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ROBUST DESIGN METHOD FOR PRODUCT LIFE CYCLE CONSIDERING THE FUTURE UNCERTAINTIES

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1. Introduction

Environmental consciousness has gained more and more interest in recent years, and product life cycle design that aims to maximize total performance while minimizing its environmental load and costs should be implemented. In general, there exist significant uncertainties in product life cycle. Preferences for products and their operational conditions differ from user to user, and this causes significant uncertainties in product conditions, lifetime, and the amount of available resources for component reuse and recycling, which are important factors for a designer to determine adequate life cycle options (e.g., reuse, recycling, landfill etc.) of products and their components. Therefore, a design method of product life cycle that is robust and tolerant against these uncertainties should be established.

Many kinds of life cycle design support tools have been proposed in recent years and some of them handle the uncertainties in product life cycle. Life cycle scenario description tools [Yamagiwa 2004, Suesada et al. 2007], which support a designer to explicitly describe an expected life cycle scenario of a product, help a designer to identify future uncertainties in product life cycle. Life cycle simulation (LCS) tools are also effective for evaluation of the severity of uncertainties especially when it is used with Monte Carlo simulation methods [Kobayashi et al. 2005]. However, life cycle scenario description tool itself can not calculate the optimal values for design parameters and it is difficult for a designer to find out adequate design solution (i.e., product specification and life cycle options for components etc.) from the results of LCS due to its complex calculation model containing a large number of inter-relating parameters.

To solve these problems, this paper proposes a robust design method for product life cycle considering the various uncertainties in product life cycle. In this method, environmental and economic performance of a product throughout whole life cycle is evaluated by Total Performance Index (TPI) [Kondoh et al. 2006], which represents a balance of customer's utility value and its resulting environmental load and cost, and Taguchi's robust design method [Taguchi et al. 1989] is employed to derive a design solution as a set of optimal specification of a product and life cycle option (LCOP) for each component so as to maximize the average of TPI while minimizing its variation.

2. Approach for total performance design

Our approaches for deriving adequate solution of product specification and its life cycle option are summarized as follows;

1. Total performance index (TPI) as an objective function

Total performance index (TPI) [Kondoh et al. 2006] of a product, which represents efficiency of utility value production from environmental and economic viewpoints at the same time, is used as an objective function in this study.
2. Uncertainties represented as interval values
In order to handle various uncertainties in product life cycle (e.g., lifetime, operating condition etc.), we represent parameters that are used for calculation of TPI as interval values (i.e., from lower bound to upper bound), and calculate TPI of a product as interval values.
3. Robust design of product life cycle
The objective of this study is to derive adequate design solution that maximizes the TPI while eliminating the effect of the various uncertainties in product life cycle. To this end, we employ Taguchi's robust design method [Taguchi et al. 1989]. By employing Taguchi's robust design method, various uncertainties that cause the significant variation in objective function (i.e., TPI in this paper) can be treated as noise factors and near optimum design solution that is robust and tolerant against these factors is determined.
The remainder of this paper is organized as follows. Section 3 describes how to measure total performance of a product throughout its whole life cycle based on our previous work [Knodoh et al. 2006]. Section 4 describes life cycle design method focusing on the specification and lifetime of a product considering the uncertainties in product life cycle. Section 5 illustrates calculation procedure of our method with an example of a laptop computer. Section 6 concludes the paper.

3. Total performance of product life cycle

3.1 Total performance index (TPI)

Since all products are produced to satisfy customer needs, total performance throughout product life cycle is evaluated as balance of customer's utility value (*UV*) and its resulting environmental load and cost throughout whole life cycle. We define TPI as follows;

$$TPI = \frac{UV}{\sqrt{LCE \cdot LCC}} \tag{1}$$

where, *LCE* and *LCC* denote environmental load and cost throughout whole life cycle, respectively.

3.2 Formulation of UV

In general, UV of a product becomes better the higher product's functional performance increases and the longer it is continued to use. Thus UV of a product is defined as time integral of product value, assuming that product value is strongly correlated with its functional performance.

$$UV = \int_{st}^{tt} V(t)dt \tag{2}$$

where, *st*, *tt*, and *V(t)* denote starting and termination time of a product-use stage and product value at time *t*, respectively.
Based on Multi-Attribute Utility Theory (MAUT) [Winterfeld et al. 1986], product value at time *t* can be allocated to its dominant FRs given as follows;

$$V(t) = \sum_i V_i(t) \tag{3}$$

$$V_i(t) = w_i(t) FR_i(t) \tag{4}$$

where, i, $V_i(t)$, $w_i(t)$ and $FR_i(t)$ denote index of FRs, product value allocated to FR_i, weighted factor for FR_i, and functional performance of FR_i at time t, respectively.

Weighted factor for each FR represents its importance to the customers. In this study, we assume that a product value is measured by its market price. Therefore, importance of each FR can be estimated by conjoint analysis [Green et al. 1978] of various products with different specification.
A product value deteriorates by following two causes; namely, (i) physical causes and (ii) value causes [Daimon et al. 2004]. Physical causes include failure and degradation of product due to aging and wear. Value causes include obsolescence of FRs (including aesthetic quality) of a product. Since the value of a product is given as weighed sum of its functional performance, value deterioration along time is given by decreases in $FR_i(t)$ and $w_i(t)$.
For the sake of simplicity, we express deterioration of $FRi(t)$ and $w_i(t)$ as linear equations as follows;

$$FR_i(t) = c_i(t - st) + d_i \tag{5}$$

$$w_i(t) = a_i t + b_i \tag{6}$$

where, c_i, d_i, a_i, and b_i denote deterioration rate, initial performance, obsolescence rate, and initial importance of FR_i, respectively.
c_i and d_i are estimated by empirical data of deterioration of similar products at their use stage by applying reliability theory. a_i and b_i can be estimated by regression analysis on importance of each FR at various time t.

3.3 Formulation of LCE and LCC

In general, different performance levels imply different sets of components with different environmental load and cost. Therefore, LCE and LCC of a product should be allocated to their corresponding components in order to calculate those of products with different performance levels in FRs. Focusing on energy using products, the longer a product is continued to use, the higher LCE and LCC of a product become. Thus, the simplest representation of LCE and LCC of a product are given as follows;

$$LCE = \sum_j LCE_j \tag{7}$$

$$LCC = \sum_j LCC_j \tag{8}$$

$$LCE_j = e_j \cdot lt + f_{j,prod} + f_{j,eol} \tag{9}$$

$$LCC_j = g_j \cdot lt + h_{j,prod} + h_{j,eol} \tag{10}$$

where, j, e_j, g_j , $f_{j,prod}$, $h_{j,prod}$, $f_{j,eol}$, $h_{j,eol}$ and lt denote index for component, partial environmental load and cost allocated to each component per unit time during product use stage, those at production and end of life (EOL) treatment stages, and product life time, respectively.
LCE and LCC of a product can be calculated by conventional life cycle assessment (LCA) and life cycle costing (LCC) tools, respectively. These values are allocated to each component by referring the material and energy consumption of each component at each life cycle stage to calculate the values of parameters above.

3.3 Consideration of LCOPs

The life cycle options such as recycling and reuse have great potential to reduce environmental load and cost during production and EOL treatment stages in some cases. The potential reduction in LCE and LCC, which is represented as reduction in $f_{j,prod}$, $f_{j,eol}$, $h_{j,prod}$, and $h_{j,eol}$, is influenced by the amount of available resources for recycling and reuse at the end of product-use stage. Given the collection ratio (rc) and yield ratio for component reuse and recycling ($rg_j^{reuse}, rg_j^{recycle}$), LCE at production and EOL treatment stages are calculated as follows;

$$f_{j,prod} = f_{j,prod}^{*} \cdot (1-rc) + f_{j,prod}^{reuse} \cdot op_j^{reuse} \cdot rc \cdot rg_j^{reuse} + f_{j,prod}^{recycle} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot op_j^{recycle} \cdot rg_j^{recycle} + f_{j,prod}^{land} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot (1 - op_j^{recycle} \cdot rg_j^{recycle}) \quad (11)$$

$$f_{j,eol} = f_{j,eol}^{*} \cdot (1-rc) + f_{j,eol}^{reuse} \cdot op_j^{reuse} \cdot rc \cdot rg_j^{reuse} + f_{j,eol}^{recycle} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot op_j^{recycle} \cdot rg_j^{recycle} + f_{j,eol}^{land} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot (1 - op_j^{recycle} \cdot rg_j^{recycle}) \quad (12)$$

where, $f_{j,prod}^{reuse}$, $f_{j,eol}^{reuse}$, $f_{j,prod}^{recycle}$, $f_{j,eol}^{recycle}$, $f_{j,prod}^{land}$ and $f_{j,eol}^{land}$ denote environmental load of component j at production and EOL treatment stages when it is reused, recycled and landifilled, respectively. $f_{j,prod}^{*}$ and $f_{j,eol}^{*}$ denote interval values covering $f_{j,prod}^{reuse}$, $f_{j,prod}^{recycle}$, and $f_{j,prod}^{land}$ and $f_{j,eol}^{reuse}$, $f_{j,eol}^{recycle}$, and $f_{j,eol}^{land}$, respectively, to represent the uncertain environmental load considering uncollected components at production and EOL treatment stages. op_j^{reuse} and $op_j^{recycle}$ are decision variables, which are assigned 1 when component j is reused and recycled, 0 otherwise, respectively.

LCC at production and EOL treatment stages are also given in same manner as follows;

$$h_{j,prod} = h_{j,prod}^{*} \cdot (1-rc) + h_{j,prod}^{reuse} \cdot op_j^{reuse} \cdot rc \cdot rg_j^{reuse} + h_{j,prod}^{recycle} \cdot op_j^{recycle} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot rg_j^{recycle} + h_{j,prod}^{land} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot (1 - op_j^{recycle} \cdot rg_j^{recycle}) \quad (13)$$

$$h_{j,eol} = h_{j,eol}^{*} \cdot (1-rc) + h_{j,eol}^{reuse} \cdot op_j^{reuse} \cdot rc \cdot rg_j^{reuse} + h_{j,eol}^{recycle} \cdot op_j^{recycle} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot rg_j^{recycle} + h_{j,eol}^{land} \cdot rc \cdot (1 - op_j^{reuse} \cdot rg_j^{reuse}) \cdot (1 - op_j^{recycle} \cdot rg_j^{recycle}) \quad (14)$$

where, $h_{j,prod}^{reuse}$, $h_{j,eol}^{reuse}$, $h_{j,prod}^{recycle}$, $h_{j,eol}^{recycle}$, $h_{j,prod}^{land}$, and $h_{j,eol}^{land}$ denote LCC of component j at production and EOL treatment stage when it is reused, recycled, and landifilled, respectively. $h_{j,prod}^{*}$ and $h_{j,eol}^{*}$ are interval values covering $h_{j,prod}^{reuse}$, $h_{j,prod}^{recycle}$, and $h_{j,prod}^{land}$ and $h_{j,eol}^{reuse}$, $h_{j,eol}^{recycle}$, and $h_{j,eol}^{land}$, respectively.

4. Total performance Design considering the uncertainties

4.1 Taguchi's robust design method

The objective of optimization is minimizing variation of TPI while maximizing the average of TPI considering the various uncertainties in product life cycle. To this end, we employ Taguchi's robust design method [Taguchi et al. 1989]. In order to apply Taguchi's robust design method to optimization of TPI, noise factors, their influence on TPI, and control factors (design parameters) should be identified.

4.2 Control factors

In optimization of TPI, the control factors change when a designer employs different business strategies. In this study, we focus on *closed-loop manufacturing strategy*, where products are completely collected at the end of product-use stage and sent back to their manufactures so as to promote reuse and recycling of products. Some manufacturers of photocopier and one time use camera employ this strategy to enhance its environmental and economic performance simultaneously.

In closed-loop manufacturing strategy, a manufacturer can control product specification, lifetime and life cycle options (LCOPs) for components at EOL treatment stage. Thus, the design parameters are d_i, lt, op_j^{reuse} and $op_j^{recycle}$.

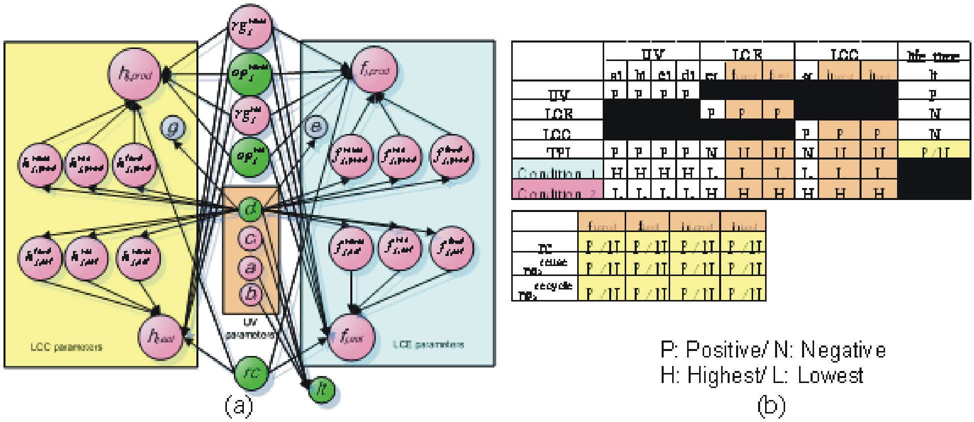

Figure 1. Resulting variation in TPI

4.3 Noise factors and the their resulting variation in TPI

Product life cycle contains many uncertainties and these uncertainties are treated as noise factors, of which values are represented as interval values, in this study. Focusing on product-use stage, the difference in operating condition (e.g., operation time, temperature, and frequency of usage etc.) of a product may cause variation in c_i, e_j, g_j, rg_j^{reuse}, and $rg_j^{recycle}$ in equations 5, 9, 10, 11, 12, 13, and 14. In addition, user's preference for a product differs from user to user and this also causes the significant variation in a_i and b_i in equation 6. These variations in product-use stage also influence on lifetime of a product and collection ratio of products (rc). LCE and LCC during production and EOL treatment stages also vary as a result of variations of rc, rg_j^{reuse}, and $rg_j^{recycle}$. Therefore, all the parameters except product initial specification (di) should be treated as noise factors, if these values can not be controlled by a designer.

Interdependency among all parameters used for calculating TPI is shown in Figure 1(a). Nodes and arcs in this figure represent parameters and interdependency among them, respectively. Considering the interdependency in Figure 1 (a), conditions 1 and 2, where TPI have the highest and the lowest values under the variations in parameters a_i, b_i, c_i, d_i, e_j, $f_{j,prod}$, $f_{j,eol}$, g_j, $h_{j,prod}$, and $h_{j,eol}$, respectively, can be identified as shown in Figure 1 (b). For example, Figure 1 (b) shows that a_i, b_i, c_i, d_i have positive effect on TPI, which means that TPI increases as a_i, b_i, c_i, d_i increase. Thus, these parameters should have the highest and lowest values in condition 1 and 2, respectively.

4.4 Flow of total performance design

Flow of the optimization of TPI of a product is summarized as follows;

Step 1: Identification of control factors

The first step of optimization is identifying the possible set of control factors considering the business strategy which a designer can employ. The levels of control factors are also set in this step. Commonly, two or three levels are selected for each factor.

Step 2: Estimation of UV, LCE and LCC

UV, LCE, and LCC of a product are estimated by using conjoint analysis, LCA, and LCC methods, respectively. From these results, original estimate of parameters a_i, b_i, c_i, d_i, e_j, $f_{j,prod}^{reuse}$, $f_{j,prod}^{recycle}$, $f_{j,prod}^{land}$, $f_{j,eol}^{reuse}$, $f_{j,eol}^{recycle}$, $f_{j,eol}^{land}$, g_j, $h_{j,prod}^{reuse}$, $h_{j,prod}^{recycle}$, $h_{j,prod}^{land}$, $h_{j,eol}^{reuse}$, $h_{j,eol}^{recycle}$, $h_{j,eol}^{land}$ are determined.

Step 3: Identification of noise factors

Considering the uncertainties in product life cycle, the levels of noise factors are determined and incorporated into the original estimate calculated in Step 2. Collection ratio (*rc*) and yield ratio for reuse and recycling of components (rg_j^{reuse} and $rg_j^{recycle}$) are also estimated in this step.

Step 4: Optimization by control factors

Taguchi's robust design method contains two optimization steps. First one is minimization of variation in output value of a target system. And the second one is maximization of the mean of output value of a target system, when the larger the output value the better. Basically, signal-to-noise (S/N) ratio, which is the ratio of the mean (signal) to the standard deviation (noise), is used as a design metric for the first optimization.

In this study, the output value is TPI of a product. Considering two noise parameter arrangements (i.e., conditions 1 and 2 in Figure 1), S/N ratio η in each design parameter setting is given as follows;

$$\eta = 10\log(\frac{\mu}{\sigma})^2 \tag{15}$$

$$\mu = \frac{TPI_{\max,1} + TPI_{\min,2}}{2} \tag{16}$$

$$\sigma^2 = (TPI_{\max,1} - \mu)^2 + (TPI_{\min,2} - \mu)^2 \tag{17}$$

where, μ, σ, $TPI_{max,1}$, and $TPI_{min,2}$ denote the mean and standard deviation of TPI over conditions 1 and 2, maximum TPI over the range of estimated lifetime in condition 1, and minimum TPI over the range of estimated lifetime in condition 2, respectively.

Based on the number of control factors and their alternative levels determined in Step 1, adequate orthogonal array is selected for reducing the number of calculation configuration. Average S/N ratio and the TPI for each level of each control factor are calculated from the result of calculations to separate out its effects on the variation and the mean of TPI. Based on these values, a designer selects adequate levels of control factors that minimize variation of TPI while maximizing the mean of TPI.

5. Example

In the following, the calculation procedure for the total performance design is illustrated, using an example of a laptop computer.

5.1 Product definition

Dominant FRs of a laptop computer is summarized in Table 1. The performance of each FR is measured by functional parameter given in the 1st column in Table 1. Eight components corresponding to these FRs are identified as shown in the 8th column in Table 1.

5.2 Identification of control parameters

For this example, three alternative levels were identified for initial specification of FR2, FR4, FR5, and FR6, and two alternative levels were identified for those of FR1 and FR3, as shown in the 5th, 6th and 7th column in Table 1. Lifetime of a laptop computer was assumed to be controlled from 48 months to 50 months. Three alternative LCOPs (i.e., reuse, recycling and landfill) for each component are also considered with their resulting environmental load and cost at production and EOL treatment stages. Performance level tow for FRs and landfill option for components represent the initial setting (reference setting) for the control factors.

Table 1. FRs of a laptop computer

Column No.	1	2	3	4	5	6	7	8	9
FRs	Functional parameters	Obs. rate (ai)	Init. importance (bi)	Det. rate (ci)	Specification (di)			Corresponding components	Lifetime
					level 1	level 2	level 3		
FR1: Computing speed	Processor speed [GHz]	-0.46	58.8609	-0.004	0.49	1		Main board	120 [month]
FR2: Compute large-capacity data	Memory size [GB]	-1.92	116.767	-0.001	0.125	0.25	0.5	Memory card	120 [month]
FR3: Storage capacity	HDD size [GB]	-0.03	1.79353	-0.417	20	40		HDD	48 [month]
FR4: Portability	Weight [kg]	-0.08	21.3097	-0.011	1.3	2	3	Housing, LCD	120 [month]
FR5: Easily viewable	Display size and luminance [mm*cd/m^2]	0	0.0015	-200	40000	60000	76200	Powre supply, Battery, LCD	30000 [hour]
FR6: Handle multiple recording media	Number of available recording media	-0.4	29.3591	-0.021	1	2	3	CD/DVD drive	48 [month]

5.3 Estimation of UV, LCE, and LCC

The value deterioration due to value causes were calculated by conjoint analysis of a laptop computer at different two years, 2002 and 2006, as described in our previous work [Kondoh et al. 2006]. For example, the weighted factor for "FR1: Computing speed" was calculated as 58.65 [kJPY/GHz] and 36.95 [kJPY/GHz] at 2002 and 2006, respectively, and a_1, which denotes the obsolescence rate of FR1, is calculated as –0.45638, by substituting these two values to equation 6. For the initial importance of each FR, the importance value at 2002 is used. For the sake of simplicity, deterioration rate (c_i) and initial importance for each FR (a_i) are assumed to be same for three alternative levels in initial performance of FR. Physical deterioration of each FR is assumed by referring physical lifetime of its corresponding components given in the 9th column in Table 1.

Table 2. Original estimate of the LCE parameters

	LCE (kgCO2)													Yieled ratio for reuse rg_j^{reuse}	Yield ratio for recycling rg_j^{rec}
	Production									Product use e_j	EOL				
	LCOPs										LCOPs				
	$f_{j,prod}^{reuse}$			$f_{j,prod}^{rec}$			$f_{j,prod}^{land}$				Reuse $f_{j,eol}^{reuse}$	Recycling $f_{j,eol}^{rec}$	Landfill $f_{j,eol}^{landfill}$		
Performance level	1	2	3	1	2	3	1	2	3						
Main board	12,8	16	19,2	51,2	64	76,83	64	80	96	0,568	0,033	0,165	0,099	0,9	0,9
Memory card	0,81	1,61	3,21	3,21	6,41	12,81	4,01	8,01	16	0,03	0,011	0,054	0,032	0,9	0,9
Hard disk drive unit	0,14	0,22	0,26	0,5	0,82	0,976	0,62	1,02	1,22	0,03	0,016	0,081	0,048	0,3	0,9
CD/DVD drive	1,3	1,44	1,58	5,08	5,64	6,198	6,34	7,04	7,74	0,075	0,038	0,188	0,113	0,3	0,9
Pow er supply	0,23	0,23	0,23	0,83	0,83	0,83	1,03	1,03	1,03	0,027	0,03	0,148	0,089	0,3	0,9
Battery	0,43	0,43	0,43	1,63	1,63	1,632	2,03	2,03	2,03	0	0,032	0,161	0,097	0,3	0,9
Housing	1,01	1,11	1,16	3,71	4,11	4,312	4,61	5,11	5,36	0	0,112	0,561	0,337	0,9	0,9
LCD	0,9	1,23	1,5	2,91	4,23	5,295	3,58	5,23	6,56	0,23	0,228	1,142	0,685	0,9	0,9
Column No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

LCE and LCC of a product were calculated by using conventional LCA and LCC methods, and these values were allocated to each component by referring its responsibility for LCE and LCC of a product at each life cycle stage. Three different values of environmental load of eight components corresponding to three alternative performance levels of FRs are summarized in Table 2. For the sake of simplicity, the difference in environmental load and cost of components at product use and EOL treatment stages among three alternative components are assumed to be negligible. Environmental load and cost of components at production and EOL treatment stages differ when different LCOPs are chosen for them. We assumed that 80% and 20% reduction in environmental load and cost at production stage are possible by reusing and recycling post-used components, respectively. We also assumed that 30% and 90% of damageable (viz., HDD, CD/DVD drive, power supply and battery) and durable components collected after product-use stage can be reused with some repair processes, respectively. 90% of all components were also assumed to be able to be recycled and from 95% to 100% of post-used products were assumed to be collected from the market.

5.4 Identification of noise factors

The result of conjoint analysis at 2006 shows that the importance values for "FR3: Storage capacity" and "FR5: Easily viewable" significantly vary among users. LCE and LCC at product-use and EOL treatment stages may vary wider than those at production stage because the usage of products and landfill operation cannot be controlled by a manufacturer. Thus, shaded parameters in Table 1 and 2 are identified as major noise factors, of which value could be 20% higher or lower than original estimate. It was also assumed that the value of other uncontrolled parameters could be 2% higher or lower than original estimate.

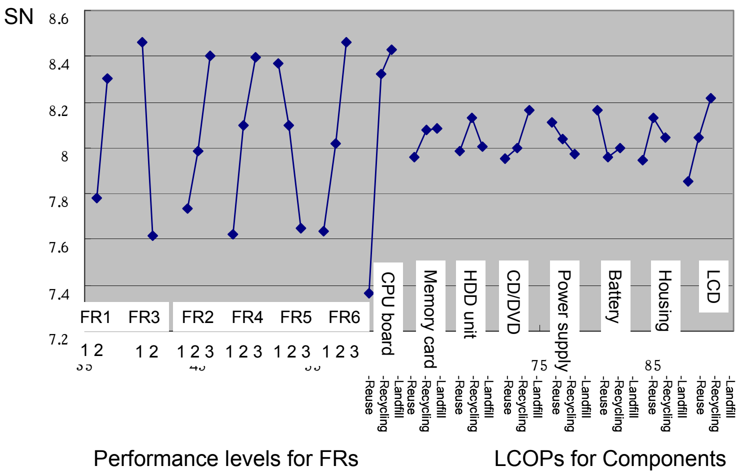

Figure 2. S/N ratio of TPI at each level in each control parameter

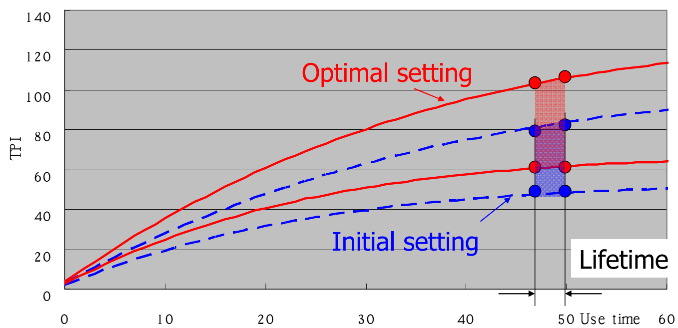

Figure 3. Optimization result

5.5 Optimization by control factors

There exist 14 control factors, namely, performance levels of six FRs and LCOPs for eight components. Thus, L36 orthogonal array (OA) is used to study the design space. Since the influence of the noise factors is identified as described in section 4.3, each calculation is conducted on two noise parameter arrangements: conditions 1 and 2 in Figure 1 (b) over the controlled lifetime (viz., 48 months to 50 months).

S/N ratio of TPI at each level in each control factor is calculated as shown in Figure 2. Figure 2 shows that the highest S/N ratio (viz., minimum variation in TPI) can be achieved by selecting level two, three, one, three, one, and three for performance levels of FR1, FR2, FR3, FR4, FR5 and FR6, respectively. It is also showed that CPU board, memory card, CD/DVD drive, and LCD should be landfilled, HDD unit and housing should be recycled, and power supply should be reused at the end of product-use stage for minimizing variation in TPI.

The highest average TPI can be achieved by selecting level two for FR1, FR2 and FR3, three for other FRs. Main board, memory card, HDD unit, CD/DVD drive, housing, and LCD should be reused and other components should be recycled for maximizing average TPI.

Considering these two optimal setting for minimization of variation in TPI and maximization of average TPI, adequate performance levels for FRs and LCOPs for components were determined. Figure 3 shows the result of optimal design solution and that of initial parameter setting where performance levels for all FRs are set two and all components are landfilled. Approximately 27% and 1.3% improvements in average TPI and S/N ratio, respectively, were achieved in optimal design solution, comparing to the initial setting.

6. Conclusion

This paper considered various uncertainties in product life cycle, discussed their influence on TPI of a product, and proposed a design method that can maximize the average of TPI while minimizing the variation in TPI resulting from these uncertainties. The optimization procedure of TPI was also illustrated with an example of a laptop computer. Future works include application of total performance design method to practical examples of various products to confirm feasibility and validity of our method.

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