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A Proposal on a Resource Efficiency Index for EEE

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Abstract

According to the widespread of EEE, run-out of certain materials so-called critical metals have become a big anxiety. Functionalities of EEE required from consumers are becoming high year by year, and such critical metals are necessary to enhance functionalities. Thus, the key of product development is to reduce the metal consumption and achieve high functionalities. In other words, high resource efficiency is the key of sustainable production. This paper proposes an index to evaluate resource efficiency of small-sized EEE. The index has value of the product based on the functionality, product reusability, and component reusability, as the numerator. And it has the total amount of environmental impact due to material consumption measured by TMR (total material requirement) minus recoverable environmental impact as the denominator. Through the case studies on mobile phones, the paper concludes that the proposed index will be useful in evaluating resource efficiency of EEE.

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Keywords: EEE; resource efficiency; product functionality; reusability; TMR.

1. Introduction

Although modern life heavily depends on natural resources, the supplies of such resources are limited. In addition, demands for natural resources are rapidly increasing because of the growing economies in developing countries. For example, reserves-to-consumption ratios [1] of some critical metals are very short [2]. If we cannot develop technologies to reduce the consumptions of such critical metals or to replace by common metals, modern lives based on such high-tech products will be endangered. It is said that 3 basic strategies are important to overcome such problems.

- Creating much more value by less consumption of resources.
- Reducing impacts on environment.
- Consuming natural resources wisely.

Plus, encouraging more efficient alternative method shown below is important.

- Reducing consumptions of natural resources by designing products compact, light-weight and using less parts.
- Using reused materials or components.
- Designing easy-to-disassemble.

Basically, if the society is more resource efficient, many problems regarding limited natural resources will be eased. High resource efficiency will be effective in reducing cost and enhancing production efficiency, at the same time. In considering the resource efficiency, the first step is to evaluate resource efficiency quantitatively. Some public organizations or private enterprises have proposed resource efficiency indexes [3, 4]. However, one of the problems is that there is no common definition of resource efficiency. At least, a common concept will be necessary. Thus, regarding this situation, the purpose of this study is to propose a concrete index to evaluate resource efficiency of products. Then, the paper also focuses on evaluating actual products based on the index to know the effectiveness of the index in evaluating efficiencies of small-sized electronic products as an example.

2. Proposal on a resource efficiency index

2.1. Eco-efficiency

Resource efficiency is based on an eco-efficiency [5] idea which is commonly defined by eq. (1)

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$$eco-efficiency = \frac{Value \quad of \quad the \quad product \quad or \quad serive}{Environmental \quad burden \quad of \quad the \quad product \quad or \quad service} \tag{1}$$

2.2. Resource efficiency index

Frequently, LCA [6] result is used for the denominator of the above-mentioned equation of eco-efficiency, to calculate the index concretely. However, sometimes carrying out LCA is not so easy. And we feel that resource efficiency index should focus on criticality of resources than the total environmental burden. Thus, we modified eq.(1) to eq.(2) which we think more suitable in evaluating resource efficiency.

$$resource-efficiency = \frac{Value \quad of \quad the \quad product \quad or \quad serive}{\mathrm{Re}source \quad usage \quad index \quad of \quad the \quad product \quad or \quad service} \tag{2}$$

2.3. How to evaluate the value

As shown in the former section, numerator of the resource efficiency index is "value" of the product or service. Since there are many functions in a product or many business values in a service, total value will be sum of individual functions based on the importance of the functions on the product. In other words, the numerator of the index will be weighed sum of functions. Eq.(3) is the numerical expression.

$$value = \sum_i w_i \cdot \frac{specific \quad value \quad of \quad function \quad i}{reference \quad value \quad of \quad function \quad i} \tag{3}$$

w_i: relative weight of the function i

However, as it was mentioned in the introduction, efficient reuse of resources should be evaluated. Thus, in this paper value of the products are evaluated by values of the original product calculated by eq.(3) plus product reuse value and component reuse value.

2.4. How to evaluate the resource usage

In focusing on resource consumption, one good index is Total Material Requirement (TMR [6]). TMR is defined as the total amount of crude metals, ores, soils, removed surface soils, etc. to obtain a unit amount of refined metals. A large TMR value means that a huge amount of ore has to be extracted from earth environment to get the material. It is equivalent that the material has a large environmental burden. Table 1 shows values of TMR of some well-known elements. Using TMR, the denominator of the index can be calculated. Reuse of materials in the aspect of efficient use of resources should be also evaluated. So, in this paper, we evaluate the resource consumption by eq.(4).

$$resource \quad usage = \sum_j TMR_j - \sum_k TMR_k \tag{4}$$

TMR_j: TMR of the material j, TMR_k: TMR of the recyclable material k

Table 1. TMR of major elements

Element	TMR
Cu	360
Fe	8
Mg	70
Ni	260
Cr	26
W	190
Al	48
Zn	36
Pb	28
Ag	4800
Au	1,100,000
Pd	810,000
Pt	520,000

2.5. Proposing index for resource efficiency

Considering all the aforementioned aspects, the paper proposes a resource efficiency index indicated by eq.(5). 2 items to evaluate product reuse value and component reuse value in the equation are expressed by eq. (6) to (8).

$$resource-efficiency = (original \quad product\,value + product \quad reuse \quad value + component \quad reuse \quad value)/(\sum_j TMR_j - C_3 \sum TMR_k) \tag{5}$$

C_3: recycling rate

$$original \quad product \quad value = \sum_i w_i \cdot \frac{specific \quad value \quad of \quad function \quad i}{reference \quad value \quad of \quad function \quad i} \tag{6}$$

$$product \quad reuse \quad value = C_o \cdot C_1 \cdot \frac{V_2}{V_1} \tag{7}$$

C_0: *collection rate*
C_1: *reusable rate*
V_2: value (price) of the second-hand product,
V_1: value (price) of the original products

$$component \quad reuse \quad value = \frac{C_o}{V_1} \cdot \sum_n C_{2n}(V_{3n} - Lc_n) \tag{8}$$

C_{2n}: reusable rate of component n
V_{3n}: value of the reused component n
Lc_n: labor cost to detach component n

3. Quantification of the value

3.1. Original product value

Since basic resource efficiency index has been proposed by now, the next step is to input concrete values in the equations to calculate the index value and examine the effectiveness of the index. Firstly, the paper tried to evaluate the value of the products by a practical example. Taking a mobile phone as an example of small-sized electronic products, since we are strongly focusing on it, a questionnaire to 83 students to know the relative importance of the functions of mobile phone was carried out. In the questionnaire, 5 functions which were listed up through the brainstorming among the authors were asked. The five functions were "continuous life of the battery," "size of the LCD," "pixels of the camera," "capacity of the storage memory" and "the speed of data transfer." The questionnaire is based on a conjoint analysis [7]. Combinations of the functions of a mobile phone are combined based on the L8 orthogonal array [8] as conjoint cards. Each correspondent looks at the conjoint cards shown in Fig.1 and answers which card is most preferable. Then, the correspondent chooses the second one, and then. Finally, preferable orders from 1 to 8 are given to all the conjoint cards.

Type A
Battery life: 1 Day
Storage memory:16GB
Data trans. Speed:30Mbps
LCD size: 2.6 inches
Camera res.: 400 mill.

Type B
Battery life: 1 Day
Storage memory:16GB
Data trans. Speed:30Mbps
LCD size: 3.7 inches
Camera res.: 800 mill.

Type C
Battery life: 1 Day
Storage memory:32GB
Data trans. Speed:60Mbps
LCD size: 2.6 inches
Camera res.: 400 mill.

Type D
Battery life: 1 Day
Storage memory:32GB
Data trans. Speed:60Mbps
LCD size: 3.7 inches
Camera res.: 800 mill.

Type E
Battery life: 2 Day
Storage memory:16GB
Data trans. Speed:60Mbps
LCD size: 2.6 inches
Camera res.: 800 mill.

Type F
Battery life: 2 Day
Storage memory:16GB
Data trans. Speed:60Mbps
LCD size: 3.7 inches
Camera res.: 400 mill.

Type G
Battery life: 2 Day
Storage memory:32GB
Data trans. Speed:30Mbps
LCD size: 2.6 inches
Camera res.: 800 mill.

Type H
Battery life: 2 Day
Storage memory:32GB
Data trans. Speed:30Mbps
LCD size: 3.7 inches
Camera res.: 400 mill.

Fig. 1. The set of conjoint cards

By averaging the ranking of card A, B, C and D, average ranking of the specification "Battery life: 1 Day" can be calculated. And then, by comparing it to those of card E, F, G and H, it can be calculated that how the difference in "Battery life" is important for the respondent. The importance of "Storage capacity" can be clarified by comparing A, B, E and F versus C, D, G and H. The other functions are the same. As the result of the analysis, relative importance of each function can be calculated by eq.(9) shown below.

$$relative \quad importance \quad of \quad function \ i = \frac{D_i}{\sum_{i=1}^{5} D_i} \tag{9}$$

D_i: difference of the ranking of low level and high level

Then the relative importance of 5 functions were calculated as Table 2. However, since the last function is not a function depends on the design of the mobile phone itself, but depends on the infrastructure, this item was eliminated from the functions. Fig.2 shows the relative importance of other 4 functions. Table 3 is the reference specifications of the 4 functions. Finally, original product values of mobile phones can be calculated by eq.(10).

Table 2. Relative importance of the 5 functions of a mobile phone

	Data trans. speed	Battery life	LCD size	Camera res.	Storage capacity
Relative importance	0.3818	0.2492	0.1347	0.1250	0.1093

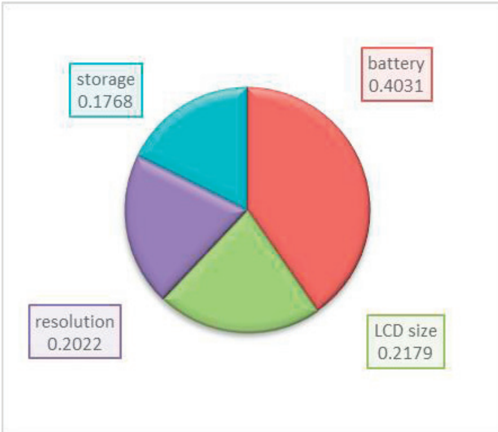

Fig. 2. Relative importance of the functions of a mobile phone

Table 3. Reference specifications of functions of a mobile phone

LCD size [inch]	Resolution [million dot]	Storage capacity [number of photos]	Battery life [h]
3.15	717.9	2,020	488.7

$$original \quad product \quad value =$$
$$0.4031 \times \frac{Battery \quad life}{488.7} + 0.2179 \times \frac{LCD \quad size}{3.15}$$
$$0.2022 \times \frac{Camera \quad resolution}{717.9} + 0.1768 \times \frac{Storage \quad capacity}{2020} \tag{10}$$

3.2. Product reuse value

The next step is to quantify the product reuse value. An existing survey [9] identifies how the consumers handle their used mobile phones. Fig.3 shows the result. So, 0.088 is taken for the reuse rate. Based on eq.(7), product reuse value can be expressed like eq.(11).

$$product \quad reuse \quad value = 0.088 \cdot \frac{V_2}{V_1} \tag{11}$$

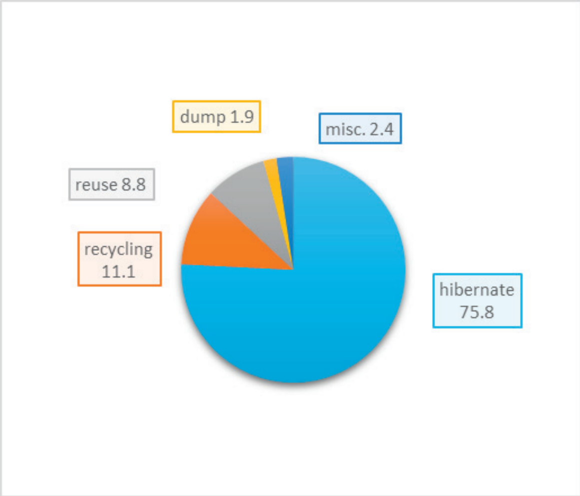

Fig. 3. End-of-life treatment of used mobile phone in percentage. (original data from [9])

3.3. Component reuse value

The next item, component reuse value, is also estimated from Fig.2. Among the used products sent to recyclers, some are manually disassembled to reuse components. Because the only successful example of component reuse is about LCD. It is said [10] that from 30 to 40% of used mobile phones, reusable LCD can be extracted. Labor cost is estimated to be about 1,007JPY per hour in average. So, finally, component reuse value is calculated by eq.(11).

$$component\ \ reuse\ \ value = \frac{1}{V_1} 0.039(V_{3n} - 1{,}007 \cdot \frac{t}{3600}) \tag{11}$$

t: time to disassemble LCD (second)

4. Quantification of resource usage

As for the denominator of the index, based on the existing study [6], an average TMR value of a mobile phone is used in this paper. Table3 shows the estimation of composing materials and weight of each material of a mobile phone and corresponding TMR. In current recycling process, Cu, Au, Ag, Pd, Pt are the target materials to recover from used mobile phones. So, about these 5 materials, TMR of recycled amount should be considered. According to Fig.3 recycling rate is about 0.11. So, it is estimated that 11% of these 5 materials can be recovered from used mobile phones in average. According to the calculation based on the data shown in Table 4, TMR per unit weight can be calculated as 1.69×10^{-4} per gram.

Table 4. Composing materials and corresponding TMR

Composing materials	Weight [g]	TMR	TMR in a mobile phone	TMR of recyclable
Plastic	71.84			
Cu	11.78	360	0.004241	0.004241
Glass	7.83			
Fe	6.66	8	0.0000533	
Mg	3.37	70	0.000236	
Ni	0.74	260	0.00019	
Cr	0.62	26	0.000016	
W	0.55	190	0.00010	
Al	0.34	48	0.000016	
Zn	0.04	36	0.000001	
Ga	0.04	14000	0.0006	
Mn	0.04	14	0.000001	
Pb	0.10000	28	0.000002800	
Ag	0.01147	4800	0.00005506	0.00005506
Au	0.00682	1100000	0.00750	0.00750
Pd	0.00423	810000	0.00343	0.00343
Pt	0.00230	520000	0.00120	0.00120
misc	0.28			
Total	104.25		0.0176	0.0164

5. Evaluation of practical examples and interpretation of the results

Based on the consideration in section 3 and 4, finally, the resource efficiency index can be written by eq.(12).

$$\text{Resource efficiency} = \frac{0.2179 \times \frac{S_1}{3.15} + 0.2022 \times \frac{S_2}{717.9} + 0.4031 \times \frac{S_3}{488.7} + 0.1768 \times \frac{S_4}{2020}}{1.67\text{M} \times 10^{-4}} + \frac{0.088 \times \frac{V_2}{V_1} + \left[\frac{1}{V_1} \left\{ 0.039 \left(V_3 - 1007 \frac{t}{3600} \right) \right\} \right]}{1.67\text{M} \times 10^{-4}} \tag{12}$$

S_1: size of the LCD of evaluating model [inch],
S_2: resolution of the camera of the evaluating model [mill.dot],
S_3: battery life of the evaluating model [h],
S_4: storage capacity [photos],
V_1: value of the original product [Yen],
V_2: value of the second-hand product [Yen],
V_3: value of the reused components [Yen],
t: time to detach LCD [s],
M: total weight of the evaluating model [g]

By using the proposed equation, resource efficiencies of some mobile phones were practically evaluated. Table 5 indicates the resource efficiencies of some mobile phone models.

Table 5. Resource efficiencies of some models of mobile phones

Model	Value of the original product	Value of product reuse	Value of componen t reuse	Total TMR	Resource efficiency
A	0.575	0.017	0.00393	0.0166	32.7
B	0.690	0.005	0.00121	0.0193	32.8
C	0.721	0.009	0.00092	0.0155	43.0
D	0.725	0.004	0.00144	0.0179	37.1
E	0.506	0.004	0.00074	0.0167	27.8
F	0.509	0.004	0.00096	0.0178	26.4
G	0.591	0.004	0.00082	0.0193	28.1

According to Table 5, it seems that the value of the original product are all much lower than 1. This is because the reference model is a relatively new model, while the evaluated models are old models which are all made in 2006, 2007. It was found that even the mobile phones made in similar year and having similar functions, resource efficiencies are rather different. Basically it can be said that the proposed resource efficiency index can identify the characteristics of the product well.

On the other hand, of course there are some problems in the analysis in the paper.

- Conjoint analysis was carried out to know the relative importance of functions, to students in Engineering department. There might be some deviations.
- Since it is very difficult to know the future value of the secondhand product or component prices, we used tentative prices. But, such prices heavily depends on the conditions of the used products. This might be a problem in evaluating the reuse value precisely.
- Disassembly time may depend on the skill of the worker. Estimation of the time may not be exact.
- In this paper, TMR of each product was calculated using average value and the weight. To evaluate the precise and specific resource efficiency this point should be improved.

6. Conclusions

In response to the increasing voices from industry, the paper tried to propose a resource efficiency index which can evaluate how the product can utilize the precious materials better. The paper proposed an index which has the Total Material Requirement (TMR) of the product minus TMR of the recyclable materials as the denominator. Total of original product value (functional value) plus product reuse value and component reuse value was used as the numerator.

Taking mobile phones as examples, the original product value was defined as weighed sum of different functions of a mobile phone. To know the importance of different functions, conjoint analysis was applied. The result showed that the life of the battery was the most important specification among 4 basic requirements.

In calculating the denominator, some survey results including the collection rates of the old products and average material composition in an existing study were used. Finally, the proposed index was applied to some models of mobile phones. It was concluded that the index is helpful in identifying the resource efficient product.

As the future work, it is necessary to estimate the real TMR of the products by measuring the specific material composition. Then, much more examples have to be evaluated in order to know the effectiveness of the proposed index.

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