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ASSESSING THE GREENNESS OF PRODUCT LIFETIME EXTENSION

Minjung Kwak
Department of Industrial and Information Systems Engineering
Soongsil University
No. 369, Sangdo-Ro, Dongjak-Gu, Seoul 156-743, Korea
mkwak@ssu.ac.kr

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Abstract. *Whether to extend a product's lifetime or replace it with a new one is a common question in durable good markets. This paper addresses the issue that there exist products that are more suitable for lifetime extension, but assessment models for identifying such products are scarce. As a means to discern whether or not a product is appropriate for lifetime extension, this paper proposes an index for the greenness of product lifetime extension. The index evaluates the greenness of lifetime extension by reflecting the nature of a product, including the intensity of remanufacturing, technological trends and their influences on product design and user satisfaction, and the intensity of customer use in terms of its environmental impact. Numerical examples are presented to illustrate the use of the index.*
Keywords: Durability, Eco-design, Optimal replacement, Environmental impact

1. **Introduction.** In a durable good market, whether to use a product more (extend its lifetime) or replace it with a new one is a question commonly encountered by consumers. Recently, the issue of lifetime extension is receiving increasing interests, as awareness and concern for environmental problems increase. Extending product lifetime through reuse or remanufacturing is commonly claimed as greener than replacement, as it avoids the resource consumption and waste generation associated with new products [1]. Considering rapid technological advances, however, an extended lifetime implies more obsolescence and inefficiency of the original product, leading to higher environmental impact (e.g., carbon footprint, waste) from customer use [2,3]. Given the trade-off, it is not clear for a product which option is better from the environmental perspective.

This paper addresses the issue that there exist products that are more suitable for lifetime extension, but assessment models for identifying such products are scarce. As a means to discern whether or not a product is appropriate for lifetime extension, this paper proposes an *index for the greenness of product lifetime extension.* The index evaluates the environmental appropriateness of lifetime extension by reflecting the nature of a product. To be more specific, the following three factors are incorporated:

- **Intensity of reuse or remanufacturing**: energy and emissions required for extending the lifetime of the product;
- **Technological trends in product design**: trends in material contents, energy efficiency, and functionality and their consequences on environmental impact and user satisfaction; (See the cell phone example in Figure 1. There is an increasing trend in the impact of manufacturing; in contrast, there is a decreasing trend in the impact of use.)
- **Intensity of customer use**: the ratio of the impact of use to the impact of manufacturing. (See the examples in Figure 2. Some products generate more impact at the production stage, while some do at the use stage.)

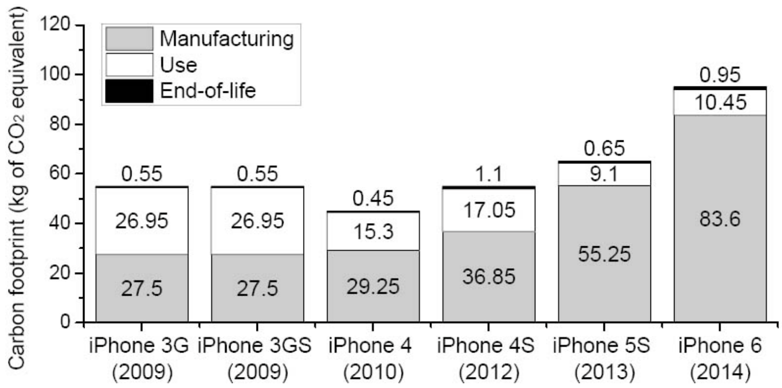

FIGURE 1. Trends in environmental impact of cell phones [4]

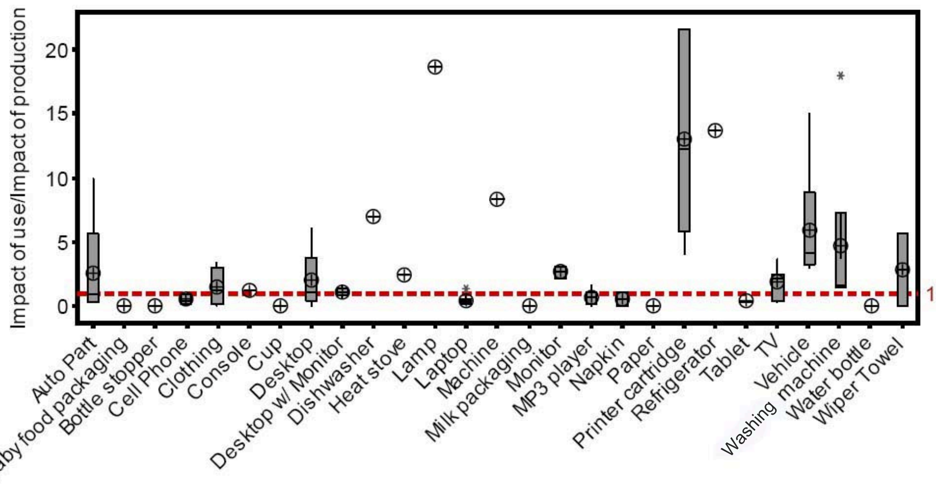

FIGURE 2. Ratio of the impact of use to the impact of manufacturing (adapted from [5])

Over the past decades, a great deal of research has been conducted on the economic consequence of product lifetime, with an aim to find out optimal replacement strategies that minimize the consumer's total cost. (For more information, refer [6].) The environmental consequence of product lifetime, however, has received less attention. In relatively recent years, only a little research has been done on the relationship between product lifetime and its potential environmental impact. [7-10] are among the examples. Although the current paper shares the goal of finding optimal lifetime strategy for a product, it is differentiated from others in that it incorporates the value of a product that the consumer experiences during the use of the product. Unlike the others focusing only on the total environmental impact, this paper considers how much value consumers can gain from the use of the product and spotlights 'the impact per unit value offered by the product'.

The remainder of this paper is organized as follows. Section 2 describes the environmental assessment model. Section 3 presents numerical examples for illustration. Section 4 summarizes the contribution and concludes the paper.

2. **Environmental Assessment of Product Lifetime.** In this paper, the appropriateness of lifetime extension is evaluated by comparing the potential environmental impacts of two scenarios: (1) to replace it with a new one at time T_O, i.e., at the end of use of the original product; (2) to extend the lifetime of the original product through reuse or remanufacturing and continue to use the product for another αT_O. Figure 3 describes

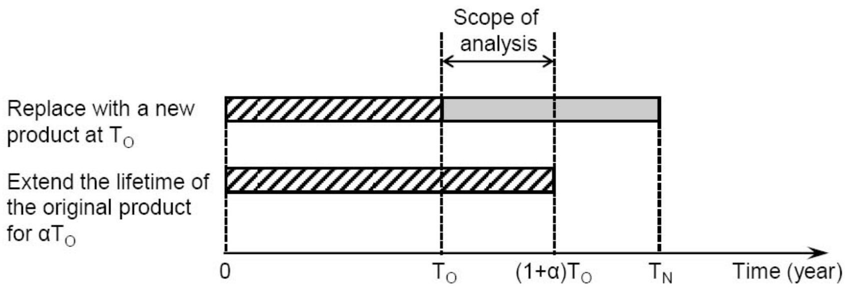

FIGURE 3. Scenarios and the scope of assessment

the scenarios and the scope of assessment considered in this paper. Since the two scenarios are the same for the time period $[0, T_O]$, the scope of analysis is limited to the period $[T_O, (1+\alpha)T_O]$. This section first describes an environmental assessment model for measuring the impact of each scenario. Then, an index for the greenness of product lifetime extension is proposed that can help quickly discern whether or not a product is appropriate for an extended lifetime.

Assumptions. Here, environmental impact assessment is conducted based on the following assumptions.

- The impact of end-of-life treatment is negligible [5]. Only manufacturing and use phases are considered.
- The impact of the manufacturing stage is proportionally divided over the lifetime of the product. Thus, if the scope of the analysis includes only a portion of a product's lifetime, e.g., αT out of T years, then α of the manufacturing impact is included in the consideration.
- The wear and tear due to aging and deterioration over the lifetime are not considered. The impact of use for a unit time (a year here) is constant.
- There exist technological trends in product design, such as increasing energy efficiency, improved functionality, and increasing use of advanced materials, which makes trends in environmental impact. Also, the trends are predictable for the scope of the analysis.

Assessment Model. Equations (1) and (2) calculate the environmental impact of the two scenarios, i.e., lifetime extension and replacement, respectively. Instead of the total impact, they quantify the impact per unit value offered by the product (hereinafter, impact per value). The scope of assessment is $[T_O, (1+\alpha)T_O]$, so the impact for αT_O is of focus.

The impact of lifetime extension includes the impact of reuse/remanufacturing that is represented as a portion β of the initial manufacturing impact. The impact of replacement considers the impact of a new product, but only $\alpha T_O/T_N$ of the manufacturing impact is included. In Equation (2), δ values represent technological changes in the new product.

$$I_E = \frac{\beta \cdot P_O + u_O \cdot \alpha \cdot T_O}{v_O \cdot \alpha \cdot T_O} \tag{1}$$

where
I_E = Impact per value for the scenario of lifetime extension
T_O = Original lifetime of the product in year (before extension)
P_O = Impact of manufacturing a unit of the original product
u_O = Impact of customer use per unit time (here, a year)
v_O = Value offered to the customer per unit time (year) by the original product
α = Extended lifetime in ratio to T_O

β = Impact of extension in ratio to the original manufacturing impact P_O

$$I_N = \frac{(\alpha \cdot T_O/T_N) \cdot \delta_{mfg} \cdot P_O + \delta_{use} \cdot u_O \cdot \alpha \cdot T_O}{\delta_{value} \cdot v_O \cdot \alpha \cdot T_O} \quad (2)$$

where

I_N = Impact per value for the scenario of replacement
T_N = Expected lifetime of the new product
δ_{mfg} = Change in the impact of manufacturing, in ratio to P_O
δ_{use} = Change in the impact of customer use, in ratio to u_O
δ_{value} = Change in the value offered to the customer, in ratio to v_O.

Equation (3) simplifies Equations (1) and (2) by assuming $T_R = T_N = T$ and defining the impact of customer use as a ratio to the impact of manufacturing (i.e., $u_O T = \gamma P_O$).

$$I_E = \frac{\beta \cdot P_O + u_O \cdot \alpha \cdot T}{v_O \cdot \alpha \cdot T} = \frac{\beta \cdot P_O + \alpha \cdot \gamma \cdot P_O}{v_O \cdot \alpha \cdot T}, \quad I_N = \frac{\alpha \cdot \delta_{mfg} \cdot P_O + \delta_{use} \cdot u_O \cdot \alpha \cdot T}{\delta_{value} \cdot v_O \cdot \alpha \cdot T} = \frac{\delta_{mfg} \cdot P_O + \delta_{use} \cdot \gamma \cdot P_O}{\delta_{value} \cdot v_O \cdot T} \quad (3)$$

To justify lifetime extension, the impact per value of the extension case should be less than or equal to the impact per value of replacement, i.e., $I_E \leq I_N$ or $I_N/I_E \geq 1$. Equation (4) proposes $G = I_N/I_E$ as the index for the greenness of lifetime extension. Then, Equation (5) shows the condition where lifetime extension is greener than replacement.

$$G = \frac{I_N}{I_E} = \frac{\delta_{mfg} \cdot P_O + \delta_{use} \cdot \gamma \cdot P_O}{\delta_{value} \cdot v_O \cdot T} \times \frac{v_O \cdot \alpha \cdot T}{\beta \cdot P_O + \alpha \cdot \gamma \cdot P_O} = \frac{\alpha \cdot (\delta_{mfg} + \delta_{use} \cdot \gamma)}{\delta_{value} \cdot (\beta + \alpha \cdot \gamma)} \quad (4)$$

$$G \geq 1 \text{ or } \beta \leq \frac{\alpha \cdot (\delta_{mfg} + (\delta_{use} - \delta_{value}) \cdot \gamma)}{\delta_{value}} \quad (5)$$

3. **Numerical Example.** To illustrate the application of the index, this section presents three numerical examples, each of which simulates a cell phone, washing machine, and general product, respectively. Figures 4-6 show the assessment results. In the figures, a grey area indicates that $G \leq 1$, or replacement is appropriate for the cases in them.

Considering the general technological trends (i.e., $\delta_{use} \leq 1$ and $\delta_{value} \geq 1$), Figure 4 indicates that lifetime extension is appropriate for cell phones in general, unless a significant increase in customer value (more than 40-50%) is expected. This supports a popular claim that extending product lifetime is a greener option than adopting a new product. Figure 5, however, addresses that this may not be always true. Figure 5 indicates that replacement is more suitable for washing machines. Such results do not vary much with the changes in α. A possible explanation is that cell phones and washing machines have different product natures. Cell phones has higher environmental impacts

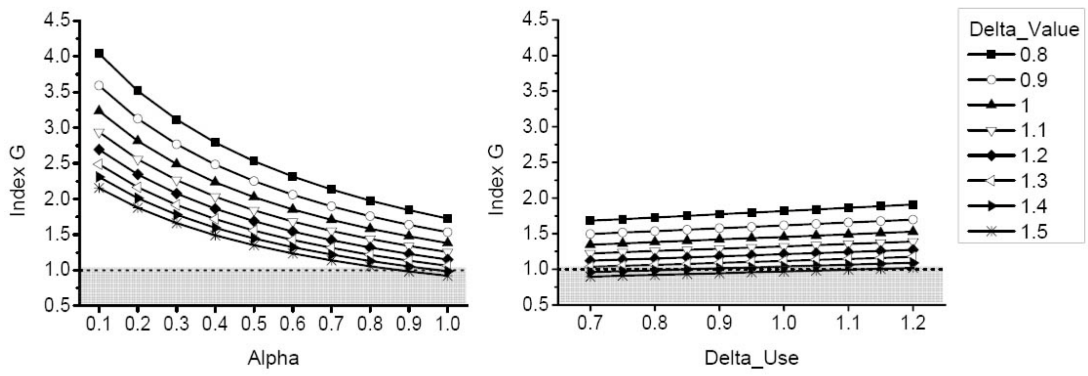

FIGURE 4. Assessment results for a cell phone: (Left) $\beta = 0.7 \cdot \alpha^2$, $\gamma = 0.4$, $\delta_{mfg} = 1.2$, $\delta_{use} = 0.8$; (Right) $\alpha = 1$, $\beta = 0.7$, $\gamma = 0.4$, $\delta_{mfg} = 1.2$

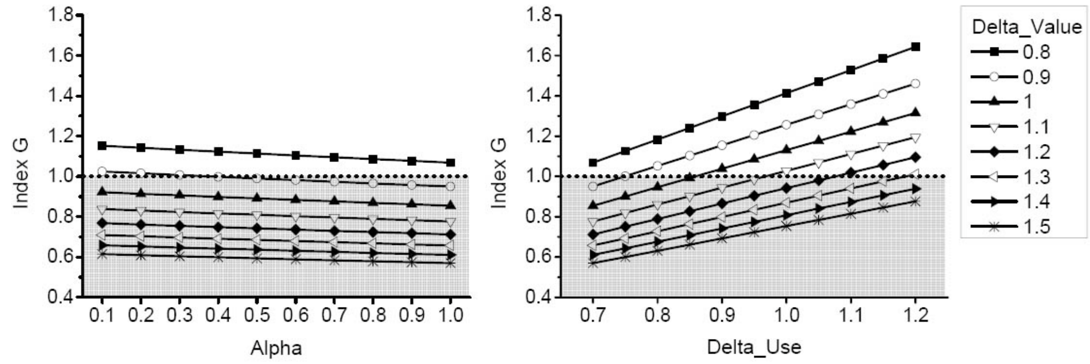

FIGURE 5. Assessment results for a washing machine: (Left) $\beta = 0.44 \cdot \alpha^2$, $\gamma = 5$, $\delta_{mfg} = 1.15$, $\delta_{use} = 0.7$; (Right) $\alpha = 1$, $\beta = 0.44$, $\gamma = 5$, $\delta_{mfg} = 1.15$

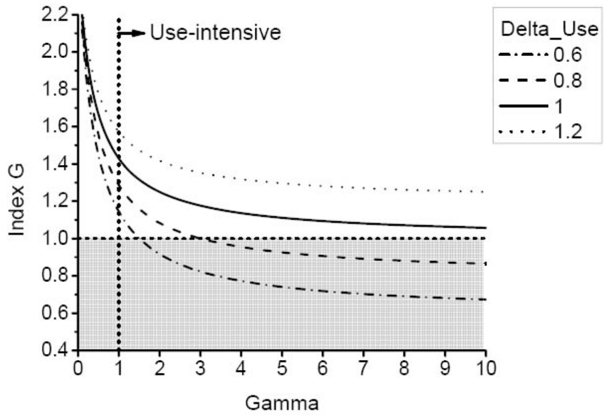

FIGURE 6. Assessment results for a general product: $\alpha = 0.5$, $\beta = 0.2$, $\delta_{mfg} = 1$, $\delta_{value} = 1$

from manufacturing stage ($\gamma = 0.4$). Since it can reduce the environmental impact from manufacturing, extending product lifetime seems more suitable for this type of products. Compared to cell phones, washing machines is a use-intensive product ($\gamma = 5$). They typically generate the majority of its impact at the usage stage. Considering improved energy efficiency of newer products, replacement with a more efficient product seems as a better option in that it reduces the impact from customer use.

Figure 6 shows how the intensity of customer use γ makes the index value change for a general product with $\alpha = 0.5$, $\beta = 0.2$, $\delta_{mfg} = 1$, and $\delta_{value} = 1$. The sensitivity analysis confirms that the greater the intensity of use is, the lower the G index is.

4. **Summary and Future Work.** This paper suggested an environmental assessment model for evaluating product lifetime and proposed an index for the greenness of lifetime extension. The index establishes a link between product nature and the greenness of product lifetime, which allows evaluating whether or not a product is appropriate for lifetime extension. The current index reflects environmental consequences only. Incorporating economic consequences of lifetime extension can be a promising future work.

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