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LIFE CYCLE OPTION SELECTION BASED ON THE DIFFERENCE OF VALUE AND PHYSICAL LIFETIMES FOR LIFE CYCLE DESIGN

Yasushi Umeda[1], Takayuki Daimon[2] and Shinsuke Kondoh[3]
[1] Osaka University
[2] Tokyo Metropolitan University
[3] National Institute of Advanced Industrial Science and Technology

ABSTRACT

Many products, such as cellular phone and personal computer, are thrown away because of obsoleteness of their functionality, although they still work well. This fact aggravates the waste problem and the shortage of resources. In order to avoid this problem, a designer should determine best mixture of life cycle options of a product and its components so as to utilize them until the very end of their lifetimes. One of the most critical factors is the mismatch between "value lifetime," the time until a product is thrown away because of the above-mentioned reasons and "physical lifetime," the time until a product breaks down. However, there are no methodologies to estimate the value lifetime, while physical lifetime can be estimated by using the reliability theory. This paper proposes a methodology for estimating both of physical and value lifetimes and selecting life cycle options of components based on the estimated lifetimes. The basic idea is to divide a product disposal distribution into a value disposal distribution and a physical disposal distribution of the product. This paper proposes "LCOP Selection Chart" for the latter issue. This paper also illustrates case studies of cellular phone, vacuum cleaner, new car, and secondhand car. The result of the case studies revealed obvious differences in disposal patterns of these products and successfully supported in selecting life cycle options. Therefore, the case studies verified feasibility and effectiveness of the proposed methodology.

Keywords: Design for Sustainability, Life Cycle Design, Life Cycle Option, Lifetime, Physical Lifetime, Value Lifetime, Disposal Cause Analysis Matrix

1. INTRODUCTION

Many products, such as cellular phone and personal computer, are thrown away because of obsoleteness of their functionality, although they still work well. This fact aggravates the waste problem and the shortage of resources. In order to avoid this problem, a designer should determine best mixture of life cycle options (LCOPs) (such as maintenance, upgrading, remanufacturing, reuse, and recycling) of a product and its components so as to utilize them until the very end of their lifetimes. This task is modeled as a mapping from life cycle properties, including lifetime, sales period, disposal amount, and structure of the product, to the best mixture of life cycle options of a target product life cycle. Such rational selection of life cycle options is the central issue at the early stagy of life cycle design [1][2].

In order to support this task, various researchers have proposed various methodologies; for instance, Wimmer *et al.* [3][4] proposed practical ecodesign guidelines, Masui *et al.* [5] proposed QFDE, Ishii *et al.* [6] proposed a LCOP selection method based on product lifetime and technology cycle, and Kobayashi [7] developed practical computational tool to select LCOPs based on life cycle properties. We also proposed a method for selecting LCOPs based on disposal causes of a product [8].

Among others, lifetime is one of the most critical factors for selecting LCOPs, because lifetime is a basis for estimating disposal amount of products, their obsoleteness, and their reusability. Especially, the mismatch between "value lifetime" and "physical lifetime" is critical for utilizing a product until the very end of its lifetime. Here, physical lifetime is, on one hand, the time until a product breaks down; in other words, the lifetime the reliability theory deals with. On the other hand, value lifetime is the time until a product is disposed when its performance, functionality or appearance cannot satisfy customer's needs any more, although the product itself might work well. It is clear that value lifetime is qualitatively shorter than physical lifetime (*e.g.*, [6][9]). However, there are no methodologies to measure or estimate the value lifetime, while the reliability theory measures and estimates the physical lifetime.

Therefore, this paper proposes a methodology for estimating both of physical and value lifetimes and selecting life cycle options of components based on the estimated lifetimes. The basic idea for estimating lifetimes is to divide a product disposal distribution into a value disposal distribution and a physical disposal distribution of the product by using Disposal Cause Analysis matrix. Moreover, the latter is realized as "LCOP Selection Chart." As a result, this paper aims at reducing the mass disposal problem and increase resource efficiency of the product.

The rest of this paper is composed as follows. Section 2 proposes the methodology for estimating lifetimes and selecting LCOPs. Section 3 illustrates case studies of application of our methodology to several products; *viz*., cellular phone, vacuum cleaner, new car, and secondhand car. Section 4 discusses advantages and issue of the proposed methodology and Section 5 concludes this paper.

2. LCOP SELECTON METHOD BASED ON LIFETIME

2.1. Framework

As discussed in the previous section, we focus on the stage of decision of life cycle strategy, an important stage in the life cycle design. In this stage, a designer should determine life cycle options of a target product and its components by considering various factors and, among others, this paper focuses on the mismatch between the value lifetime and the physical lifetime.

The whole procedure of the proposed methodology is shown in *Figure 1*. This is a decision support tool for life cycle strategy from the viewpoint of lifetime. As shown in this figure, the procedure consists of estimation of lifetimes and selection of LCOPs. In order to realize this procedure, there are two issues to be solved. One is how to estimate lifetimes, especially value lifetimes of a product and its components. And the other is how to determine LCOPs based on the estimated lifetimes. For the former issue, we propose a lifetime estimation method employing "Disposal Cause Analysis (DCA) matrix" [8]. While details of the DCA matrix is described in Section 2.2, this is a QFD-like tool that analyses the causes why users throw a target product away and extracts hits for reducing product disposals. We decompose a disposal distribution of a product into a disposal distribution because of value causes (value disposal distribution) and a distribution because of physical causes (physical disposal distribution) by using the DCA matrix and then estimate physical and value lifetimes from these distributions. Details are described in Section 2.3. For the latter issue, we propose a LCOP Selection Chart as described in Section 2.4.

The features of the proposed method include:

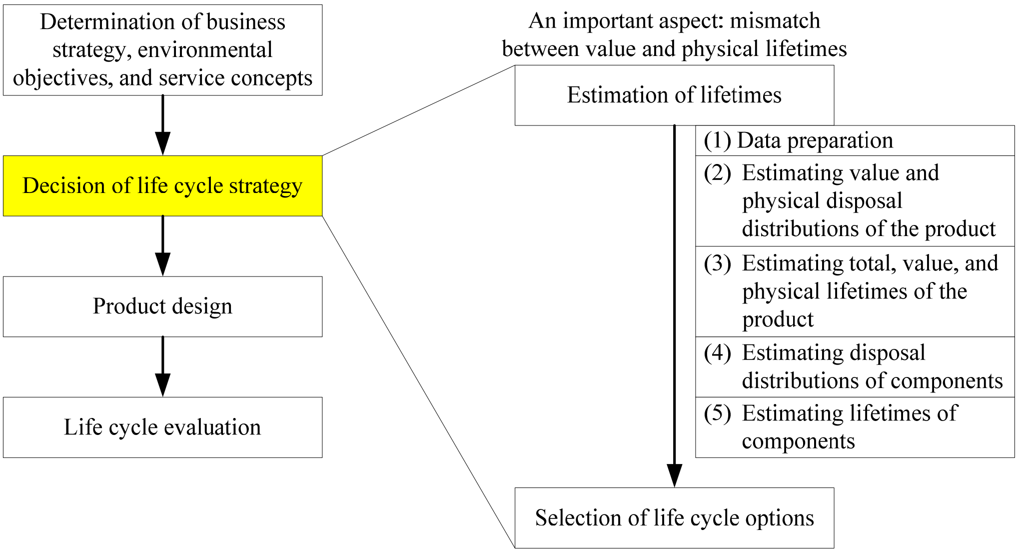
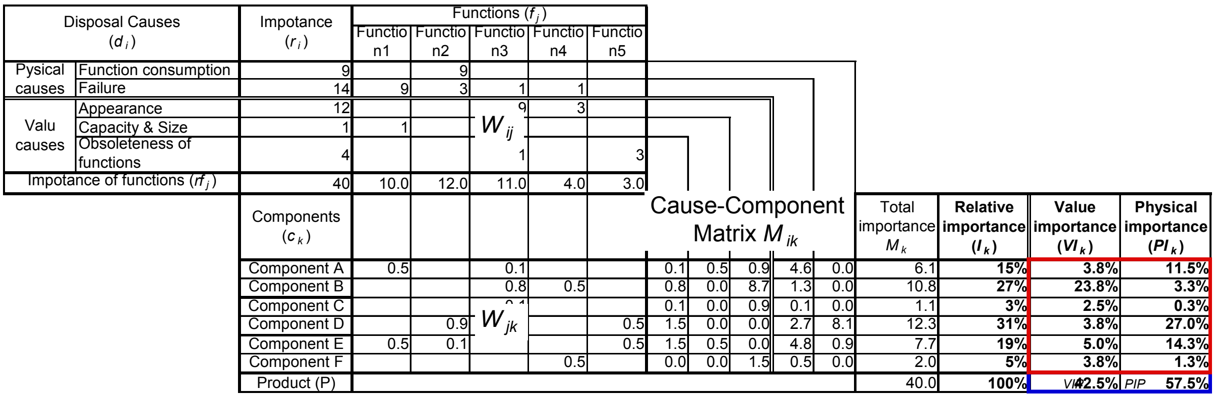


Figure 1. Flow of LCOP selection based on lifetimes



Disposal Causes (d_i)		Impotance (r_i)	Function1	Function2	Function3	Function4	Function5
			Functions (f_j)				
Pysical causes	Function consumption	9		9			
	Failure	14	9	3	1	1	
Valu causes	Appearance	12			9	3	
	Capacity & Size	1	1				
	Obsoleteness of functions	4			1		3
Impotance of functions (rf_j)		40	10.0	12.0	11.0	4.0	3.0

W_{ij}

Components (c_k)						Cause-Component Matrix M_{ik}					Total importance M_k	**Relative importance (I_k)**	**Value importance (VI_k)**	**Physical importance (PI_k)**
Component A	0.5		0.1			0.1	0.5	0.9	4.6	0.0	6.1	**15%**	**3.8%**	**11.5%**
Component B			0.8	0.5		0.8	0.0	8.7	1.3	0.0	10.8	**27%**	**23.8%**	**3.3%**
Component C			[illegible]			0.1	0.0	0.9	0.1	0.0	1.1	**3%**	**2.5%**	**0.3%**
Component D		0.9			0.5	1.5	0.0	0.0	2.7	8.1	12.3	**31%**	**3.8%**	**27.0%**
Component E	0.5	0.1			0.5	1.5	0.5	0.0	4.8	0.9	7.7	**19%**	**5.0%**	**14.3%**
Component F				0.5		0.0	0.0	1.5	0.5	0.0	2.0	**5%**	**3.8%**	**1.3%**
Product (P)											40.0	**100%**	VIP **42.5%**	PIP **57.5%**

W_{jk}

Figure 2. Disposal cause analysis matrix [8]

- It quantifies the value lifetime that have not been modeled.
- It estimates value and physical lifetimes in a uniform manner and estimates those of a product and of its components.
- It provides a visual tool, LCOP Selection Chart, for selecting LCOPs based on the estimated lifetimes.
- In addition to lifetimes, it also plots temporal changes of value and physical disposals (disposal distributions) at both of the product level and the component level, which gives us various hints for determining life cycle strategy and for extracting different user clusters.

2.2. Disposal cause analysis matrix

In order to analyze disposal causes, we have proposed "Disposal Cause Analysis matrix (DCA matrix)" [8]. Here, a disposal cause is the reason why a user throws his/her product away and can be classified into two types; physical causes (including function consumption and failure) and value causes (including obsolete appearance, unsatisfied capacity & size, and value deterioration) [8]. Physical causes and value causes determine the physical lifetime and the value lifetime, respectively.

The DCA matrix, which is based on quality function deployment (QFD) technique [10], consists of three sub-matrices (see *Figure 2*); namely, disposal cause-function matrix W_{ij}, function-component matrix W_{jk}, and cause-component matrix M_{ik}. In this figure, disposal cause-function matrix W_{ij} indicates importance of a disposal cause i related to a function j affecting to the product disposal and this information is acquired from, *e.g.*, user questionnaire. Importance r_i for a disposal cause i is calculated by $r_i = \sum_j W_{ij}$ .Function-component matrix W_{jk} denotes correlations between components and functions; in other words, how much a component contributes to a function and designers, rather than users, determine values of this sub-matrix. From these two sub-matrices, the cause-component matrix M_{ik} is calculated by using Equation (1). This sub-matrix represents importance of each pair of a component and a disposal cause to overall disposal of the target product. This sub-matrix is the main information of the DCA matrix.

Here, we added three additional rows to the original matrix at the bottom right side in *Figure 2*; namely, relative importance I_k, value importance VI_k, and physical importance PI_k. Here, total importance M_k of a component k and relative importance I_k are defined as Equations (2) and (3), respectively (where, i is a disposal cause). Relative importance I_k indicates the ratio of the product disposal because of component k to the total amount of disposal.

$$M_{ik} = W_{ij} \times W_{jk} \tag{1}$$

$$M_k = \sum_i M_{ik} \tag{2}$$

$$I_k = \frac{M_k}{\sum_k M_k} \tag{3}$$

Each relative importance I_k is broken down into physical importance PI_k and value importance VI_k of a component k according to whether the importance comes from the physical causes or the value causes, (see Equations (4) and (5)). Note that, in these equations, i = 1,2 denote physical causes and i = 3~5 are value causes. Moreover, *VIP* and *PIP* denote value and physical importance of the whole product, respectively, as shown in Equations (6) and (7).

$$PI_k = \frac{\sum_{i=1}^{2} M_{ik}}{\sum_{k} M_k} \tag{4}$$

$$VI_k = \frac{\sum_{i=3}^{5} M_{ik}}{\sum_{k} M_k} \tag{5}$$

$$VIP = \sum_{k} VI_k \tag{6}$$

$$PIP = \sum_{k} PI_k \tag{7}$$

For example, in this figure, these indicators of component A (k=1) are calculated as follows:

$$I_1 = \frac{0.1+0.5+0.9+4.6+0}{40} = 15.25(\%) \approx 15(\%)$$

$$PI_1 = \frac{4.6+0}{40} = 11.5(\%)$$

$$VI_1 = \frac{0.1+0.5+0.9}{40} = 3.75(\%) \approx 3.8(\%)$$

Namely, the importance I_1 of component A to the product disposal is 15% and this is broken down to importance of physical causes PI_1 and that VI_1 of value causes as 11.5% and 3.8%, respectively. In this paper, we introduce an assumption that these numbers are in proportional to number of disposals. Therefore, in the above example, we assume that 15% of total number of product disposal is caused by component A and so on.

2.3. Estimation of lifetimes

In this methodology, we decompose a given temporal disposal distribution of a product into physical and value distributions by using the DCA matrix; in other words, by making the DCA matrices periodically (*e.g.,* once a month). This is based on our assumption that the number of disposed products can be divided into the number of value disposals and the number of physical disposals according to their relative importance (*viz*., *VIP* and *PIP*). The validity of this assumption is discussed in Section 4. Then, physical and value lifetimes are calculated from the distributions. The procedure of the estimation is as follows (see *Figure 1*):

(1) Data preparation

The methodology requires two kinds of data; namely, temporal disposal distribution $D_t(t)$ of a target product and temporal series of the DCA matrices. While the disposal distribution may be obtained by, *e.g.*, the market survey, the temporal DCA matrices are made periodically by interviewing sampled customers who threw the products away in that period. Here, in *Figure 2*, while the function-component matrix W_{jk} is constant since the designer determines it, we periodically ask value of the disposal cause-function matrix $W_{ij}(t)$ to the sampled customers and calculate $VIP(t)$, $PIP(t)$, $VI_k(t)$, and $PI_k(t)$ for each time t.

(2) Estimating value and physical disposal distributions of the product

Based on the above mentioned assumption, the disposal distribution $D_t(t)$ is decomposed into value disposal distribution $D_v(t)$ and physical disposal distribution $D_p(t)$ by using the relative value and physical importance $VIP(t)$ and $PIP(t)$ ($VIP(t) + PIP(t) = 1,\ 0 \le VIP(t), PIP(t) \le 1$) by using Equations (8) and (9), respectively. *Figure 3* illustrates an image of this step.

$$D_v(t) = D_t(t) \times VIP(t) \tag{8}$$

$$D_p(t) = D_t(t) \times PIP(t) \tag{9}$$

(3) Estimating total, value, and physical lifetimes of the product

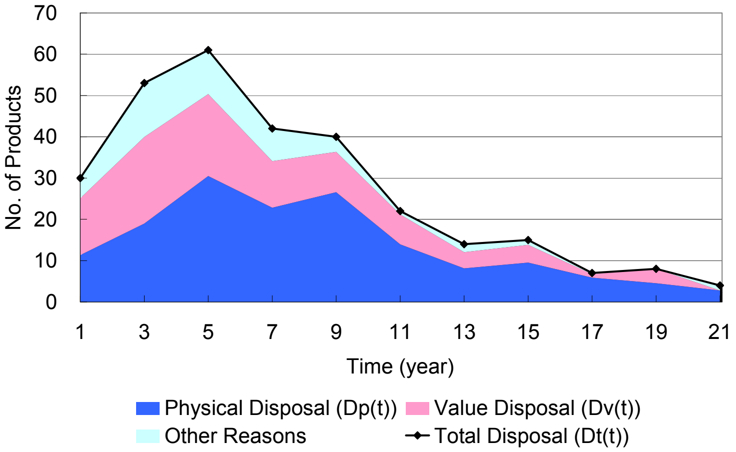


Figure 3. Decomposing disposal distribution of a product

In this step, total, value, and physical lifetimes of the product is calculated from the estimated distributions in Step (2). Obtaining the disposal distributions is, of course, one of our objectives and we can extract various kinds of information about disposal pattern of the product from these distributions. However, it is useful to calculate lifetime as a representative value of the distributions. As a result of various trials, we found that the average value of a disposal distribution does not correctly represent the lifetime. One of its reasons is that the traditional normal distribution does not fit to these distributions. Therefore, we here take the following approach that employs "cumulative hazard method" [11] in the reliability theory.

First, we define *disposal rate* $\lambda(t)$ as shown in Equation (10), which is the analogy to *failure rate* in the reliability theory [11], where $f(t)$ denotes rate of products disposed at time t and $R(t)$ is rate of products still in use at time t. In calculating $\lambda(t)$, we employ cumulative hazard function $H(t)$ (see Equation (11)), because of its stability against incomplete data in statistical analysis. Here, these equations are so general that $R(t)$ can be modeled with any distributions, such as Weibull distribution and normal distribution.

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{-dR(t)/dt}{R(t)} = -\frac{d\ln R(t)}{dt} \tag{10}$$

$$H(t) = -\ln R(t), \lambda(t) = \frac{dH(t)}{dt} \tag{11}$$

Then, we use the idea of "safe life" [11] for representing lifetime. Safe life t_x is the time until x% of total number of products are thrown away; for example, *B50 life* t_{B50}, which represents the time until 50% of all products are thrown away, and *B10 life* t_{B10} are often used. Namely, t_{B50} and t_{B10} are the time when $H(t)$ values satisfy Equations (12) and (13), respectively.

$$H(t_{B50}) = -\ln(1-0.5) = 0.693 \tag{12}$$

$$H(t_{B10}) = -\ln(1-0.1) = 0.105 \tag{13}$$

In this way, we estimate lifetimes from the disposal distributions by calculating the cumulative hazard function; namely, total lifetime lt, value lifetime vlt, and physical lifetime plt are calculated from the total disposal distribution $D_t(t)$, the value disposal distribution $D_v(t)$, and the physical disposal distribution $D_p(t)$, respectively. Here, we use t_{B50} for estimating these lifetimes of the product.

(4) Estimating disposal distributions of components in the product

Next, the estimation goes from the product level to the component level. First, for estimating disposal distributions of each component, we decompose the total disposal distribution of the product into the total, value, and physical disposal distributions, of each component in the same manner as Step (2). Here, the value (physical) disposal distribution $D_v^k(t)$ ($D_p^k(t)$) of a component k means the temporal distribution of disposed products because of value (physical) causes of the component. And, the total distribution of the component is the sum of them. Equations (14)-(16) define these distributions of components:

$$D_v^k(t) = D_t(t) \times VI_k(t) \tag{14}$$

$$D_p^k(t) = D_t(t) \times PI_k(t) \tag{15}$$

$$D_t^k(t) = D_v^k(t) + D_p^k(t) \tag{16}$$

(5) Estimating lifetimes of components
For each component *k*, total lifetime *lt(k)*, value lifetime *vlt(k)*, and physical lifetime *plt(k)* are estimated from the disposal distributions $D_t^k(t)$, $D_v^k(t)$, and $D_p^k(t)$, respectively, in the same manner as Step (3). Here, B10 life t_{B10} is employed because a product is a serial system of components and disposed products contain many components that work well.

2.4. Selection of life cycle options

The proposed methodology also supports a designer to select life cycle options (LCOPs) based on the estimated value and physical lifetimes. Here, LCOPs include all paths a product can take in a product life cycle, such as maintenance, upgrading, remanufacturing, reuse, material recycling, energy recovery, and dumping. In this paper, we classify these LCOPs into two levels:

Level I: LCOPs related to lifetimes of products or components, such as long life design, maintenance, upgrading, remanufacturing, and component reuse and

Level II: LCOPS not related to lifetimes, such as material recycling, energy recovery, and dumping.

The strategy for LCOP selection here is to apply Level I LCOPs as much as possible to make full use of products and components and, then, Level II LCOPs are applied in order to reduce wastes and to recover resources when the product cannot be used any more.

We further classify level I LCOPs as follows from the viewpoint of value and physical lifetimes:

I-a: LCOPs extending physical lifetimes; long life design and maintenance,

I-b: LCOPs extending value lifetimes; upgrading, and

I-c: LCOPs utilizing excessive physical or value lifetimes of components after product disposal; component reuse and remanufacturing.

The selection of LCOPs in this paper is formalized as the task to choose the most appropriate level I LCOP (*viz*., I-a, I-b, or I-c) for each component by using the estimated lifetimes, so as to extend the product life and to make full use of components until they break down completely.

For this purpose, this paper proposes two indicators; namely, "lifetime efficiency *lfe(k)*" and "relative lifetime *lfr(k)*" defined in Equations (17) and (18), respectively. While *lfe(k)* indicates which is critical the value lifetime *vlt(k)* or the physical lifetime *plt(k)* in a component, *lfr(k)* indicates which component is critical in a product lifetime.

$$lfe(k) = vlt(k) / plt(k) \tag{17}$$

$$lfr(k) = \frac{lt(k)}{\underset{k \in P}{Avg}(lt(k))} \tag{18}$$

Where,

lt(k): lifetime of a component *k*

Avg(): a function calculating average value

P: component set of the target product

Here, *Figure 4* plots all components in a target product by using these indicators. Horizontal and vertical axes indicate the relative lifetime *lfr* and the lifetime efficiency *lfe*, respectively. We have classified the area into four. I-a LCOPs (long life design or maintenance) should be applied to components in area (1), because their physical lifetime is critical in a product. I-b LCOPs (upgrading) should be applied to those in area (2), because their value lifetime is critical. I-c LCOPs (reuse) should be applied to those in area (3), because both of value and physical lifetimes have enough margins to be used again. On the other hand, components in (4) are ideal, since their value and physical lifetime in

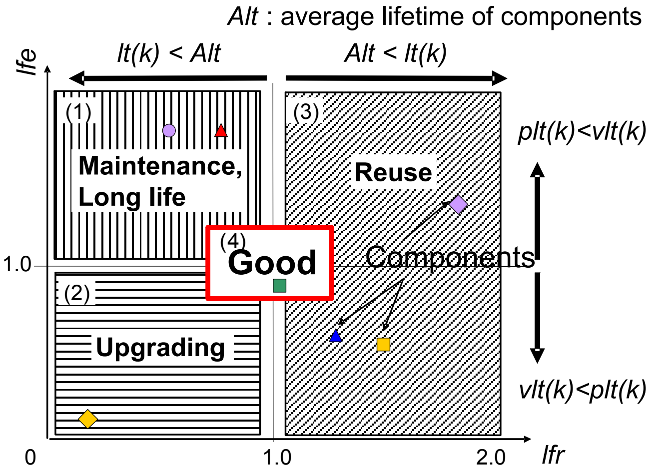


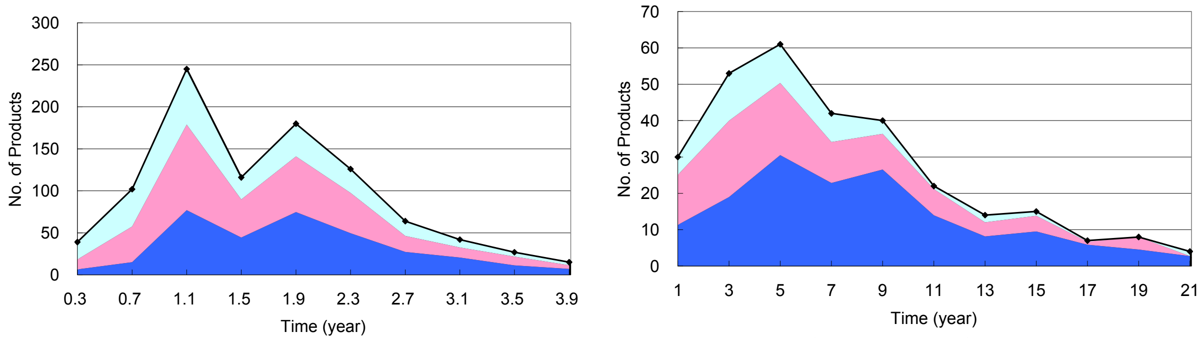
Figure 4. LCOP selection chart

average of all components. In other words, the objective of LCOP selection here is to minimize sum of distances of components to (1.0, 1.0) point. After applying these LCOPs, Level II LCOPs should be applied to all components according to, *e.g.*, recyclability. This paper does not discuss how to choose Level II LCOPs, since there are many existing methodologies.

3. CASE STUDIES

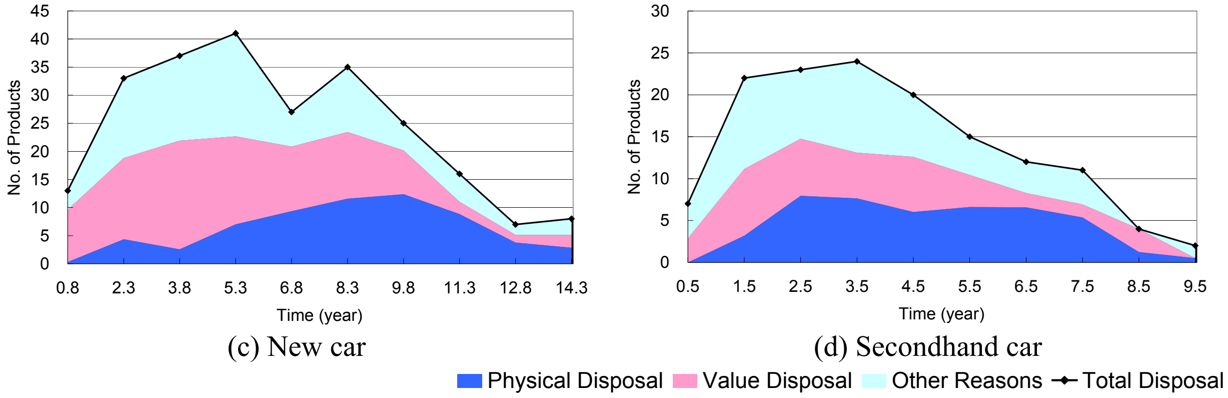
This section illustrates case studies of cellular phone, vacuum cleaner, new car, and secondhand car in order to examine availability of the proposed methodology. We chose these products because of variety of disposal patterns; in other words, the cellular phone might have short lifetime and value causes might be dominant, the vacuum cleaner might have long lifetime and physical causes might be dominant, and the cars might stay in the middle.

For collecting the disposal data, we performed three questionnaire surveys of disposal causes of these products on the people who had thrown away their products. These surveys presented questions about the timing of purchase and disposal, disposal causes (d_i in *Figure 2*), and critical functions for disposal (f_j in *Figure 2*). The numbers of responses are 1,000 for cellular phone, 300 for vacuum cleaner, and



(a) Cellular phone

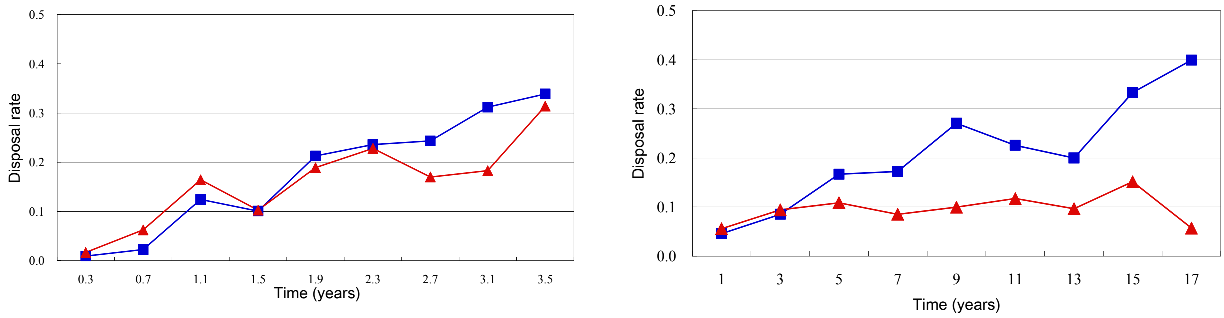
(b) Vacuum cleaner



(c) New car

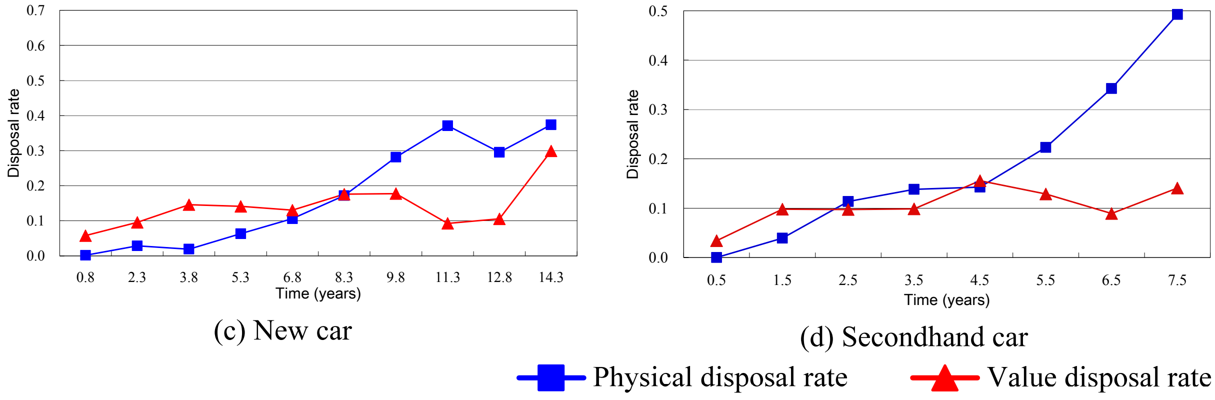
(d) Secondhand car

Figure 5. Disposal distributions



(a) Cellular phone

(b) Vacuum cleaner



(c) New car

(d) Secondhand car

Figure 6. Disposal rates

400 for both of new and secondhand cars. For example, we constructed 73 monthly DCA matrices from 1,000 responses in the cellular phone.

The proposed methodology originally targets a certain type of a product (*e.g.*, Toshiba XXX vacuum cleaner) and assumes that the market data (*viz*., sales and disposal amount) of this type of product can be obtained. However, since we could not obtain the market data of a certain type and we could not execute the questionnaire survey focusing on a certain type of products, we took a product category (*e.g.*, vacuum cleaner) as the target.

3.1. Disposal distributions and lifetimes

Figure 5 depicts derived disposal distributions of the four categories of products. As shown here, the proposed methodology succeeded in decomposing disposal distributions into value and physical disposal distributions. Obviously, these figures show that disposal patterns are quite different among these products and even in the same category of products, namely, the new car and the secondhand car. On the other hand, we can find out common patterns among all products. For example, the peaks of the value disposals are always earlier than those of the physical disposals. This agrees with our intuition and may suggest existence of different user groups that have different motivations of disposal.

Figure 6 also illustrates differences of disposal patterns. This figure depicts changes of the disposal rates, defined in Section 2.3, according to time. As shown in this figure, physical disposal rates (blue lines) of all products increase according to time. This is what we expected and, according to the reliability theory, this fact indicates that disposed products are in the wear-out failure period. In other words, products are literally thrown away because of physical lifetimes. On the contrary, while value disposal rates (red lines) of the cellular phone and the new car increase according to time, the rates of the vacuum cleaner and the secondhand car do not. This is against our expectation, since we thought all value disposal rates would increase. We may say that this is a new discovery. And this fact gives new suggestions for considering the value lifetime.

Table 1 summarized estimated lifetimes of the products. In this table, "physical: value: other" denotes ratio of physical disposal, value disposal, and other reasons to the total disposal of each product. Here, other reasons include the call charge of the cellular phone, accidental breakdown, and so on. This row indicates that the physical cause is the dominant disposal cause for the vacuum cleaner, the value cause is for the new car, and both of the physical and the value are for the cellular phone and the secondhand car. One of the advantages of the proposed method is to quantify these differences of disposal patterns. The two rows from the bottom in this table are survey for customers *who bought new products* [9] and the row “fault : upper : other” means the reason of buying new products; namely, failure of the old products, buying better products, and other reasons, respectively. Although it might be difficult to compare our result with this data because of the difference of standpoints, we may say, at least, that our result does not conflict with this data.

3.2. Lifetimes of components and life cycle options

Next, let us illustrate how we select life cycle options based on the method described in Section 2.4, taking the data of cellular phone as an example.

First, we estimated total lifetime *lt(k)*, value lifetime *vlt(k)*, and physical lifetime *plt(k)* of a component *k* as shown in Table 2 by using the cumulative hazard function. For example, total lifetime *lt* of CPU Board is estimated as 1.2 years. In this table, the value “4.0” means that the cumulative hazard function of this component does not reach B10 life before 4.0 years; in other words, the component’s life is long enough. From Table 2, the LCOP Selection Chart for the cellular phone is achieved as shown in Figure 7. This figure clearly indicates difference of value and physical lifetimes of each component and, therefore, we could easily select appropriate LCOPs for components. We easily found out two life cycle strategies from this figure; namely, one is to extend the product’s life (long life strategy) and the other is to keep the product’s life and reuse components as much as possible (reuse strategy).

When we employ the long life strategy, the target point is set to the point (1,1) in Figure 7, as the methodology assumes. Therefore, by calculating distance of each component to the target, we find that Battery and CPU Board are critical since their distances are large. As a result, LCOP of each component are selected quite easily as shown in the column “LCOP” in the long life strategy in Table 2. When we employ the reuse strategy, which assumes the product life is same as the life of the existing cellular phone, the target point is set to the point (0.58, 0.96) that is the product’s point in Figure 7. In this case, critical components are Battery, Option 2, Microphone, and Others, and LCOPs are selected as shown in the rightmost column in the table. In LCOPs of the reuse strategy, the LCOP of Battery is strange; although its total life is almost same as the total life of the whole product, its value life is too long and, therefore, we should reduce value lifetime of Battery with keeping the total life. This may reduce the cost of Battery.

In this way, the proposed methodology succeeded in estimating value and physical lifetimes of components and a design can easily determine life cycle strategies and LCOPs of components for the strategies.

Table 2. Lifetimes of cellular phone components

Component	plt(k) (yrs)	vlt(k) (yrs)	lt(k) (yrs)	lfe(k)	lfr(k)	Long life strategy (target point =(1,1))		Reuse strategy (target point =(0.58,0.96))	
						distance to target	LCOP	distance to target	LCOP
CPU Board	**2.2**	**1.6**	**1.2**	0.75	0.43	0.63	Upgrading	0.26	Good
Battery	**1.6**	**3.1**	**1.4**	1.99	0.51	1.11	Mainte. or Long Life	1.04	Lower value design
Display	**2.8**	**2.3**	**1.7**	0.83	0.62	0.41	Upgrading	0.14	Good
Body	**2.8**	**2.2**	**1.7**	0.82	0.63	0.41	Upgrading	0.15	Good
Keyboard	**3.7**	**3.7**	**2.4**	1.00	0.87	0.13	Good	0.30	Reuse
Option 3 (Camera & Movie)	*4.0*	**3.1**	**2.7**	0.79	1.00	0.21	Good	0.46	Reuse
Antenna	*4.0*	*4.0*	**2.9**	1.00	1.06	0.06	Good	0.49	Reuse
Speaker	*4.0*	*4.0*	**3.2**	1.00	1.18	0.18	Good	0.60	Reuse
Option 1 (Internet & Mail)	*4.0*	**3.7**	**3.5**	0.94	1.30	0.30	Reuse	0.72	Reuse
Option 2 (Game & Appli.)	*4.0*	*4.0*	*4.0*	1.00	1.46	0.46	Reuse	0.88	Reuse
Microphone	*4.0*	*4.0*	*4.0*	1.00	1.46	0.46	Reuse	0.88	Reuse
Others	*4.0*	*4.0*	*4.0*	1.00	1.46	0.46	Reuse	0.88	Reuse
Average	3.4	3.3	2.7	1.01	1.00				
Minimum	1.6	1.6	1.2	0.7	0.4				
Product	2.3	2.2	1.6	0.96	0.58				

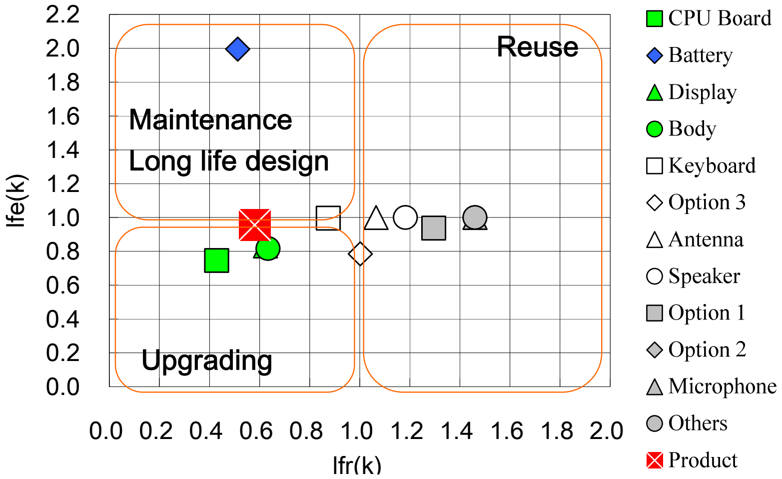


Figure 7. LCOP selection chart for cellular phone

4. DISCUSSIONS

As shown in Section 3, the proposed methodology succeeded in estimating value and physical lifetimes of products and their components. Especially, there are no other methods that can estimate the value lifetime. Therefore, this method is the first method that succeeded in quantifying the value lifetime. Actually, the case studies revealed distinguishing characteristics of disposal patterns. Namely, we found that disposal patterns are quite different according to product categories and, especially, they are different even in a product category as shown in the cases of the new car and the secondhand car. We also found that physical disposal rates increase according to time in all of studied products as we expected, but value disposal rates in the vacuum cleaner and the secondhand car do not increase while the rates in the cellular phone and the new car increase. This fact is quite important for determining life cycle strategies.

The proposed method also succeeded in rationally supporting for deciding life cycle options of components based on the estimated value and physical lifetimes of components. Here, the LCOP Selection Chart plays the central role for supporting this task, since the chart is visual and easy to understand.

Let us discuss issues of the proposed methodology. It was our big assumption that we can decompose disposal distributions into value and physical distributions according to importance of disposal causes in the DCA matrix. This methodology might be criticized for its estimative nature based on empirical data. Because the value lifetime essentially depends on subjective judgment of users, we think that such nature is unavoidable for estimating the value lifetime. The results of the case study revealed that at least our results agree with the public data [9]. Moreover, the proposed methodology intends to support the early stage of the life cycle design in which it is very difficult to obtain precise data of the target product and, hence, overall tendencies are enough. Therefore, we may conclude that the proposed methodology is effective enough for supporting selection of the life cycle options.

In estimating lifetimes, amount of the customers' data was critical. Because the proposed methodology allocates the disposal data to components, amount of the allocated data should be large enough for statistical estimation. A hundred data for a product category was not enough in the case studies. The analysis of the cellular phone, which has a thousand data, might be correct enough.

One of our future issues is to introduce user clusters for the analysis of disposal patterns. If we take the new car as an example, there might be differences in disposal patterns and users' purchasing behavior between users who threw away their cars because of value causes at third or forth year and who threw them away because of physical causes at tenth or twelfth year. Therefore, life cycle strategies should be determined corresponding to these differences of user clusters. The influence of this mixture of user clusters might have been larger in the case studies, since the case studies do not distinguish product types in a product category. In other words, we can guess that these two user clusters do not buy the same type of cars; namely, the former user cluster may purchase luxurious cars and the latter may purchase standard cars.

When we discuss the proposed methodology in the context of life cycle design support, we can point out three issues. One is embodiment of the selected life cycle options. While the methodology supports for rationally selecting life cycle options and indicates how much value or physical lifetime of a component should be extended, it does not support how to realize these life cycle options in a product structure. In this sense, the coverage of this methodology is similar to that of life cycle planning [7], but our methodology estimates the value lifetime. While supporting product design for realizing life cycle options is an important issue in the life cycle design community, as an approach, we are trying to support this by describing a life cycle scenario [12]. Moreover, although designing lifetimes of a product is a very difficulty issue, design for reliability is useful for controlling the physical lifetime and design for upgradability [13] will be effective for the value lifetime.

This leads to the second issue. When we can design physical and value lifetimes, where is the desirable region in the LCOP Selection Chart? Basically, the desirable region is the point (1.0, 1.0) as described above, but it may depend on life cycle strategy. For instance, if we take the reuse strategy, the desirable region goes to the left side; *e.g.*, (0.5, 1.0), since it increases reusable components in the chart. And if we take longer life strategy with maintenance, the desirable region goes right.

And the third issue is evaluation of the effect of the LCOP selection. Final evaluation, on one hand, should be done by using LCA, or more appropriately life cycle simulation [14] since the life cycle has various loops, after embodiment of LCOPs into the product structure at the later stage of the life cycle design. On the other hand, some approximated evaluation may be useful. At least, we can make a kind of sensitivity analysis on the correlation between changes of lifetimes of components and the factor x of the product by using Table 2.

5. CONCLUSIONS

This paper proposed a methodology for estimating both of physical and value lifetimes and selecting life cycle options of components based on estimated lifetimes. The basic idea is to divide a product disposal distribution into a value disposal distribution and a physical disposal distribution of the product by using Disposal Cause Analysis matrix. For selecting appropriate life cycle options of components based on the estimated components' lifetimes, this paper proposed "LCOP Selection Chart."

We illustrated case studies by collecting the actual data of cellular phone, vacuum cleaner, new car, and secondhand car. Value and physical lifetimes are successfully estimated in the case studies and the result revealed obvious differences in disposal patterns of these products and even in a product category; namely, new car and secondhand car. We found some facts opposed to our expectation. For example, physical disposal rates increase according to time in all products because of deterioration as we expected, but value disposal rates in some products do not increase. Moreover, we succeeded in selecting appropriate life cycle options in these products. The LCOP Selection Chart is visual and easy to understand. In this way, the case studies verified feasibility and effectiveness of the proposed methodology.

We expect that the proposed methodology is used at the planning phase of product development. In this phase, a team of product planners (including staffs in charge of marketing, design, manufacturing, and environment) should determine life cycle strategy in addition to product concept, sales plan, and manufacturing plan. The proposed methodology will be one of the main tools for determining life cycle strategy of the product to be designed, mainly from the viewpoint of lifetime. The analysis will be based on the market data of existing products. As a result, the methodology helps the planners to find out appropriate life cycle business, paths of circulation of the product and its components, design targets for extending product (value) life, and market segment for appropriate use of the product.

Future issues include introduction of user clusters in analysis of disposal distributions and quantitative evaluation of derived life cycle strategies after applying LCOPs.

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Contact: Yasushi Umeda
Osaka University
Department of Mechanical Engineering, Graduate School of Engineering
Yamada-oka 2-1, Suita
Osaka, 565-0871
Japan
Tel: +81 6 6879 7260
Fax: +81 6 6879 7260
e-mail: umeda@mech.eng.osaka-u.ac.jp
URL: http://www-lce.mech.eng.osaka-u.ac.jp/english/index-e.html