https://doi.org/10.20965/ijat.2016.p0690

Paper:

Upgradable Design for Sustainable Manufacturer Performance and Profitability and Reduction of Environmental Load

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[Received April 10, 2016; accepted August 26, 2016]

This study proposes an upgradable product design method that falls under the category of "environmentally conscious" product design methods. The method enhances the product's performance by exchanging or adding only a few of its components. In addition, the proposed method reduces the usage as well as wastage of resources by preventing the disposal of the product itself. This study primarily focuses on manufacturer profit, which was presented as an ill-argued topic in a previous study on upgradable product design methods that potentially provide enhanced sales strategies for upgradable products with an underlying consideration of company sustainability. Moreover, the proposed method in this study assesses how design information uncertainties associated with future prediction (as a ranged value) apply to the concept of set-based design to ultimately obtain ranged sets of design solutions and sales strategies that satisfactorily meet profit, environmental, and functional requirements. Finally, the proposed method obtains ranged design solutions that can realize low environmental loads, low product price, and a highly profitable upgradable product via exclusive application to a multifunctional laser printer scenario. The results of this study indicate the effectiveness of such an upgradable product design method as a vital approach in building a sustainable society.

Keywords: design for upgradability, preference set-based design, CO_2 emission, sustainability, profitability

1. Introduction

To achieve a sustainable society, reductions in resource usage, disposal, and environmental load emissions are essential. The development of environmentally conscious design methods such as reuse, recycle, upgradable product design methods, and promotion of 3R (reduce, reuse, and recycle) is a necessary component and approach for realizing such a society [1]. Currently, numerous manufacturers regularly implement environmentally conscious product design methods, such as design for disassembly (DfD) and remanufacturing [2], and have configured their supply chains for sustainability [3]. Usually, environmentally conscious products aim to reduce resource usage/disposal and the amounts of environmental byproduct loads such as CO_2, NO_x, and SO_x. However, consideration of the manufacturer and consumer sustainability is also vital for attaining and preserving a sustainable society. Pro-environmental activities often culminate in lower environmental loads with associated risks to profit; therefore, companies and consumers often resist such actions. Consequently, this study focuses on upgradable product designs and aims to propose design methods for upgradable products that simultaneously achieve sustainability from the perspectives of the society, consumers, and manufacturers. According to previous studies, upgradable products have effectively demonstrated their adaptability to competition, user needs (i.e., the consumer aspect) [4], and CO_2 reduction (i.e., the social aspect) [5]. In addition, few upgradable products have been distributed as eco-friendly products [6]. Therefore, this study focuses on the principles of cost and profit (i.e., the manufacturer aspect). The authors achieved upgradable product design methods for sustainability by considering their characteristics; i.e., only a handful of upward 2nd generation product components should be manufactured, sold, and disposed of. Thus, these characteristics indicate that a potential exists for upgradable products to maintain up-to-date performance at low cost (price) and low environmental load compared with conventional products. **Fig. 1** shows the ideal relationship between product price, cost, and profit.

2. Related Works and Their Limitations

2.1. Design Support and Planning System

In this section, previously proposed upgradable product design methods and their achievements and agendas are introduced. First, Ishigami et al. proposed an upgradable product design support system and algorithm

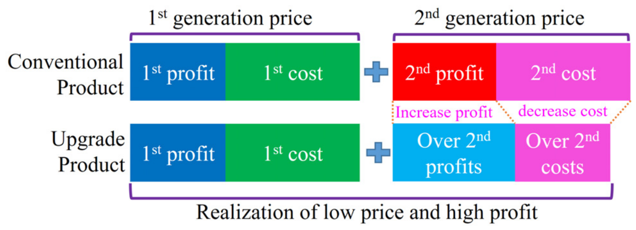

Fig. 1. Ideal relationship between product price, cost, and profit.

for searching design solutions [7]. In this system, they collected product and component databases that would be distributed in the future and defined design solutions as serial combinations of these components. This system also represents future market functional demands as a ranged value according to a set-based theory [8] to adapt to future uncertainties. Watanabe et al. proposed an upgrade planning method [9] based on the work of Ishigami et al. and its prototype system. They developed functional roadmaps on the basis of information in the aforementioned databases. To adapt to various consumer demands, the method divides a ranged roadmap and qualitatively allocates consumers to the roadmap as either high-end range or low-end range. These efforts ultimately acknowledged the prospect(s) of future uncertainties and user-demand diversity. However, these efforts also require additional evaluations regarding potentially unexpected circumstances such as changes to roadmaps and user demands or modifications in an upgrade plan. Thus, the components or design parameters needing reassessment should always be of prime focus.

2.2. Design Support System Based on 3D CAD

Fukushige et al. proposed an upgradable product design method [10] based on three-dimensional computer-aided design (3D CAD) that can universally satisfy a component's geometric constraint. Their method was proposed as a follow-up to those of Ishigami et al. and Watanabe et al. They achieved a state of multigenerational upgrade planning while satisfying geometrical constraints by utilizing three separate types of components, namely, platform, adaptive, and upgrade-target. However, these methods involved Ishigami et al. and Watanabe et al. are ultimately evaluating their applicability from a functional viewpoint without invoking economic or environmental quantitative considerations.

2.3. Upgradable Design Based on Set-Based Design

Inoue et al. proposed an upgradable product design method [11] based on a set-based design method [12]. This method adapts to future uncertainties derived from market trend predictions by using ranged values. In particular, this method can provide a design solution represented by ranged functional and design values. Ishigami et al.'s method was also based on set-based theory with its design solution represented as a serial combination of components, whereas that of Inoue et al. depicts a ranged

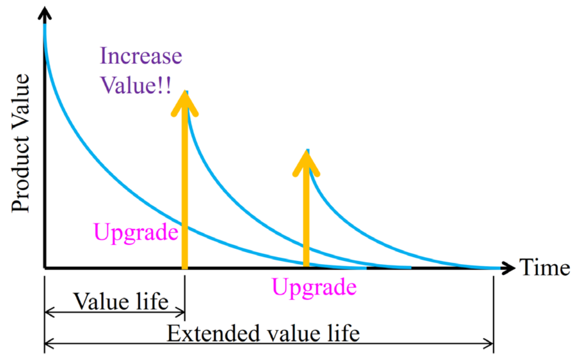

Fig. 2. Temporally debased value and its upgrading [13].

value of component design variables. Therefore, if a design scenario is changed, this method has the potential for successful implementation of such a change without the need to rethink component specifications and design parameters.

In addition, Inoue et al. preliminarily considered adverse effects caused by potential component exchanges and qualitatively evaluated the effects of reducing environmental load and product price. The results of their study indicate that upgradable products can reduce environmental loads and product price through the realization of functional improvement and various consumer demands. However, these results are still being debated with regard to how the reductions may affect manufacturer profitability during the product lifecycle.

3. Design for Upgradability to Support a Sustainable Society

3.1. Purposes and Agendas of Design for Upgradability

The upgradable product design method can enhance a temporally deteriorated product value (i.e., extend the life of product's value) and ultimately prevent product disposal caused by such deterioration. This is shown in **Fig. 2**, where the life of the product's value is extended by some upgrading. In addition, this method aims to design upgrade-compatible products in advance via future market predictions. Generally, to implement upgrade design into product design, the following agendas consistently require attention and adequate resolution:

- Adaption of future uncertainties
- Handling adverse effects
- Decision for appropriate upgrade timing
- Evaluation of cost, environmental load, and reliability

In previous studies, one proposed method predicted future required performance as a ranged value and found that certain combinations of product components can achieve the desired performance levels within a predicted range [7, 9]. An additional method also predicts the ranged performance and obtains design variables as ranged values by applying a set-based design method that can obtain ranged sets of design solutions that optimally satisfy multi-objective requirements [11]. From previous studies, the following versatilities are hence validated: an upgradable product results in a lower product price, adapts to various consumer demands, maintains up-to-date functionality [11], and reduces the environmental load over the entire product lifecycle [14]. In this study, the authors considerably focus on manufacturer profitability because if an upgradable product design method does not yield profit, a company will likely not attempt to implement such a method into its product design policy. Thus, the proposed method aims to design a new upgradable product that can provide sustainability to the manufacturer (higher lifecycle profit), consumer (lower lifecycle product price, frequent functional upgrades), and society (lower lifecycle environmental load) simultaneously. To achieve such a design, this study postulates certain hypothetical design assumptions required at future upgrade times as ranged values. In addition, the proposed method applies a preference set-based design method [15] that can obtain multi-objective-ranged design solutions and provide certain indicators of final point-based design solution decisions to designers under the constraint of design condition uncertainties. Consequently, the proposed method can lead to the attainment of appropriate design solutions that yield maximum profit, reduced price, and minimal environmental loads. The protocols of such a proposed method are described below.

3.2. Design Protocols for the Proposed Method

The proposed method broadly comprises six design phases: decision of target product, estimation of upgrade time, definition of upgradable functions and components, consideration and resolution of adverse effects, definition of requirements, and obtaining/evaluating design solutions. In the following subsections, the details for each design phase are discussed.

3.2.1. Deciding the Target Product

First, a designer must decide on a potential target upgrade product. From prior studies, it was validated that upgradable product design promotes state-of-the-art performance, lowers consumer prices, and reduces environmental loads; this ultimately extends product lifetimes. Thus, technologically innovative and high-priced products with high environmental loads and short durable lives should ultimately be selected. After this decision is rendered, the designer then collects information regarding a target product's functions, performance, components, and replacement/disposal cycles to predict future market trends. In addition, the designer develops a structural model of the target product as shown in **Fig. 3**, which hierarchically portrays the relationships between product demands, functions, units, sub-units, and components. This figure is created after determining the target product decision and investigation of consumer demands and their priority, functions needed for realization of these demands, product units needed for these functions, and components that consist of these units. In executing proper upgrading for demand and priority, the proposed method transfers the priority to each layer and identifies functions and units/components that should be upgraded.

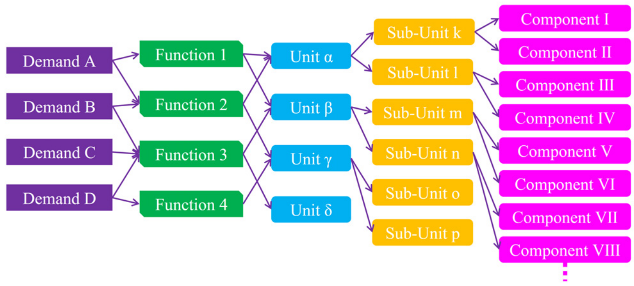

Fig. 3. Structural model of an upgradable product.

3.2.2. Estimation of Upgrade Time

Second, the designer defines a product's upgrade time. There are two separate approaches that may be implemented for the execution of this task: (1) to initially define a concrete upgrade time and accordingly design an associated upgradable product that can provide maximum profit, minimum price, and reduced environmental load and (2) to initially estimate a rough upgrade time and subsequently ensure an optimal upgrade time that can provide maximum profit, minimum price, and reduced environmental load. In either case, upgrade time is defined on the basis of previous replacement or disposal cycles and legal durable years [16].

3.2.3. Definition of Upgradable Function and Component

Next, the designer defines upgradable functions and components. Upgradable functions denote product functions that are to be enhanced at upgrade time. Moreover, an upgradable component means a product component that closely relates to an upgradable function and will be exchanged at upgrade time. To define these, the designer needs to set consumer-demand priorities. Analytic hierarchy process (AHP) [17] and conjoint analysis [18] are efficient methods for ranking such demands. Then, the designer translates these demand priorities into product functions. Quality functional deployment (QFD) [19] is one method for efficiently conducting this process. The function that has the highest priority is ultimately designated as the "upgradable function." In addition, the designer transfers an upgradable function's priority to product units, sub-units, and components in sequence and accordingly defines the "upgradable component" as the one with the closest relationship (or correlation) with the upgradable function. From the viewpoint of cost and environmental load, the product component or sub-unit selection is often recommended as the upgradable component. However, for cases where upgradable components or sub-units are not easily disassembled (e.g., a laptop's CPU),

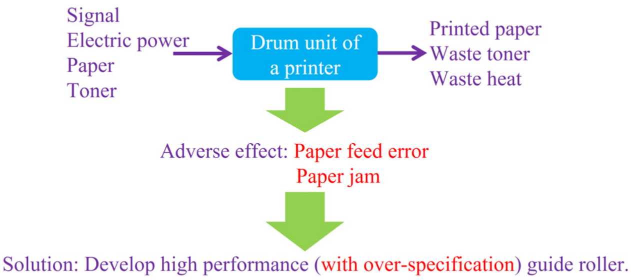

Fig. 4. Determination and handling process of adverse effects.

the designer should ultimately redefine the product unit that contains such a potential component or sub-unit as an upgradable component.

3.2.4. Consideration and Resolution of Adverse Effects

Exchanging upgradable components occasionally not only enhances the upgradable functions but also generates adverse effects. For example, in the case of a laser printer, if the designer exchanges drum units to enhance print speed, paper feed and ejection errors and/or misprinting may occur at a higher frequency than before. The designer assumes the occurrence of adverse effects by referring to the relationship between the inputs and outputs of an upgradable component, as shown in **Fig. 4**. In the aforementioned case, inputs indicate electric signal and power, paper, and toner; outputs indicate printed paper, waste toner, and heat. To reduce or avoid potential adverse effects, the designer defines upgrade-assist components and accordingly adds over-specifications to such components. Upgrade-assist components denote product components that closely relate to potential adverse effects and include over-specifications. In the printer case, the adverse effects emerged as paper feed and ejection errors; thus, the designer defines paper guide roller as the upgrade-assist component and develops an over-engineered roller based on his knowledge. Adding excess over-specifications to upgrade-assist components, however, may result in increased production costs and environmental loads. Therefore, the designer is required to add an "appropriate level" of over-specification. There are two recommended approaches for mounting upgrade-assist components to upgradable products: (1) mounting assist-components with over-specifications to first-generation upgradable products and using them for the entire product lifecycle and (2) mounting assist-components without over-specifications to first-generation upgradable products and subsequently exchanging such assist-components with upgradable components in each product generation. In the case where upgrade-assist components are highly durable, the designer is encouraged to employ the former method. Otherwise, the latter method should be applied.

3.2.5. Definition of Requirements

After determining the upgradable functions and components and the adverse effects, and rendering upgrade-assist components, the designer then predicts future performance requirements. Because accurate prediction is very difficult, the future performance requirements and design variables are defined as ranged values to adapt to uncertainties. In addition, the proposed method obtains ranged design solutions using a preference set-based design method. Thus, the designer may discretionarily add a preference to these ranges with consideration to design intent. The initial ranges of performance and design variables that the designer predicts are estimated on the basis of temporal performance shifts of previous or similar products.

To obtain ranged design solutions by applying preference set-based design methods, the designer needs to prepare equations that represent relationships between product functions and components. In the absence of equations, the designer should define approximate mathematical relationships based on past findings.

During the sale of an upgradable product, the customer purchases the entire first-generation product and only a second-generation upgradable component. Therefore, the extent of sales and profit may possibly be lower than the amounts normally specified for the product. The proposed method develops a highly profitable upgradable product by adding a high profit rate to the upgradable component even though the number of product sales ultimately reduces. Production costs of upgradable components include a number of economic uncertainties as well owing to rising raw material costs and exchange rate fluctuations. Hence, the designer must estimate production costs based on previous exchange rate fluctuations and material price shifts and ultimately derive a potential profit rate range that can achieve both higher profits and lower consumer prices.

The amount of environmental load in a product's lifecycle can fluctuate because of a subject component's producing country and electric power company. In addition, the amount of environmental load entails considerable additional uncertainties because upgradable components are produced and distributed at a future upgrade time. Therefore, calculation and evaluation of the environmental load are conducted as well using a ranged value. Consequently, proposed method recommends handling any uncertainties as ranged value.

3.2.6. Obtaining and Evaluating Design Solutions

In the proposed design method, a design solution is obtained as shown in **Fig. 5**. In **Fig. 5**, input indicates the preferences attached to initial ranges of design variables (e.g., dimensions, upgrade time, profit rate, etc.), functions (e.g., performance, profit, environmental load, etc.), and equations, which mean the relationship between design variables and functions. By applying the preference set-based design method, solution ranges (output) are obtained. The resultant solution ranges denote multi-

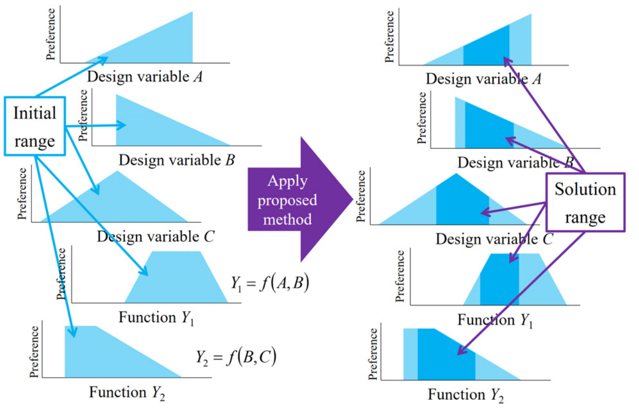

Fig. 5. Concept of obtaining ranged design solutions with preference.

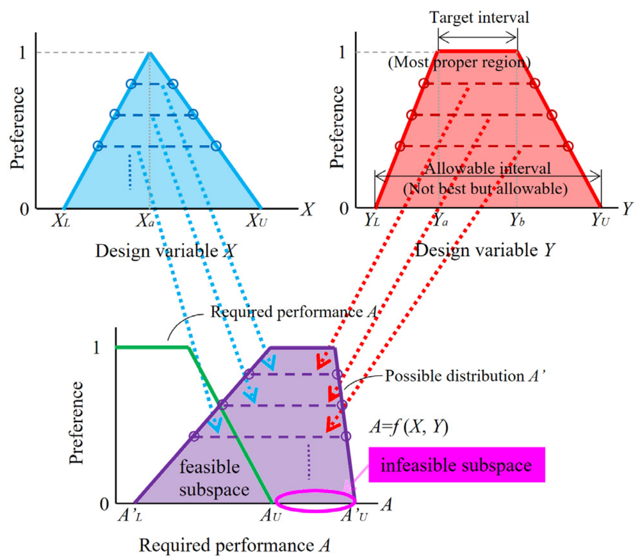

Fig. 6. Schematic illustration of the set propagation process.

objective ranges that can simultaneously satisfy the entire variables and functions within the initial ranges.

The designer selects a point-based final design proposal from the obtained ranged values with reference to a preference. In the absence of ranged solutions that satisfy all requirements, the designer needs to modify requirements or initial design variable ranges and ultimately apply these to the preference set-based design method once again.

4. Preference Set-Based Design Method [15]

4.1. Set Representation

This section describes the preference set-based design (PSD) method, which is the key concept of the proposed upgradable product design method. The PSD method is an improved set-based design method with the concept of preference number and comprises the following steps: set representation, set propagation, set modification, and set narrowing. In the set representation step, the designer defines the required performance and design variables as ranged values with a preference number. The preference number indicates the designer's intents on the design and defines each intent as a number from 0 to 1. A preference number of "0" expresses the least preferable range, and the number "1" expresses the most preferable range as shown **Fig. 6**. These numbers are assigned to the ranged values based on the designer's experience and knowledge.

4.2. Set Propagation

Next, the PSD method calculates the performance intervals using initial design variable ranges and their preference numbers. This interval is called the possible distribution and indicates the product's expected performance range derived from the design variables and equations that represent the relationships between the performance and design variables. Possible distribution is calculated by decomposing the range of the ordinate (i.e., preference number) [0, 1] into a finite number and obtaining the minimum and maximum values of the interval for each preference level by using the PSO (particle swarm optimization) algorithm [22]. **Fig. 6** depicts the calculation process for the possible distribution. In **Fig. 6**, possible distribution A' (purple area) is computed by using the equation, $A = f(X,Y)$ and the intervals of design variable X (blue area) and Y (red area).

4.3. Set Modification

If all the intersections of possible distributions and initial required performance ranges exist, it means that a feasible subrange exists within the initial range. Otherwise, the required performance ranges and/or design variable ranges should be modified.

4.4. Set Narrowing

In the case where all possible distributions and initial required performance ranges have common feasible subranges, some distributions may have infeasible subranges as well (e.g., in **Fig. 6**, the pink highlighted area in purple possible distribution). Therefore, such subranges should be cut off to obtain the specific design solution ranges that satisfy multiple performance requirement ranges and design variable ranges. In particular, the range of each design variable is divided into smaller subranges and the combinations of the divided intervals of the design variables are propagated into required performance ranges. This process is repeated until all combinations are located inside the corresponding performance interval. **Fig. 7** illustrates this process. In **Fig. 7**, the ranges of design variables X and Y are divided into two subranges individually and propagated. Propagated possible distribution A'_1 (green area), which is derived from the left subrange of X (light blue area) and left subrange of Y (red area), is located within the required performance range. Thus, possible distribution A'_1 indicates feasible interval. On the other hand, propagated possible distribution A'_2 (orange area), which is derived from the right subrange of X (dark blue area) and left subrange of Y (red area), has both feasible

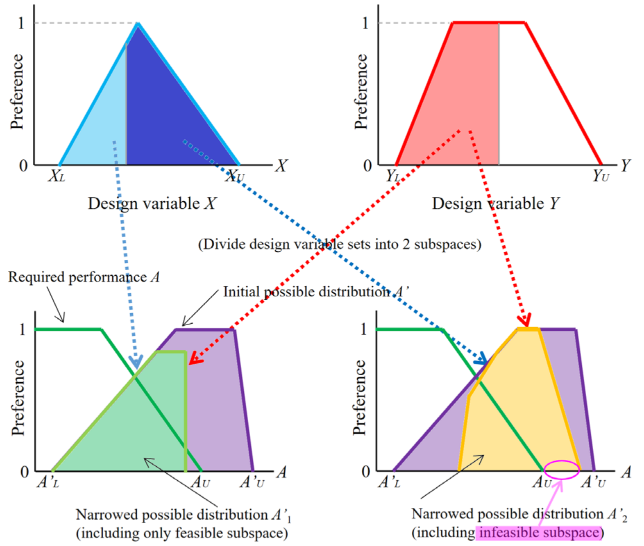

Fig. 7. Schematic illustration of the set narrowing process.

and infeasible ranges. Therefore, possible distribution A'_2 should be narrowed down by dividing the dark blue and red areas and propagating again.

5. Case Study: Multifunction Printer Design Problem

5.1. Design Conditions

This study applies its proposed design method to the design problem of a multifunction laser printer in order to verify its applicability. **Table 1** shows the assumed design conditions of the case study. The authors assumed consumer demands for the multifunction laser printer and configured the associated design conditions by independently conducting AHP and QFD. In this case study, a guide roller is defined as the upgrade-assist component. Generally, the guide roller is one of the components of the drum unit and this upgrade-assist component is also upgradable. Therefore, it was decided that adding over-specification to preemptively reduce the potential adverse effects was not necessary. However, the authors did assume increases in production costs and environmental loads over second-generation upgradable components and ultimately obtained a ranged design solution that could achieve low environmental load, low price, and high profitability even though such increases had occurred.

5.2. Evaluation of the Advantages of an Upgradable Product

The laser printer case study evaluated the utility of an upgradable product compared with a conventional product from the viewpoint of product price, profit, and the amount of environmental load during the entire product lifecycle. The study assumed an evaluation period of 120 months from the distribution of the first generation product. The conventional product is assumed to be replaced after 60 months (legal durable years of a multifunction printer) after first distribution. In the case of the upgradable product, the authors defined upgrade time as the design variable and obtained a ranged upgrade time that is maximally compatible with low price, low environmental load, and high profitability using the preference set-based design method. Therefore, upgradable components will probably be exchanged more than once. In addition, the authors assumed that 70 to 80% of customers will upgrade their product.

Using the abovementioned data, this application obtained ranges of upgrade times and profit rates of upgradable components that can achieve low price, low environmental load, and high profitability under the condition of 70 to 80% upgrade rate.

Table 1. Laser printer design conditions.

Upgrade rate (Constant)	: From 70% to 80%
Unit Sales (1st generation)	: 10,000
Upgrade time	: Within 3 to 7 years
Upgradable (UG) function	: Print Speed
Upgradable component	: Drum unit
Adverse effects	: Paper feed error, jam
Upgrade-assist component	: Guide roller (Drum unit)
UG Component Cost [Yen]	: from 25,000 to 30,000
UG Component environmental load [kg]	: from 18 to 40

5.3. Assumptions Regarding Environmental Load, Production Cost, and Profit

The case study application evaluated and calculated environmental load as the quantity of CO_2 emission during the entire product lifecycle. To calculate this amount, the authors investigated previous life cycle inventory (LCI) data [20] and information about the material and weight of the multifunction laser printer and CO_2 emission basic units [21]. The authors consequently assumed that the amounts of CO_2 emission from the first and second conventional products are the same. In the case of the upgradable product, however, the amount of CO_2 emission from the upgradable component is estimated as a ranged value because this amount entails uncertainties such as fluctuations of basic units.

The authors assumed that the product price usually includes a 5% manufacturer's profit. In addition, the product price, cost, and profit of the first and second conventional products were all assumed to be the same in value. In the case of the upgradable product, however, the production cost of the upgradable component was estimated as a ranged value because of possible fluctuations due to rising raw material costs and exchange rate variations.

5.4. Results and Discussion

Figure 8 shows the ranged design solution and preference for the printer design variables. In **Fig. 8**, the resultant range indicates that over 2nd gen drum unit profit

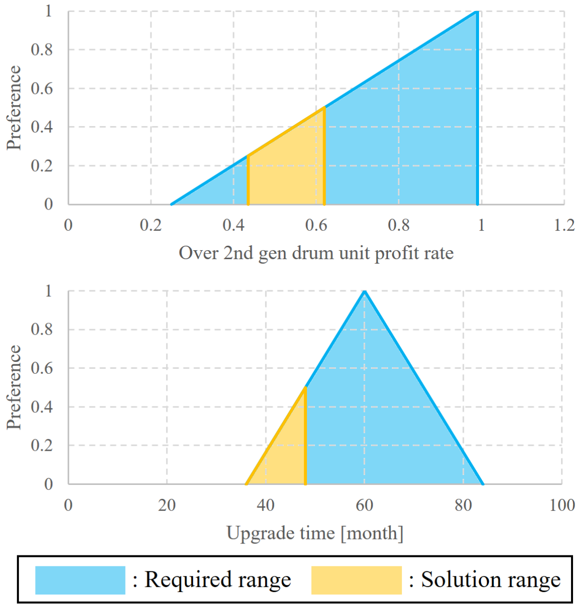

Fig. 8. Obtained ranged solutions of design variables.

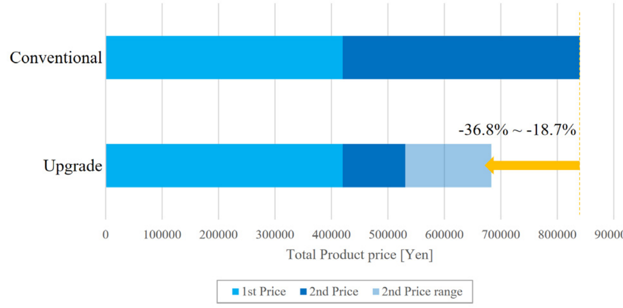

Fig. 9. Solution ranges of the total product prices of conventional and upgradable products.

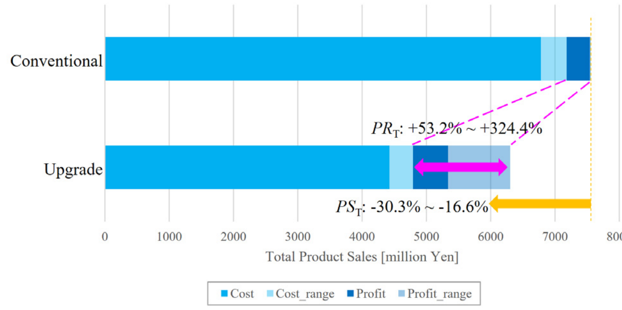

Fig. 10. Solution ranges of the total product sales and profits of conventional and upgradable products.

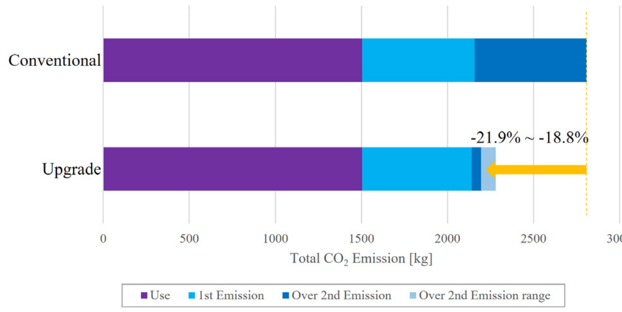

Fig. 11. Comparison of CO_2 emissions for an entire multifunction printer lifecycle.

rate is able to configure from 43.5 to 62.0% (62.0% is the most preferable value and conventional printer's profit rate is assumed 5%) and upgrade time is recommended to be scheduled between 36 to 48 months (48 months is the most preferable) from the first distribution and/or every upgrade timing. Therefore, an upgradable printer is able to enhance its function twice or even three times, i.e., as frequently as a conventional printer. **Figs. 9**, **10**, and **11** show the obtained ranged design solution in terms of the product price, amounts of sales and profits, and CO_2 emissions, respectively. **Fig. 9** shows that the total product price of an upgradable product could be reduced from 36.8 to 18.7% compared with the conventional product. Moreover, **Fig. 10** shows that the total profit could be increased from 53.2 to 324.4% compared with the conventional product even though the total product sales declined from 30.3 to 16.6%. Because the cost of the upgradable component is very small (from 6.3 to 7.5% of total product cost) and the profit rate of such component is very high, these results (realization of low lifecycle product price and high lifecycle profit) are obtained.

Figure 11 shows that the total amount of CO_2 emissions from the upgradable product was reduced from 21.9 to 18.8%. Consequently, the upgradable product was able to simultaneously enhance product function (more frequently), reduce product price and environmental load, and yield higher profits for manufacturers compared with the conventional product.

6. Conclusions

This study proposed an upgradable product design method focusing on the product functional enhancement cycle, environmental load reduction, and manufacturer profit. Moreover, the proposed design method presents several uncertainties such as future required performance levels and procurement costs as ranged values. This study addresses future uncertainties by applying preference set-based design methods that assist in the attainment of a ranged design solution with preferences that can simultaneously satisfy requirements regarding product function, price, manufacturer profit, and environmental load. The proposed method was successfully applied to an example design problem of a multifunction laser printer, which consequently demonstrated its overall viability in the attainment of a multi-objective ranged design solution. Hence, it was altogether demonstrated that an upgradable product design method is a vital approach that will significantly contribute to a sustainable society paradigm.

However, this study focused only on manufacturer profitability but did not consider those of material production entities and parts suppliers. Therefore, developing new upgradable product design methods that consider profitability of all involved companies supporting the subject process is planned in the future. In addition, this study demonstrated the potential that upgradable products have for readily resolving product reliability issues regarding component durability (e.g., components of an upgradable product need not be expensive and overly durable) because these products have to frequently exchange their components. Furthermore, they are allowed to have "enough" durability and be inherently less expensive. Hence, upgradable product designs should have the ability to significantly enhance the reliability of product systems at low cost. This compelling issue will also be given a major emphasis and evaluation in the authors' future study on this subject.

Acknowledgements

This work was partially supported by JSPS KAKENHI Grant Number 26870628.

References:

[1] http://www.env.go.jp/en/wpaper/2014/pdf/00.pdf [accessed Dec. 26, 2015]

[2] K. Masui, "Current Status of Environmentally Conscious Design Among Japanese Manufacturers," Int. J. of Automation Technology, Vol.3, No.1, pp. 19-25, 2009.

[3] T. Yamada, Y. Yoshizaki, N. Itsubo, and M. Inoue, "Low-Carbon and Economic Supplier Selection Using Life Cycle Inventory Database by Asian International Input-Output Tables," Proc. of 12th GCSM, 2012.

[4] O. Pialot and D. Millet, "Why upgradability should be considered for rationalizing materials?," Proc. of the 21th CIRP Int. Conf. on Life Cycle Enginering, pp. 379-384, 2014.

[5] S. Yamada, T. Yamada, S. Bracke, and M. Inoue, "Upgradable Design for Reduction of Production Cost and CO_2 Emission – Case Study of a Laptop Computer," Applied Mechanics and Materials, Vol.761, pp. 589-593, May 2015.

[6] J. Ospina, P. Maher, C. Fitzpatrck, S. Hickey, K. Schischke, I. Vidorreta, J. Garatea, M. Yang, G. Obersteiner, E. den Boer, and I.D. Williams, "The D4R laptop computer – from prototype to market leader," Proc. of CARE INNOVATION 2014, November 2014.

[7] Y. Ishigami, H. Yagi, S. Kondoh, Y. Umeda, Y. Shimomura, and M. Yoshioka, "Development of a design methodology for upgradability involving changes of functions," Proc. of EcoDesign 2003 Int. Sym., pp. 235-242, 2003.

[8] W. W. Finch and A. C. Ward, "Generalized set propagation operations over relation of more than three variables," AIEDAM, Vol.9, pp. 231-242, 1995.

[9] K. Watanabe, Y. Shimomura, A. Matsuda, S. Kondoh, and Y. Umeda, "Upgrade planning for upgradeable product design," Quantified Eco-Efficiency, Vol.22, pp. 261-281, 2007.

[10] S. Fukushige, M. Arino, and Y. Umeda, "Computer-aided design for product upgradability under geometric constraints," Proc. of EcoDesign 2011 Int. Sym., pp. 828-831, 2011.

[11] M. Inoue, S. Yamada, T. Yamada, and S. Bracke, "An Upgradable Product Design Method for Improving Performance, CO_2 Savings, and Production Cost Reduction: Vacuum Cleaner Case Study," Int. J. of SCM, Vol.3, No.4, pp. 100-106, 2014.

[12] D. K. Sobek, A. C. Ward, and J. K. Liker, "Toyota's Principles of Set-Based Concurrent Engineering," Sloan Manag. Rev., Vol.40, No.2, pp. 67-83, 1999.

[13] S. Bracke, J. Michalski, M. Inoue, and T. Yamada, "CDMF-RELSUS concept: reliable products are sustainable products- influences on product design, manufacturing and use phase," Int. J. of Sustainable Manufacturing, Vol.3, No.1, pp. 57-73, 2014.

[14] S. Yamada, T. Yamada, K. Nakano, S. Bracke, and M. Inoue, "An Environmental Conscious Product Design Method for Sustainability of Product's Value," Proc. of CARE INNOVATION 2014, November, 2014.

[15] M. Inoue, Y.-E. Nahm, K. Tanaka, and H. Ishikawa, "Collaborative engineering among designers with different preferences: application of the preference set-based design to the design problem of an automotive front-side frame," CE: Research and Applications, Vol.21, No.4, pp. 252-267, 2013.

[16] https://www.keisan.nta.go.jp/survey/publish/34255/faq/34311/faq_34353.php [accessed Apr. 14, 2015]

[17] Y. Hirayama, Y. Matsuno, and H. Honda, "Application of Analytic Hierarchy Process to Analysis of Consumers' Decision Making," Environ Sci., Vol.18, No.3, pp. 217-227, 2005 (in Japanese).

[18] P. E. Green and V. Srinivasan, "Conjoint Analysis in Consumer Research: Issues and Outlook," J. of Consumer Research, Vol.5, No.2, pp. 103-123, 1978.

[19] Y. Akao, "QFD: quality function deployment- integrating customer requirements into product design," Productivity Press, 2004.

[20] M. Ishikawa and M. Akai, "LCA Guidebook for Companies," Nikkan Kogyo Shimbun, 2001 (in Japanese).

[21] http://www.cms-cfp-japan.jp/calculate/verify/pdf/CO2kansanryo_db_ver4_jp_20120410.pdf [accessed May. 21, 2014]

[22] J. Kennedy and R. Eberhart, "Particle Swarm Optimization," Proc. of IEEE Int. Conf. on Neural Networks, Vol.4, pp. 1942-1948, 1995.

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