INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15-18, 2005

PROPOSAL OF “MARGINAL REUSE RATE” FOR EVALUATING REUSABILITY OF PRODUCTS

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Abstract

While reuse is an effective life cycle option in terms of environmental loads and value of reutilization, reuse has inherent difficulties. Our naïve questions include why component reuse of electric home appliances seems impossible while that of photocopiers succeeded. This paper clarifies that it is essential for successful reuse to balance supply and demand of reusable components and proposes an index named “marginal reuse rate,” which indicates upper limit of reusability from the viewpoint of the balance. By using the marginal reuse rate, this paper analyses reusability of single use camera, photocopier, and automatic teller machine (ATM) and clarifies that the relation between sales period and lifetime in a product type determines the marginal reuse rate and effective measures for increasing reusability differ according to the relations; namely, prolongation of the sales period for shorter life products, part commonization design among generations for middle life products, and controlling sales and disposal distributions for longer life products. The marginal reuse rate indicates that design of life cycle, in addition to product design for reusability, is indispensable for successful reuse. In this sense, the analysis with the marginal reuse rate is an indispensable tool for appropriate life cycle design.

Keywords: Environmentally conscious design, life cycle design, reuse, marginal reuse rate

1. Introduction

For solving the environmental issues, the importance of environmentally conscious design increases rapidly. Especially, design of whole product life cycles is essential so as to circulate resources appropriately in a product life cycle [1]. While material recycling is actively practiced, successful cases of reuse of products and components are not many. Nevertheless, we believe that reuse is a hopeful life cycle option with higher environmental efficiency than material recycling in general. Moreover, reuse may reduce procurement cost of components and subassemblies. In this paper, we include product remanufacturing, product reuse, and component reuse into the term “reuse.” Our naïve questions include why component reuse of electric home appliances seems impossible while that of photocopiers succeeded and there must be some critical factors besides so-called reuse rate and design for reusability. The objectives of this research are to clarify and formalize these critical factors for reusability. Especially, we clarify that one of these critical factors is the balance between supply of reusable products and components and their demand and that it is indispensable for successful reuse to design product life cycles appropriately, in addition to designing products reusable. For this purpose, this paper proposes an index named “marginal reuse rate,” which indicates upper limit of reusability from the viewpoint of the balance of supply and demand. Analysis of a product life cycle with the index gives us various cues for guiding eco-conscious life cycle design (*e.g.*, [2], [3]) toward successful reuse.

The rest of this paper consists as follows. Section 2 clarifies features and issues of reuse and introduces several types of component reuse. And then this section proposes “marginal reuse rate.” Section 3 analyses some practical product life cycles with the marginal reuse rate. Examples include single use camera, photocopier, and automatic teller machine (ATM). Section 4 summarizes the messages obtained from the case studies and shows the effectiveness of the analyses to the life cycle design. Finally, Section 5 concludes this paper.

2. Marginal reuse rate

2.1. Basic characteristics of reuse

In this paper, we define “reuse” as a life cycle option where components or modules are extracted from a product, cleaned and repaired if necessary, and used again in another product with same functions. The life cycle option “reuse” includes sales of secondhand products, product remanufacturing, product reuse, and component reuse. Let us here focus on component reuse, since the distinction between product reuse (or product remanufacturing) and component reuse is not essential.

Component reuse can be classified into four types according to the difference of supply and demand (see Figure 1). *Product installation reuse* extracts components from disposed products and reuses components for manufacturing the same type of or similar products. Typical examples of this type include remanufacturing of single use cameras and photocopiers. *Spare parts reuse* utilizes old components as spare parts for maintenance tasks. This type is further classified into two types: On one hand, reusable components can be extracted from disposed products (let us call this type *spare parts reuse from disposed products*). Examples of this type include reuse of automobile components and junk computer

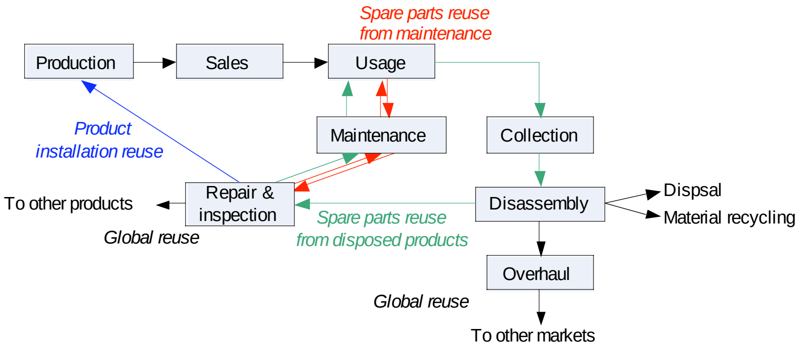

Figure 1. Four paths of component reuse.

components. On the other hand, like reuse of printer cartridges, we can obtain reusable components as a result of maintenance tasks. After cleaning and repair (refill of toner in the cartridge example), the component is reused again as a spare part for another maintenance task. Let us call this type *spare parts reuse from maintenance*. There are other reuse loops, such as reuse components to other products (*e.g.*, reusing a car engine to a motorboat) and to reuse products in other markets (*e.g.*, export secondhand machinery to developing countries). However, these are beyond the focus of this paper, since the key player in such loops is the distribution industry rather than the manufacturing industry.

While reuse has potential advantages in terms of environmentally consciousness and value of reutilization, successful reuse should satisfy the following conditions. In general, conditions of successful reuse are more severe than those of material recycling. Obviously, the conditions 1 and 4, among the following four conditions, are not serious in recycling.

1. Physical lifetime
   Remaining physical lifetime of a component to be reused should be long enough comparing to lifetime of a product in which the component is installed (let us call it a *destination product*). If it is short, maintenance should be incorporated.

2. Costs
   Costs for reusing components should be affordable comparing to costs for manufacturing new components and treating old components as wastes when they are not reused. It is not easy to satisfy this condition because of additional efforts for collection, cleaning, inspection, and so on. However, according to our investigation, component reuse of single use cameras and photocopiers has recently satisfied this condition; in other words, profitable.

3. Value and quality
   Remaining value and quality of the reusable component should satisfy required those for a destination product.

4. Balance between supply and demand of reuse components
   Even if a component has enough remaining lifetime and value and, therefore, can be reused, it is not reused if the manufacturer do not manufacture destination products that can use the reusable component.

While the conditions 1, 2, and 3 are obvious for making reuse successful, the condition 4 has not well investigated by existing design methodologies for reusability (*e.g.*, [4]). Therefore, this paper focuses on the condition 4, balance between supply and demand of reuse components, and clarifies prerequisites for successful reuse from this viewpoint by introducing an index “marginal reuse rate.”

2.2. Marginal reuse rate

For discussing the issue of the balance, let us take the simplest type of reuse as an example, same type product installation reuse where components are extracted from disposed products

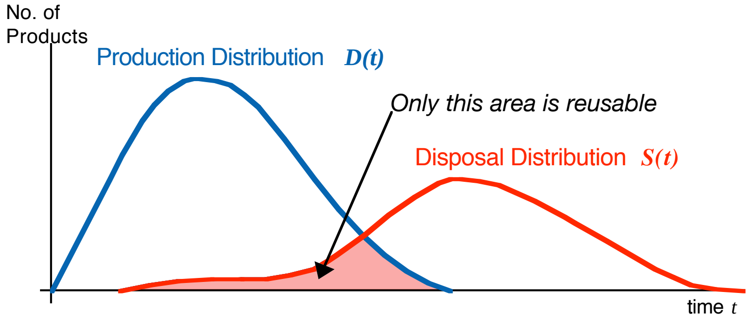

Figure 2. Marginal reuse rate for same type product installation reuse

and reused for manufacturing the same product type like the single use camera. In this case, these components cannot be reused if the same product type is not manufactured. Figure 2 represents this relationship. In this figure, "Production Distribution" represents production amount of the product type at each time period. Each product is used for a while and thrown away. "Disposal Distribution" represents amount of disposed products at each time period. Therefore, the amount of products of which components are reusable is only the red area in this figure; in other words, when both of production and disposal of the product type occur. This is the basic idea of "marginal reuse rate," which we define as the rate of reusable products to the total number of products. Mathematically, marginal reuse rate MR is defined as Equation (1), where $S(t)$ and $D(t)$ denote supply and demand distributions of the target product, respectively, and $min(f(t),g(t))$ represents smaller value of $f(t)$ and $g(t)$ at the time t. In this equation, the denominator represents the total number of the product.

$$MR = \int_0^\infty min(S(t),D(t))dt \bigg/ \int_0^\infty S(t)dt \qquad (1)$$

In the example of Figure 2, $S(t)$ and $D(t)$ correspond to the disposal and the production distributions, respectively[1]. While models of $S(t)$ and $D(t)$ are given in Section 3.1, the marginal reuse rate shows theoretical upper limit of reusability; actual reuse rate cannot be higher than this rate, even if design for reusability is applied perfectly, collection rate is 100%, and all of extracted components work well. For example, Figure 3 illustrates the situation of electric home appliances in Japan and shows that it is almost nonsense to discuss reuse of them under the traditional life cycle. In this way, analyses with the marginal reuse rate clarify essential applicability of the reuse option to a product life cycle.

Traditionally, the reuse rate has been used as the main index of reusability. The reuse rate is the rate of weight or number of reusable components in *one* product and is deeply dependent on design for reusability and reuse process. Since this index focuses on each product, this index is effective only in the overlapped area in Figure 2. From the viewpoint of resource saving and reduction of wastes, a more important index is the rate of actually reused

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[1] As opposed to the normal manufacturing, product disposal is the supply of reusable components and production is the demand of the components in the product installation reuse.

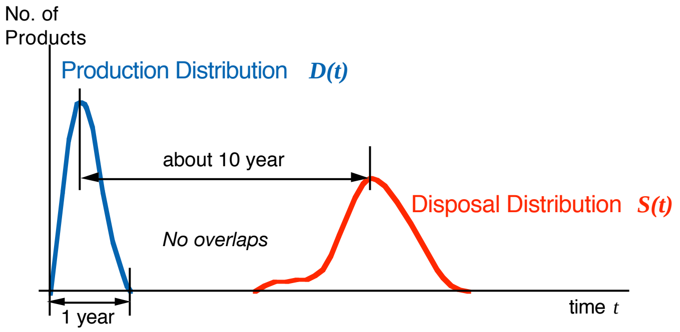

Figure 3. Marginal reuse rate of electric home appliances.

components to the total demand of the component. Let us call it *reuse sufficiency*. For example, when 100 motors are required for manufacturing a product type and 30 motors extracted from disposed products are reused, the reuse sufficiency is 30%. Mathematically, Equations (2)-(4) denote the relationship among the reuse rate, the reuse sufficiency, and the marginal reuse rate.

$$RR_n = n(R)/n(P) \tag{2}$$

$$RS_i = MR \times c \times y_i \tag{3}$$

$$RS_p = MR \times c \times \frac{\sum_{i \in R} y_i}{n(P)} \tag{4}$$

Where,

RR_n: Nominal reuse rate based on number of components, which represents the rate of number of (expected or designed) reusable components to the total number of components in a product.

P: A set of all components in a product.

R: A set of (expected) reusable components, which is a subset of P.

$n(*)$: Number of elements in a set *.

RS_i: Reuse sufficiency for a component i.

c: Collection rate of the disposed products.

y_i: Yield rate of a component i; in other words, the rate of actually reusable components, which work well, to all of the same kind of component in disposed products.

RS_p: Reuse sufficiency for the target product type.

In Equation (4), $\sum_{i \in R} y_i$ represents number of reused components considering yield rate of each component and, therefore, $\sum_{i \in R} y_i \Big/ n(P)$ shows the net (or resulting) reuse rate and is smaller than RR_n. For example, let us assume a camera consisting of ten components and eight components among ten are reusable. In this case, the nominal reuse rate RR_n is 80%. But, if the marginal reuse rate MR is 30%, collection rate is 80%, and yield rates of those eight components are 80%, the product reuse sufficiency RS_p falls down to 15.4%. In other words, although this camera is well designed for reuse (80% of reusability), the resulting effect, which indicates reduction of resource consumption and waste generation, is only 15%.

In short, since both of c and y_i are smaller than one, the reuse sufficiency RS_p is always smaller than the marginal reuse rate MR and, therefore, the marginal reuse rate indicates the theoretical upper limit of reusability. This means that the marginal reuse rate is an approximated index for effectively supporting decision making of life cycle design, especially determining whether reuse is employed or not, even without knowing detailed data of reuse rate, yield rate, and collection rate.

As shown in Equation (4), means for increasing effectiveness of reuse include increase of collection rate, which depends on the life cycle design and collection system, yield rate of extracted components, which depends on product design and reuse processes, nominal reuse rate, which again depends on design for reusability, and the marginal reuse rate. When we assume the product installation reuse, means for increasing the marginal reuse rate depend on the life cycle design and are summarized as follows (see Figure 2):

- Control of time: Examples include extension of the production and sales periods, shortening of the product life, and common use of a component type among multiple generations (*i.e.*, component commonization design among generations).
- Extension of amount: An example is component commonization design among multiple types of products.

We will discuss detailed analyses of the marginal reuse rate and effective means with some case studies in Section 3.

2.3. Variants of marginal reuse rate

In Section 2.2, we mainly focused on the product installation reuse. By focusing on supply and demand patterns of reusable components, the reuse types discussed in Section 2.1 can be classified as shown in Table 1. In this table, “Maintenance Distribution” means number of maintenance occurrence in a product type at each time period. This table denotes that, for example, the reuse path from disposed product to product production is the product installation reuse and characteristics of supply and demand in this reuse type are represented as product disposal distribution and production distribution, respectively. In this table, we have not known the reuse path where broken-down components are extracted as a result of maintenance tasks and are reused for producing new products after repair.

This section discusses how the marginal reuse rate is represented in each reuse type.

Table 1. Reuse types.

				Supply	
	Process			Dispsal	Maintenance
		Target		Product	Component
			Characteristic Distribution	Product Dispsal Distribution	Maintenance Distribution
Demand	Production	Product	Production Distribution	*Product Installation Reuse* Examples: - Single Use Camera - Photocopier	N/A
	Maintenance	Component	Maintenance Distribution	*Spare Parts Reuse from Disposed Products* Examples: - Car components - PC components	*Spare Parts Reuse from Maintenance* Examples: - Toner Cartridge - Mother Board of PC

(1) Product installation reuse

We have already discussed the product installation reuse into the same product type in Section 2.2. In the case of product installation reuse into a different product type (including different generation of a same product type), the same discussion holds. In Figure 4, the rate of red area is the marginal reuse rate from product A to product B in this reuse type. In other words, Equation (1) is valid for this reuse type, except that $D(t)$ is production distribution of another product type (*viz.*, product B). This implies that the manufacturer can arbitrarily determine the $D(t)$ curve, while the product lifetime determines the relationship between $S(t)$ and $D(t)$ in the product installation reuse into the same product type. Then, we can expect higher marginal reuse rate in the product installation reuse into a different product type.

(2) Spare parts reuse from disposed products

In this reuse type, while Equation (1) also holds, the marginal reuse rate looks like the rate of the red area in Figure 5. Here, let us assume that destination products are the same type to the disposed product. While $S(t)$ in Equation (1) is same as that in the product installation reuse, $D(t)$ is modeled as Equations (5)-(7). Here, we assume that maintenance distribution can be calculated by multiplying failure rate by number of products in use. In this way, $S(t)$ and $D(t)$

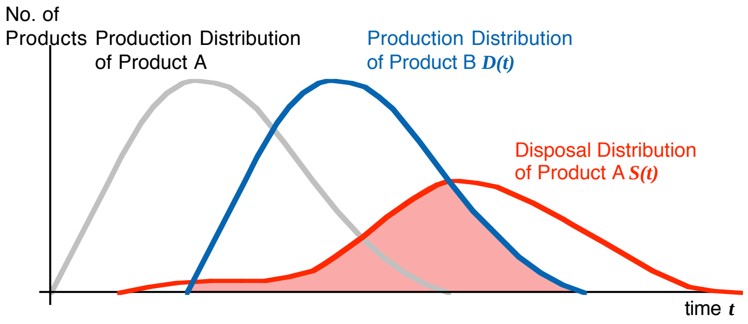

Figure 4. Marginal reuse rate of product installation reuse for different product type

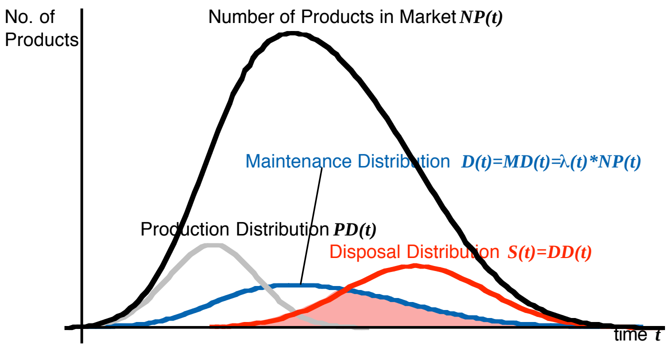

Figure 5. Marginal reuse rate of spare parts reuse from disposed products

in a single product type are deeply related with each other and, therefore, the life cycle design is indispensable.

$$NP(t) = \int_0^t (PD(\tau) - DD(\tau))d\tau \tag{5}$$

$$D(t) = MD(t) = \lambda(t) \times NP(t) \tag{6}$$

$$S(t) = DD(t) \tag{7}$$

Where,

$NP(t)$: Number of products used in the market.
$PD(t)$: Production distribution of the target product type.
$DD(t)$: Disposal distribution of the target product type.
$MD(t)$: Maintenance distribution of the target product type.
$\lambda(t)$: Failure rate of the target product type.

(3) Spare parts reuse from maintenance

This reuse type is peculiar since *S(t)* and *D(t)* are identical if we assume the destination product is the same type of the source (see Table 1). Therefore, by definition, the marginal reuse rate is a hundred percent. While we do not go into details, we have examined marginal reuse rate for redecoration of condominiums, which is a kind of spare parts reuse from maintenance, with practical data [5]. This analysis revealed that, while the marginal reuse rate is surely a hundred percent, the dominant factor for the reuse sufficiency is the failure rate, namely, the probability of occurrence of redecoration.

While we do not discuss the spare parts reuse in Section 3, based on the discussion so far, conditions for successful spare parts reuse are summarized as follows:

- The product should need maintenance and have longer lifetime.
- Disposal distribution should be wider; for example, car components are suitable since cars are disposed because of accidents in addition to failure.
- Components to be reused should have longer lifetimes and higher failure rates.

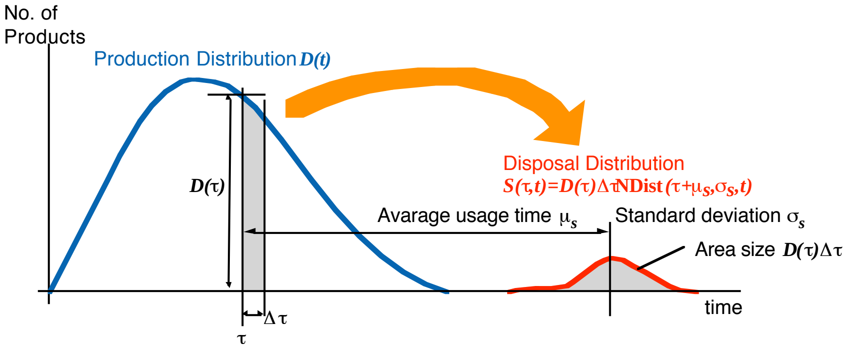

Figure 6. Model of disposal distribution.

- Collection rate and yield rate should be high enough.

3. Analyses of reusability using the marginal reuse rate

In this section, we analyze reusability of practical products by using the marginal reuse rate. Namely, we analyze product installation reuse of single use camera, photocopier, and automatic teller machine (ATM). Among them, product installation reuse of single use camera and photocopier are practiced, but single use camera has a short lifetime and photocopier has a longer lifetime. On the other hand, ATM has a very long lifetime and its product installation reuse is not practiced. These are the reasons why we chose these products. Here, the data used in this section are real data we obtained from manufacturers of these products.

3.1. Modeling the marginal reuse rate

In order to analyze of these products, we model the disposal distribution *S(t)* and the production distribution *D(t)* as follows. For the sake of simplicity, we represent *D(t)* as the normal distribution as shown in Equation (8), where *A*, μ_d, and σ_d denote total amount of manufactured products, mean, and standard deviation, respectively.

$$D(t) = A\,\mathrm{NDist}(\mu_d, \sigma_d, t) \tag{8}$$

Where, $\mathrm{NDist}(\mu,\sigma,t)$: Normal distribution with mean μ and standard deviation σ; *viz.*,

$$\mathrm{NDist}(\mu,\sigma,t) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(\frac{-(t-\mu)^2}{2\sigma^2}\right)$$

For modeling *S(t),* we assume that products manufactured at the time τ will be disposed in accordance with another normal distribution with mean usage period μ_s and standard deviation σ_s (see Figure 6). As shown in Figure 6, the amount of manufactured products at the time between τ and $\tau+\Delta\tau$ is $D(\tau)\Delta\tau$. Disposal distribution of these products $S(\tau,t)$ is represented as Equation (9) by assuming the above normal distribution. As a result, disposal distribution of all products is sum of $S(\tau,t)$ for all production time ($\tau = 0\cdots\infty$) (see Equation (10)). This is our model of disposal distribution. In the following case studies, we use this distribution curve.

$$S(\tau,t) = D(\tau)\Delta\tau \,\mathrm{NDist}(\tau + \mu_s, \sigma_s, t) \tag{9}$$

$$S(t) = \sum_{\tau=0}^{\infty} S(\tau,t) = \int_{\tau=0}^{\infty} D(\tau)\mathrm{NDist}(\tau + \mu_s, \sigma_s, t)d\tau \tag{10}$$

3.2. Single use camera

The marginal reuse rate of a type of single use camera was estimated as shown in Figure 8. In this figure, rectangles and triangles denote the number of sold products and that of *actually* collected products, respectively. Therefore, the former correspond to the demand distribution and the latter represent the supply distribution multiplied by the collection rate of the product. In this case, we model the demand distribution by combining the normal distribution and a liner equation, because the manufacture strategically extents sales period of the product (after 38 months in this figure). Namely, Equation (11) represents the demand distribution. The parameters are identified by using the least squares fitting[2]; $\mu_d = 16.0$, $\sigma_d = 11.4$, $t_0 = 38.5$, $t_e = 67.9$, and the total amount of products *A* is normalized as 1. Equation (10) is used for estimating the supply distribution without any modification and parameters were identified as $\mu_s = 4.22$ and $\sigma_s = 3.93$. Moreover, by calculating ratio of the total collected amount to the total sold amount, the collection rate (CR) of this product is estimated as 60%. In Figure 8, blue, red, and green curves show estimated *D(t), S(t),* and $S(t) \times CR$, respectively.

$$D(t) = \begin{cases} A\,\mathrm{NDist}(\mu_d, \sigma_d, t) & t \le t_0 \\ D(t_0)\dfrac{t - t_e}{t_0 - t_e} & t_0 < t \end{cases} \tag{11}$$

As shown in Figure 8, we may say that the estimated curves fit well to the actual data and, therefore, the models proposed in Section 3.1 are adequate. As a result, the marginal reuse rate of this product life cycle is estimated as 85.1%. Moreover, if we define *usability rate of collected products UR* as the rate of the collection distribution $S(t) \times CR$ overlapped with the demand distribution *D(t)* (see Equation (12)), *UR* of this life cycle is 98.4%. In other words, at most, 98.4% of collected products have the chance to be reused into the production of the same product. In this way, we conclude that the manufacturer succeeded in constructing the product life cycle suitable for the product installation reuse.

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[2] In Section 3, all parameter identifications employ the least squares fitting.

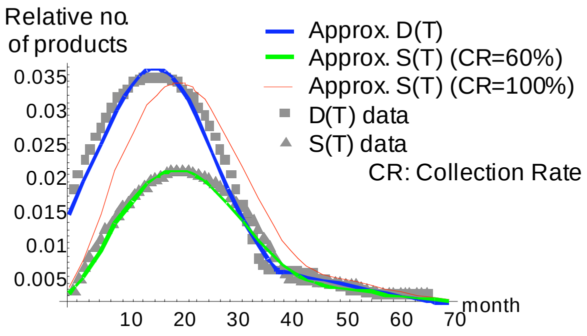

Figure 8. Supply and demand distributions of single use camera.

$$UR = \int_0^\infty min(S(t)\times CR, D(t))dt \Big/ \int_0^\infty (S(t)\times CR)dt \tag{12}$$

The manufacturer takes the strategy of prolongation of sales period for increasing reusability based on their experiences (*viz.*, after 38 months in this figure). Our estimation verified that this strategy increases both of the marginal reuse rate and the usability rate by several percents. Messages from this analysis are summarized as follows:

- The life cycle of this product is well designed for the product installation reuse.
- Shorter life products, to be exact, products of which lifetime is short enough comparing to its production period, are suitable for the product installation reuse.
- Prolongation of the sales period is an effective strategy for increasing the marginal reuse rate. However, component commonization design among multiple generations is less effective, since the marginal reuse rate is already high enough.
- Collection rate of this life cycle seems to be optimized in terms of the usability rate. This is important for cost reduction of reuse, since lower usability rate will result in higher costs for collection and disposal of excessive products.

3.3. Photocopier

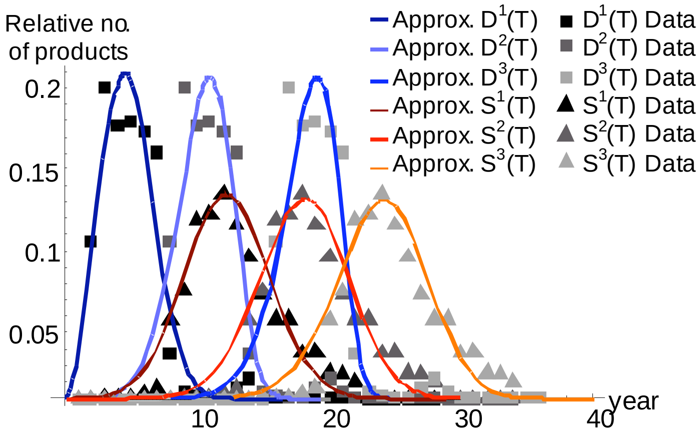

Figure 7. Supply and demand distributions of photocopier.

Table 2. Marginal reuse rates of a photocopier.

(%)

to \ from	1	2	3
1	14.5	0	0
2	46.2	14.5	0
3	24.4	46.2	14.5

The type of a photocopier discussed here has about seven years lifetime, which is between the single use camera and the ATM, and is actually reused for manufacturing new products. Figure 7 illustrates supply and demand distributions for three generations of a photocopier. Note that, while the distributions for the first generation is the actual data, we assumed the distributions for the second and the third generations by copying those of the first generation with consulting experts of the manufacturer, since they do not have them. In this figure, $S^i(t)$ and $D^i(t)$ denote supply and demand distributions for *i*th generation; for example, $D^1(t)$ represents production distribution for the first generation. In this case, we used the normal distribution and parameters are identified as $\mu_d^1 = 4.7$, $\mu_d^2 = 10.7$, $\mu_d^3 = 16.7$, $\sigma_d^1 = \sigma_d^2 = \sigma_d^3 = 2.0$, $\mu_s^1 = \mu_s^2 = \mu_s^3 = 7.6$, and $\sigma_s^1 = \sigma_s^2 = \sigma_s^3 = 2.6$. In this case, the normal distribution is not so accurate approximation as that of the single use camera; for example, the demand distribution has a peculiar projection, but we consider that this approximation is enough for designing life cycle strategy. This issue will be discussed in Section 4. The marginal reuse rates from *i*th generation to *j*th generation *MR(i,j)* are estimated as shown in Table 2. As shown in this table, although this product is actually reused, the marginal reuse rate for the same generation is not so high. Roughly speaking, in practice, one quarter of reusable photocopiers, which are chosen out of collected products, are used for manufacturing the same generation and the rest, three quarters, are for the next generation. This fact is consistent with our estimation, because *MR(1,2)* is three times of *MR(1,1)*. Messages from this analysis are summarized as follows:

- For middle life products, of which lifetime is comparatively same as length of production period, the product installation reuse among generations is the most suitable reuse type.
- For increasing the marginal reuse rate in this type, part commonization design between the generations that have high *MR(i,j)* is indispensable.

3.4. Automatic teller machine (ATM)

ATM has the longest lifetime among the three products. Figure 9 illustrates estimated supply and demand distributions for two generations of ATM based on the actual data for eleven years. Also, in this case, we used the normal distribution and we may say that the estimated curves fit well to the actual data. Distribution parameters are identified as $\mu_d^1 = 5.58$, $\mu_d^2 = 10.7$, $\sigma_d^1 = 2.41$, $\sigma_d^2 = 2.53$, $\mu_s^1 = \mu_s^2 = 12$, and $\sigma_s^1 = \sigma_s^2 = 2$. Note that we could obtain data for disposals only for three years (*viz.*, 9-11 year) and we could not for disposals

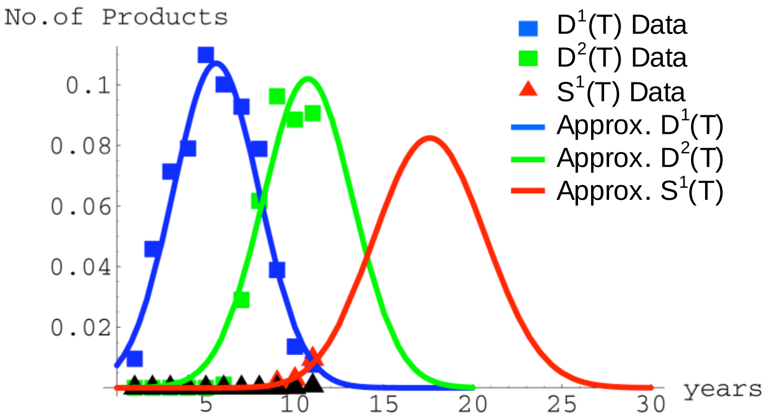

Figure 9. Supply and demand distributions of ATM.

of the second generation. Therefore, the estimated disposal distributions may be inaccurate and we assumed that the disposal distribution of the second generation (*viz.*, μ_s^2 and σ_s^2) is identical to that of the first generation. However, it is one of advantages of the proposed mathematical model that we can estimate these distributions with small amount of data.

The marginal reuse rates are estimated as $MR(1,1) = 2.6\%$, $MR(2,2) = 3.7\%$, and $MR(1,2) = 15.9\%$. This result suggests that ATM with the traditional design and sales strategy (*i.e.*, just selling products) has very low applicability of the product installation reuse. Even in such a case, the marginal reuse rate for the next generation (*MR(1,2)*) is seven times larger than that for the same generation (*MR(1,1)*). Moreover, by varying parameters of the curves (*viz.*, means and standard deviations), *MR(1,2)* arrived at about 86% when $D^2(t)$ almost coincides with $S^1(t)$. This indicates that the product installation reuse for the next generation in ATM is essentially plausible and effective if the manufacturer can control sales and disposal distributions. These results illustrate advantages of the analysis with the marginal reuse rate for supporting the life cycle design. In short:

- For long life products, of which lifetime is much longer than the production period, possibility of the product installation reuse for the same product is very low.
- For increasing the marginal reuse rate in this type, part commonization design between generations that has high *MR(i,j)* is indispensable.
- Controlling sales and disposal distributions among generations, which is a part of the life cycle design, is indispensable for making reuse effective.

4. Discussions

4.1. Messages from the case studies

The analyses with the marginal reuse rate in Section 3 clarified plausibility of the product installation reuse of three types of products. In short, relation between sales period and lifetime in a product type determines the marginal reuse rate, which is a theoretical upper limit of reusability, and effective measures differ according to the relations; namely, prolongation of the sales period for shorter life products, part commonization design among generations for middle life products, and controlling sales and disposal distributions, *e.g.*, introducing rental system, for longer life products.

Experts in this domain might have known these facts based on their experiences. One of the features of this research is to clarify these facts by formalizing and quantifying them.

4.2. Generality and applicability of the marginal reuse rate

Generally speaking, it is essential for successful reuse to balance supply and demand of reusable products and components. This paper formalized and quantified this issue of reuse as the marginal reuse rate. Case studies in Section 3 verified correctness of the proposed mathematical model and its effectiveness for guiding the life cycle design. The definition of the marginal reuse rate in Equation (1) is general enough to apply it to various reuse types and product types. While we used the normal distribution for modeling $S(t)$ and $D(t)$ in Section 3, other models can be employed. Actually, we have also employed the Weibull distribution, but the results differ within several percents. Since the analysis with the marginal reuse rate aims at supporting the life cycle design, simple approximation is adequate because of lack of actual data of them. In this sense, Section 3 clarified that the approximation with the normal distribution are effective enough. When the analysis is applied to post-evaluation of a practiced life cycle, more precise models of distributions might be useful. In such a case, the mathematical extension is quite easy.

The marginal reuse rate indicates that product design for reusability (*e.g.*, disassemblability, modularity, and reliability) is inadequate for making reuse plausible and the life cycle design (including controlling sales period and disposal distribution and part commonization design among generations) is indispensable. And this is the answer to our naïve question why component reuse of electric home appliances seems impossible. The analysis with the marginal reuse rate supports a designer for deciding applicability of reuse and its conditions. In this sense, this analysis is indispensable for appropriate life cycle design. Actually, the idea of the marginal reuse rate is deployed into several companies.

5. Conclusions

While reuse is an effective life cycle option in terms of environmental consciousness and value of reutilization, reuse has inherent difficulties. Especially, it is essential for successful reuse to balance supply and demand of reusable products and components. This paper proposed the marginal reuse rate, which indicates upper limit of reusability from the viewpoint of the balance of supply and demand. The analyses with the marginal reuse rate in Section 3 clarified plausibility of the product installation reuse of three types of products. It is clarified that relation between sales period and lifetime in a product type determines the marginal reuse rate and effective measures differ according to the relations; namely, prolongation of the sales period for shorter life products, part commonization design among generations for middle life products, and controlling sales and disposal distributions among generations for long life products. The marginal reuse rate indicated that product design for reusability is inadequate for making reuse plausible and the life cycle design is indispensable. In this sense, the analysis with the marginal reuse rate is an indispensable tool for appropriate life cycle design, especially, deciding applicability of reuse and its conditions. Conversely, we believe that any products can be reused with appropriate life cycle design.

We are currently developing a general software tool for supporting the analysis with the marginal reuse rate. And other future works include extension of the theory of reuse considering other factors (*e.g.*, collection rate, yield rate, and reuse sufficiency) and development of a guideline for life cycle design in terms of reuse.

A part of basic ideas of this research is achieved through discussions in Inverse Manufacturing Forum, Manufacturing Science and Technology Center, Japan. We appreciate Fuji Photo Film Co., Ltd., Fuji Xerox Co., Ltd., and OMRON Corporation for giving us the practical data shown in Section 3. Moreover, a part of this research was financially supported by Grants-in-Aid for Scientific Research, MEXT, Japan and Tokyo Metropolitan University President’s Research Fund.

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