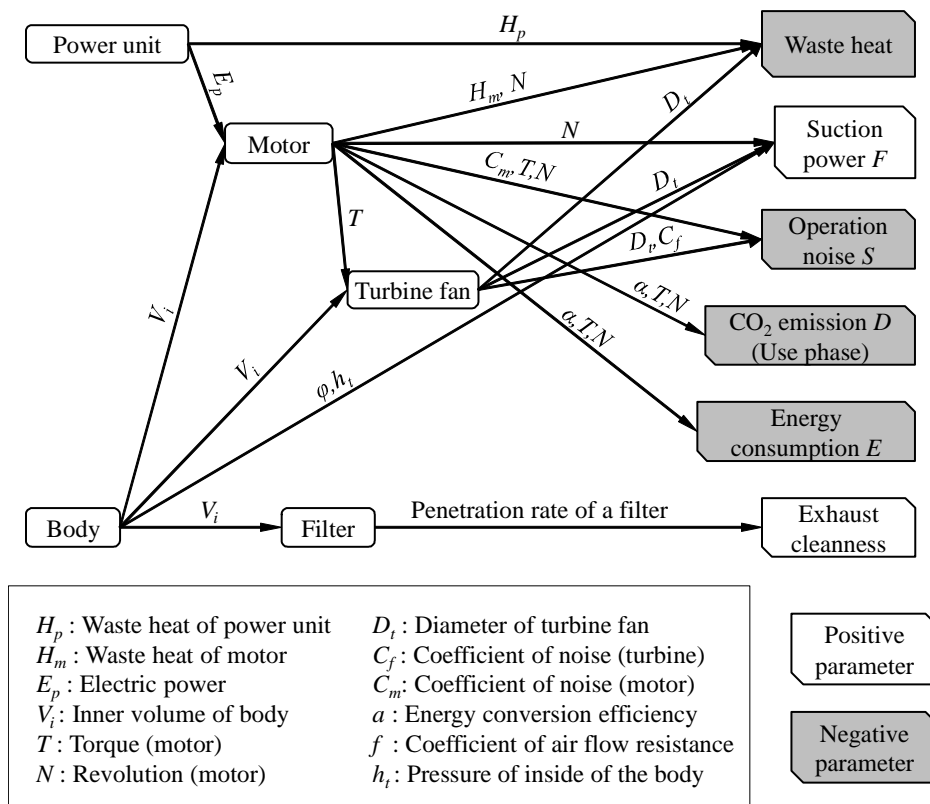


$H_p$ : Waste heat of power unit    $D_t$ : Diameter of turbine fan
$H_m$ : Waste heat of motor    $C_f$ : Coefficient of noise (turbine)
$E_p$ : Electric power    $C_m$: Coefficient of noise (motor)
$V_i$ : Inner volume of body    $a$ : Energy conversion efficiency
$T$ : Torque (motor)    $f$ : Coefficient of air flow resistance
$N$ : Revolution (motor)    $h_t$ : Pressure of inside of the body

Positive parameter

Negative parameter

**Figure 2.** Function network diagram for a vacuum cleaner and graphical representation of the performance criteria and product components

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## 2.4    Upgradable performance criteria and components

Upgradable performance criteria are defined as the product performance upon which customer emphasis is placed and evaluated by the application of quality function deployment (QFD) [11], or by performance criteria with short value life. Using the function network diagram, a designer searches for components that have close relations with the chosen upgrade performance criterion and defines them as potential upgradable components. When the number of upgradable components is identified, the candidates are narrowed down by considering the balance between upgrade performance criteria and possible upgrade-affected performance criteria and components, as described below.

## 2.5    Upgrade-affected performance criteria and components

Upgrade-affected performance criteria indicate that performance changes by exchanging upgrade components. In addition, we define the component that is closely related with an upgrade-affected performance criterion as the upgrade-affected component. Upgrade-affected performance criteria are similarly identified as the upgrade components by using the function network diagram. For example, a designer defines the performance of suction power as the upgrade performance criterion and the turbine fan component as the upgrade component. In this case, the waste heat and operation noise are defined as upgrade-affected performance criteria because the upgrade of the turbine fan causes the diameter $D_t$ of the turbine fan and the noise coefficient $C_f$ of the turbine to increase. Therefore, the power unit and motor are upgrade-affected components. Possible approaches for mitigating this condition can be developed, for example, by building low-level waste heat and low-noise motors into a first-generation vacuum cleaner, or developing and upgrading a motor with high suction power, low-level waste heat, and low noise while upgrading and changing the motor with the turbine fan. These approaches are narrowed down in the same way as that of the upgrade components.

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

In this study, we apply the PSD method to the proposed 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 such range of design solutions, the equations and range of the required product performance and functions, as well as the design variables of the components, are needed. The equations show the relations between product performance and 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.

The 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 a set of design solutions and a preference number. When the design proposal must be modified, the designer should search for a design proposal that satisfies the modified requirements from the set of design solutions. However, in the absence of a design proposal in the set of design solutions, the designer should redefine the required performance and design variables and apply them to the PSD method.

## 3.    Case Study: The Design of a Vacuum Cleaner

In this study, we discuss the application of the proposed method to designing a vacuum cleaner. According to the trade-up cycle to a new model, we assume an upgrade time of approximately seven years (for a customer trade-up percentage of 60%) from the launch time of the first-generation product. To understand the trend of the performance requirements and design variables, we create databases for launched products and performances. Figure 3 shows the product databases for the suction power of vacuum cleaners manufactured by three companies (A, B, and C) from 2005 to 2013. The component database includes motors manufactured by a single company in 2013 because there are no data for motors manufactured before 2012.

Figure 2 shows the function network diagram of a vacuum cleaner. Using the QFD result, we define suction power $F$ [W] as the upgrade performance with high level of value degradation. Using the information in Figure 2, the motor is configured as an upgrade component. In addition, the performance criteria affected by the upgrade are operation noise $S$ [dB], amount of $CO_2$ emissions $D$ [g] in the use phase, energy consumption $E$ [W] in the use phase, and total production cost. The product performance requirements and the range of design variables based on the product database and
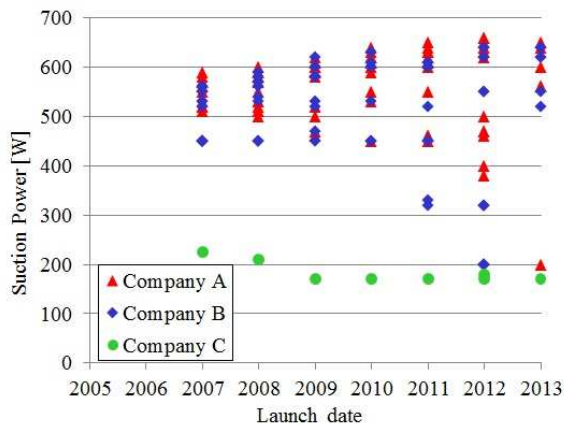
**Figure 3.** Databases for launched products and performance of vacuum cleaners manufactured by three companies

roadmap are configured. Finally, the set of design solutions is calculated using the equations between product performance and design variables from the PSD method.

The range of design variables can increase and decrease relative to the reference values that are assumed as the design variables of the first-generation product. The total production cost for the upgraded product has multiple relations with the costs of the upgrade components and the affected components (i.e., the motor and turbine fan). We assume that the cost of the components increases relative to the difference between the design variables of the first (reference value) and second generations. Therefore, the component cost (excluding the motor and turbine fan) is higher than the cost of the nonupgraded components. Presumably, if the range of design variables decreases, then the increase in total production cost is less than that in the case with increasing range of design variables.

We assume that the product performance and design variables of the components of the second-generation product without upgrade are equal to the upgraded product parameters. In addition, we assume that the cost of the second-generation product without upgrade is equal to that of the first-generation product without upgrade.

We group customer demands into three scenarios:

[scenario 1] the customer requires high suction power,
[scenario 2] the customer requires a low-noise vacuum cleaner, and

[scenario 3] the customer requires low-energy consumption.

## 4. Results and Discussion

With respect to the relations among suction power (upgraded performance), operation noise (upgrade-affected performance criterion), $CO_2$ emission (upgrade-affected performance), and production cost, Figures 4–7 show the performance-oriented solutions (scenario 1: performance-oriented customer), noise avoidance solutions (scenario 2: silence-oriented customer), and ecology-driven solutions (scenario 3: energy-savings-oriented customer).

We obtain the set of design solutions that include performance criteria, production cost, and environmental load ($CO_2$ emission) while considering future fuzzy design information.

Figure 4 compares suction power according to customer demands. The results suggest that suction power is upgraded in all scenarios. In particular, the performance of the second-generation product for scenario 1 is upgraded by about 15% compared with that of the first-generation product.

Figure 5 compares operation noise according to customer demands. Operation noise is the performance criterion affected by the upgrade. Therefore, the operation noise in the second-generation product for scenario 1 is greater by about 10% compared with that in the first-generation product. However, the operation noise in the second-generation product for scenarios 2 and 3 is reduced by about 6% and 3%, respectively.

Figure 6 compares $CO_2$ emission according to customer demands. $CO_2$ emission is also an upgrade-affected performance criterion. The results suggest that $CO_2$ emission is reduced in all scenarios. In particular, the $CO_2$ emission in the second-generation product for scenario 3 is reduced by about 23% compared with that in the first-generation product.

Figure 7 compares production cost according to customer demands. The results suggest that the total production cost of the upgraded product is reduced by about 25% compared with that of the nonupgraded product, and that suction power (upgraded performance) satisfies the required range. Therefore, we conclude that the proposed method can obtain a set of product design solutions of performance criteria, environmental load, and production cost according to the various customer preferences. However, the designers should define
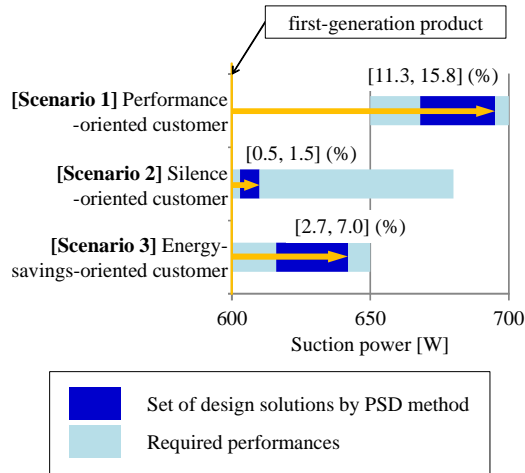
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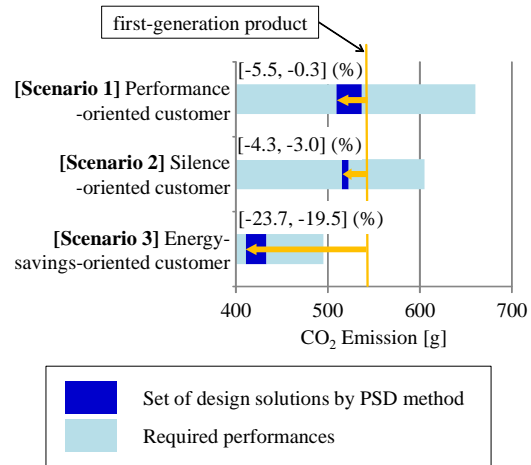**Figure 4.** Comparison of suction power according to customer demands

**Figure 6.** Comparison of $CO_2$ emissions according to customer demands
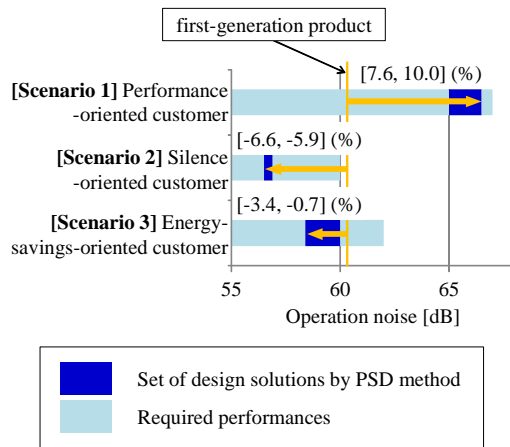
**Figure 5.** Comparison of operation noise according to customer demands

the rate of increase in the first-generation product costs for the upgraded product and include it in the product upgrade requirements.

## 5.　Conclusions

This paper proposed an upgradable design method for obtaining a set of solutions that satisfies multiple product performance criteria, $CO_2$ savings, and reduces production cost by considering uncertain design information of the various customer preferences. To obtain the set of solutions, the PSD method is used to propose an increased product value and extended product life by exchanging components with values below specified thresholds. In addition, we proposed the function network diagram to define the product performance criteria and components with short
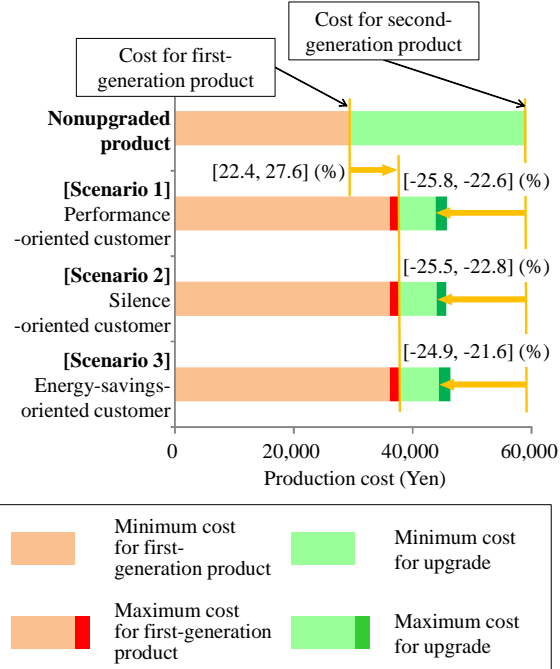
**Figure 7.** Comparison of production cost according to customer demands

value life. We demonstrated the usefulness of this diagram by considering the case of a vacuum cleaner. It is essential to calculate the product manufacturing environmental load, which we have not done, rather than the product environmental load in use.

## 6.　Future Work

In this study, the set of requirements that include future uncertainty is arbitrarily predicted on the

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basis of the distribution of the product roadmap. Moreover, this prediction is based on the designer's knowledge and experience. Therefore, predicting the set of requirements is a subject of future study. In the case of a vacuum cleaner, the motor is upgraded to upgrade suction power. However, we achieved performance upgrade just by upgrading the turbine fan. Therefore, we need to propose the most suitable quantitative method for exchanging components by understanding the effect of exchanging components. In general, durable life is longer than value life. Therefore, the component upgrade should occur before durable life ends and at about the end of value life. Nonetheless, a method is required to define the optimal balance between value life and durable life for designing components with sufficient durable life.

## Acknowledgments

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