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ASSESSING TIME-VARYING ADVANTAGES OF REMANUFACTURING: A MODEL FOR PRODUCTS WITH PHYSICAL AND TECHNOLOGICAL OBSOLESCENCE

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Abstract

For a successful remanufacturing, it is important to ensure in advance that a product is suitable for remanufacturing and that a remanufactured product will provide greater economic and environmental value than a brand-new product. This paper provides an approach to estimate the economic and environmental advantages of remanufacturing. Focusing on the fact that advantages are greatly influenced by the nature of a product, i.e., its design and lifetime characteristics, as well as the timing of remanufacturing, this paper proposes a model for assessing the time-varying advantages of remanufacturing. The model provides an objective, quantitative method to compare a remanufactured product with an equivalent brand-new version from three perspectives: unit production cost, environmental impact, and net profit. It also defines a set of conditions under which a remanufactured product will be more profitable than a brand-new product. The model is expected to help remanufacturers make informed and effective decisions concerning product design and remanufacturing strategies. To illustrate, the developed model is demonstrated with an example of a desktop computer.

Keywords: Design for X (DfX), Ecodesign, Sustainability

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1 INTRODUCTION

Remanufacturing is a process of restoring discarded or traded-in used products (i.e., end-of-life products) to like-new condition, giving them another life (Hauser and Lund, 2003; Kwak, 2012). If remanufacturing is well planned and managed, a remanufactured product can be a better option than a brand-new product, achieving both economic profitability and environmental sustainability. Since parts are reused, remanufacturers can produce the same product at only a small fraction of the original production costs (Fleischmann et al., 1997). Adverse environmental impacts of the products (e.g., greenhouse gases emission, natural resource depletion, and air and water pollution) can be avoided as well, as the amount of waste is reduced and less materials and energy are consumed in production. One concern is that such advantages of remanufacturing over producing brand-new products may not always exist, and even if so, they change over time. In general, the advantages of remanufacturing decrease over time as the product suffers from wear and tear and technological obsolescence.

This paper addresses how to estimate the time-varying value of remanufacturing; in other words, the advantage of a remanufactured product over a brand-new product. In order for remanufacturers to succeed in the market, it is important that they are capable of ensuring in advance that a product is suitable for remanufacturing and that a remanufactured product will provide greater economic and environmental value than a brand-new product at the moment of remanufacturing. To this end, an evaluation model is needed which establishes a quantitative link between the nature of the product and the time-varying value of remanufacturing from the remanufacturer's perspective. However, only a few models have been developed for this purpose, which prevents remanufacturers from making informed decisions regarding this aspect of their business.

This paper proposes a model for assessing the time-varying advantages of remanufacturing for a given product. The model compares the remanufactured and brand-new versions of a product and answers the following questions: *Is remanufacturing better than manufacturing a brand new version? How does the timing of remanufacturing affect the advantages of remanufacturing? How do market conditions, such as market preference toward the remanufactured product, existence of secondary markets for used parts, and customer requirements on product specifications, influence any advantages from remanufacturing?* In the comparison study, the model considers three perspectives, i.e., unit production cost, environmental impact, and net profit. Incorporating two time-dependent factors, i.e., technological obsolescence and physical deterioration of constituent parts, the model estimates the value of remanufacturing as a function of the time when the remanufacturing is executed (or, the age of an end-of-life product). Based on the estimates, the model derives a set of conditions under which the remanufactured product will be more profitable than a brand-new product.

The model is expected to help remanufacturers make informed and effective decisions concerning product design and remanufacturing strategies, e.g., whether or not to remanufacture a product, when to take back the end-of-life product for remanufacturing, and what price should be set for the remanufactured product.

The rest of this paper is organized as follows. Section 2 discusses the relevant literature and discusses the major contributions of this work. Section 3 describes the remanufacturing process and key assumptions, and Section 4 proposes the assessment model. Section 5 illustrates the application of the model using the example of a personal computer (PC). Finally, Section 6 concludes the paper.

2 RELEVANT LITERATURE AND CONTRIBUTION[1]

2.1 Design for Remanufacturing

In the area of Design for Remanufacturing (DfR), a number of studies have been presented with the aim of supporting remanufacturing operations by means of design evaluation and enhancement. Lund (1984) presented a set of conditions for a product that need to be fulfilled in order to ensure ease of remanufacturing, or remanufacturability. Hammond and Bras (1996) presented quantitative metrics for assessing the ease of remanufacturing of a product. Shu and Flowers (1999) investigated the effects of the designs of fasteners and joints on the profit from remanufacturing. Zwolinski and Brissaud (2008)

[1] This section is based in part on the PhD dissertation of the first author titled Green Profit Design for Lifecycle (Kwak 2012).

generated profiles of products with higher remanufacturability by analyzing past products that had been remanufactured successfully.

Some studies have selected remanufacturing profit as an evaluation criterion and developed models to obtain the profit value by finding an optimal remanufacturing plan. For instance, Kwak and Kim (2010) introduced a framework for analyzing how product design affects product recovery and what architectural characteristics are desirable for higher recovery profit. Extending their research, Kwak and Kim (2011a) developed a framework for evaluating the design of a product family.

One difficulty in remanufacturing is that the product and its parts can easily become obsolete or outdated (Bras, 2007). Design for Upgrading is another line of design principles that has a close relationship with DfR. Xing et al. (2009) proposed quantitative measures for product upgradability and developed an evaluation model that can be applied at the design stage. Ishigami et al. (2003) presented a design method to enhance upgradability of a product given an upgrade plan.

A few models have been developed to clarify the relationship between product age and the value of remanufacturing. Ferrer (1997) proposed an estimation model for the cost of remanufacturing and the selling price of a PC. The value of a PC was defined as a decreasing function of time. Guide et al. (2006) presented an exponential value decay function to model the time-dependent market value of returned commercial products reflecting the speed of technological advances. However, the models gave little attention to how product characteristics (e.g., specifications, conditions) affect the value.

2.2 Environmental Assessment of Remanufacturing

Remanufacturing is generally claimed as being more environmentally-friendly than producing new products, but some researchers (e.g., Intlekofer et al., 2010; Gutowski et al., 2011) have underlined the possibility that this may not always be true. This leads to the need for scientific methods that evaluate the environmental benefit of remanufacturing. Life cycle assessment (LCA) can be an effective tool for this purpose (For detailed reviews for LCA, see Rebitzer et al. (2004)).

With an aim to evaluate the environmental benefit of remanufacturing, many LCA studies have been reported on various products, including consumer electronics, appliances, and mechanical parts (e.g., engines and transmissions). For example, Goldey et al. (2010) provided the results from LCA studies on telecommunication equipment and demonstrated that remanufacturing can avoid an approximately 30-40% of the global warming potential (GWP). Gutowski et al. (2011) evaluated the energy savings of remanufacturing and reported a total of 25 case studies for a wide range of products. The authors demonstrated that remanufacturing may not always bring environmental benefit.

2.3 Contributions of the Proposed Model

The proposed model is a new contribution that is distinct in the following ways:

- The current model focuses on estimating the relative advantage of a remanufactured product compared to a brand-new product. Although previous DfR studies have provided an excellent base for analyzing whether a product supports remanufacturing, they have given little attention to whether the remanufactured product will surpass a brand-new version.
- The model provides a multi-dimensional assessment tool for measuring remanufacturability. In the comparison of the remanufactured and brand-new products, the model considers three perspectives simultaneously: unit production cost, environmental impact, and net profit.
- The current model clarifies how the nature of the product and the timing of remanufacturing influence the economic and environmental advantages of remanufacturing. Researchers have agreed that the advantages change over time, but many of them, especially those in the field of environmental assessment, have conducted evaluation for a static condition (e.g., product of an average age). Some (e.g., Guide et al., 2006; Ferrer, 1997) have incorporated time in their discussion, but directly linked it to the value of remanufacturing. The current model proposes a more generic approach to estimation. It starts with modeling how the product nature changes with time, and then estimates their influences on the value of remanufacturing.

3 REMANFUACTURING PROCESS AND ASSUMPTIONS

The remanufacturing process under consideration here starts with the disassembly of end-of-life products into parts. The resulting parts are sorted by type, and a determination is made whether or not they are reusable (Rose et al., 2002). Reusable parts are fed back into production for reuse, while nonreusable parts are either sold to the second-hand part market or sent to third-party recyclers to be recovered as raw materials. After being cleaned and reconditioned, the reusable parts are reassembled into remanufactured products. If parts are in short supply, brand-new parts are obtained through external procurement. In terms of design specifications, the remanufactured product is not necessarily the same as the original end-of-life product. An end-of-life product loses its original identity during remanufacturing as it changes back into a group of parts. Depending on what parts are combined, the remanufactured product may or may not have the same specifications as the end-of-life product.

In this paper, the reusability of a part is determined by two factors: physical deterioration and technological obsolescence. Even though the parts are included in one product, each part has its own lifetime characteristics. To be specific, each part deteriorates physically or technologically at its own speed and degree. Taking a computer as an example, the CPUs (Central Processing Units) are known to be extremely reliable, but easily become obsolete due to the frequent introduction of successive, better-performing models. In contrast, optical drives (e.g., DVD drive) are relatively less reliable but change less frequently from a technological perspective. Thus, depending on the required levels of reliability and technological performance, some parts will be reusable whereas others will not be.

To represent a part's technological specification and the level of obsolescence, the model proposed in this paper adopts the concept of **generational difference** (Kwak and Kim, 2013). The generational difference is a relative measure that indicates, in terms of the technology, how obsolete an existing part is compared with the cutting-edge part. As product technology advances, cutting-edge parts of a new generation appear in the market. The newer part corresponds to a greater number of generations, and the cutting-edge part corresponds to the maximum generation. Then, *the generational difference of a part is the gap between its generation and the current maximum generation of the cutting-edge part*; the generational difference of the current cutting-edge part is zero, while that of the very next former cutting-edge part becomes one. As time proceeds, the generational difference increases.

The following describes the notations used in the model.

- $C_{i,\mathrm{target}}^{new}(t), E_{i,\mathrm{target}}^{new}(t) =$ Unit cost and impact of purchasing new, target-level part *i* at *t*
- $C_i^{part}(t), E_i^{part}(t) =$ Total cost and impact of preparing part *i* for remanufacturing a product at *t*
- $I_i^{nonreuse}(t), E_i^{nonreuse}(t) =$ Total income from and impact of processing nonreusable part *i* at *t*
- $C_i^{recond}(t), E_i^{recond}(t) =$ Unit cost and impact of reconditioning a disassembled, reusable part *i* at *t*
- $V_i^{matl}(t), E_i^{matl}(t) =$ Unit income from and impact of reselling a used part *i* to recyclers at *t*
- $V_i^{resale}(t), E_i^{resale}(t) =$ Unit income from and impact of reselling a used part *i* to part market at *t*
- $C^{forward}(t), E^{forward}(t) =$ Unit cost and impact of assembling and redistributing a product at *t*
- $C^{reverse}(t), E^{reverse}(t) =$ Unit cost and impact of taking back and disassembling a product at *t*
- $w_i(t) =$ Probability that a disassembled part *i* is determined as a physically reusable at *t*
- $\delta_i^{\mathrm{target}}(t) =$ Target generational difference for part *i*
- $\delta_i(t) =$ Generational difference of disassembled part *i* at *t*
- $f_i(n,t) =$ the probability that a total of *n* generations of part *i* will appear in the market for [0, *t*]
- $P_N, P_R =$ Sale price of the brand-new and remanufactured product, respectively

For simplicity's sake, the proposed model is based on the following assumptions:

- When considering the production of brand-new products, the end-of-life product is assumed to be taken back to the original manufacturer for responsible recycling (**scenario NR**). When the take-back happens, the end-of-life product is disassembled, and then the resulting parts are sold to third-party recyclers for material recovery.
- For remanufacturing, two scenarios are considered depending on whether or not reselling disassembled parts to the second-hand part market is conducted. If part resale is not considered (**scenario RR**), all non-reusable parts that cannot pass either physical or technological requirements are recycled for material recovery. If part resale is allowed (**scenario RS**), parts that do not meet technological requirements but have good physical conditions are resold to the second-hand part market. Only the remaining parts that cannot pass both physical and technological requirements are recycled for material recovery.

- Target design specifications for the remanufactured product are given for each and every part *i* in terms of the generational difference. The target generational difference is fixed regardless of the timing of remanufacturing *t* (or, the age of the end-of-life product).
- "Conformity-based remanufacturing" is conducted; the target design specifications work as the lower limit, and only the part that conforms to the target can be reused in remanufacturing (Cade, 2009). In other words, a remanufactured product can include both a part with the target specification and one with an above-target (newer generation), i.e., $\delta_i(t) \le \delta_i^{\text{target}}(t),\ \forall i$. (Note that the lower the generational difference, the better the specification.)
- A product is remanufactured only to a product having the same-level or lower-level market position; the market position of the remanufactured product cannot surpass the original position of the end-of-life product. For instance, if a product was positioned as a mid-level product at the manufacturing stage, the remanufactured product can be positioned either as a mid-level or a low-end product. In other words, the target generational difference of the remanufactured product cannot be lower than that of the original product (at time 0), i.e., $\delta_i^{\text{target}}(t) \ \ge \delta_i(0),\ \forall i$.

4 MODEL FOR ASSESSING ADVANTAGES OF REMANUFACTURING

This section proposes a model for assessing the time-varying advantages of remanufacturing. The proposed model targets products that suffer from both physical deterioration and technological obsolescence. Here, technological obsolescence means that the product is too outdated to attract customers who prefer more advanced technologies and performance. When the product is no longer wanted in the market with its original specifications, part upgrade is needed in remanufacturing; parts from end-of-life products should be selectively reassembled with new ones to offer more advanced specifications (Kwak and Kim, 2013). As described in Section 3, the model assumes that there exist target specifications and the remanufactured product should conform to the set of target specifications. This implies that, to be approved as reusable, a part should not only be of good physical condition but also conform to the target specification. If a part is too obsolete to meet the target, part upgrade should be conducted by adopting a new, target-level part.

To estimate the value of remanufacturing, the model compares the remanufactured product with its equivalent brand-new version by considering three scenarios, i.e., NR, RR, and RS.

4.1 Unit production cost

Equations (1) and (2) show the unit production cost under the NR and RR scenarios.

$$C_{NR}(t) = C^{reverse}(t) + \sum_{i \in I} C_{i,\text{target}}^{new}(t) + C^{forward}(t) - \sum_{i \in I} I_i^{nonreuse}(t) \quad \left(\text{where } I_i^{nonreuse}(t) = V_i^{matl}(t)\right) \tag{1}$$

$$C_{RR}(t) = C^{reverse}(t) + \sum_{i \in I} C_i^{part}(t) + C^{forward}(t) - \sum_{i \in I} I_i^{nonreuse}(t)$$

$$\left(\begin{aligned} &\text{where} \quad C_i^{part}(t) = \begin{cases} w_i(t)\cdot C_i^{recond}(t) + (1-w_i(t))\cdot C_{i,\text{target}}^{new}(t) & \text{if } \ \delta_i(t) \le \delta_i^{\text{target}}(t) \\ C_{i,\text{target}}^{new}(t) & \text{else} \end{cases} \\ &\qquad\qquad\quad = C_{i,\text{target}}^{new}(t) - w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \left(C_{i,\text{target}}^{new}(t) - C_i^{recond}(t)\right)\cdot f_i(n,t), \\ &I_i^{nonreuse}(t) = \begin{cases} (1-w_i(t))\cdot V_i^{matl}(t) & \text{if } \ \delta_i(t) \le \delta_i^{\text{target}}(t) \\ V_i^{matl}(t) & \text{else} \end{cases} = V_i^{matl}(t)\cdot\left(1 - w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n,t)\right). \end{aligned}\right) \tag{2}$$

In the NR scenario, all parts that have the target generational difference are newly purchased so as to meet the target specifications. In contrast, in the RR scenario, a product is rebuilt by reassembling reusable parts from the end-of-life product; new parts are purchased only when necessary. The reusability of a part is determined by its degree of obsolescence as well as the physical condition. Only the part that is in good working condition and also conforms to the target specification (i.e., $\delta_i(t) \le \delta_i^{\text{target}}(t)$, or, the maximum increase in the generational difference allowed for part *i* for *t* years is $\delta_i^{\text{target}}(t) - \delta_i(0)$) can be reused in remanufacturing. This implies that the probability of reusing part *i* can be defined as $w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n,t)$, where *n* denotes the number of successive generations of part i being newly released in the market for [0, t] and $f_i(n,t)$ is the probability of n. In the RS scenario, part resale is allowed for working parts among the nonreusable parts. Accordingly, the production cost is similar to that of the RR scenario in Equation (2), except that $I_i^{nonreuse}(t)$ is defined as Equation (3).

$$
\begin{aligned}
I_i^{nonreuse}(t) &= \begin{cases} (1-w_i(t))\cdot V_i^{matl}(t) & \text{if } \delta_i(t) \le \delta_i^{\text{target}}(t) \\ (1-w_i(t))\cdot V_i^{matl}(t) + w_i(t)\cdot V_i^{resale}(n,t) & \text{else} \end{cases} \\
&= \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} (1-w_i(t))\cdot V_i^{matl}(t)\cdot f_i(n,t) + \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} \Big((1-w_i(t))\cdot V_i^{matl}(t) + w_i(t)\cdot V_i^{resale}(t)\Big)\cdot f_i(n,t) \\
&= (1-w_i(t))\cdot V_i^{matl}(t) + w_i(t)\cdot \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} V_i^{resale}(t)\cdot f_i(n,t)
\end{aligned} \tag{3}
$$

Equations (1) through (3) lead to Proposition 1, where the cost advantage of remanufacturing is given by comparing the NR and RR scenarios and NR and RS scenarios, respectively.

Proposition 1. The cost advantage of remanufacturing over producing the equivalent brand-new product is formulated as Equation (4). If part resale is assumed, the advantage is given as Equation (5).

$$
C_{NR-RR}(t) = \sum_{i\in I}\left[w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \Big(C_{i,\text{target}}^{new}(t) - \mathrm{C}_i^{recond}(t) - V_i^{matl}(t)\Big)\cdot f_i(n,t)\right] \tag{4}
$$

$$
C_{NR-RS}(t) = \sum_{i\in I}\left[w_i(t)\cdot \left\{ \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \Big(C_{i,\text{target}}^{new}(t) - \mathrm{C}_i^{recond}(t)\Big)\cdot f_i(n,t) + \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} V_i^{resale}(t)\cdot f_i(n,t) - V_i^{matl}(t)\right\}\right] \tag{5}
$$

4.2 Unit environmental impact

Equations (6) through (8) quantify the environmental impact of producing a unit of product under NR, RR, and RS scenarios, respectively. The calculation is similar to Equations (1) through (3); the only difference is that recycling and part resale cause environmental impact (negative influence) whereas they saved production costs (positive influence) in Equations (1) through (3).

$$
E_{NR}(t) = E^{reverse}(t) + \sum_{i\in I} E_{i,\text{target}}^{new}(t) + E^{forward}(t) + \sum_{i\in I} E_i^{nonreuse}(t) \quad \Big(\text{where } E_i^{nonreuse}(t) = E_i^{matl}(t)\Big) \tag{6}
$$

$$
\begin{aligned}
&E_{RR}(t) = E^{reverse}(t) + \sum_{i\in I} E_i^{part}(t) + E^{forward}(t) + \sum_{i\in I} E_i^{nonreuse}(t) \\
&\left(\begin{aligned} \text{where} \quad & E_i^{part}(t) = E_{i,\text{target}}^{new}(t) - w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \Big(E_{i,\text{target}}^{new}(t) - E_i^{recond}(t)\Big)\cdot f_i(n,t), \\ & E_i^{nonreuse}(t) = E_i^{matl}(t)\cdot \left(1 - w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n,t)\right) \end{aligned} \right)
\end{aligned} \tag{7}
$$

$$
\begin{aligned}
&E_{RS}(t) = E^{reverse}(t) + \sum_{i\in I} E_i^{part}(t) + E^{forward}(t) + \sum_{i\in I} E_i^{nonreuse}(t) \\
&\left(\text{where} \quad E_i^{nonreuse}(t) = (1-w_i(t))\cdot E_i^{matl}(t) + w_i(t)\cdot \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} E_i^{resale}(t)\cdot f_i(n,t) \right)
\end{aligned} \tag{8}
$$

Proposition 2 provides a formula for calculating the environmental advantage of the remanufactured product by subtracting the environmental impact of RR and RS scenarios from that of NR scenario.

Proposition 2. The environmental advantage of a remanufactured product over its equivalent brand-new is formulated as Equations (9) and (10).

$$
E_{NR-RR}(t) = \sum_{i\in I}\left[w_i(t)\cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} \Big(E_{i,\text{target}}^{new}(t) - E_i^{recond}(t) + E_i^{matl}(t)\Big)\cdot f_i(n,t)\right] \tag{9}
$$

$$E_{NR-RS}(t)=\sum_{i\in I}\left[w_i(t)\cdot\left\{\sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)}\left(E_{i,\text{target}}^{new}(t)-E_i^{recond}(t)\right)\cdot f_i(n,t)-\sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty}E_i^{resale}(t)\cdot f_i(n,t)+E_i^{matl}(t)\right\}\right] \quad (10)$$

4.3 Net Profit

Proposition 3 presents the net profit advantage of the remanufactured product, followed by its corollary showing the condition where the remanufactured product can provide greater profit than its equivalent brand-new product.

Proposition 3. Let β be the price ratio of the remanufactured product to the equivalent brand-new product, when the environmental advantage of the remanufactured product is known as $E_{NR-RR}(t)$ and $E_{NR-RS}(t)$, respectively. Then, the advantage of remanufacturing from the net-profit perspective is given as Equations (11) and (12), respectively.

$$\begin{aligned}\Pi_{RR-NR}(t)&=\Pi_{RR}(t)-\Pi_{NR}(t)=(P_R-C_{RR})-(P_N-C_{NR})\\&=(\beta-1)\cdot P_N+\sum_{i\in I}\left[w_i(t)\cdot\sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)}\left(C_{i,\text{target}}^{new}(t)-C_i^{recond}(t)-V_i^{matl}(t)\right)\cdot f_i(n,t)\right]\end{aligned} \quad (11)$$

$$\begin{aligned}&\Pi_{RS-NR}(t)=\Pi_{RS}(t)-\Pi_{NR}(t)=(P_R-C_{RS})-(P_N-C_{NR})\\&=(\beta-1)\cdot P_N+\sum_{i\in I}\left[w_i(t)\cdot\left\{\sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)}\left(C_{i,\text{target}}^{new}(t)-C_i^{recond}(t)\right)\cdot f_i(n,t)+\sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty}V_i^{resale}(t)\cdot f_i(n,t)-V_i^{matl}(t)\right\}\right]\end{aligned} \quad (12)$$

Corollary. The range of β where the remanufacture product becomes more profitable than the brand-new is $\beta\geq\beta_{RR-NR}^{*}$ and $\beta\geq\beta_{RS-NR}^{*}$ for RR and RS scenarios, respectively, where β_{RR-NR}^{*} and β_{RS-NR}^{*} are:

$$\beta_{RR-NR}^{*}=1-(1/P_N)\cdot\sum_{i\in I}\left[w_i(t)\cdot\sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)}\left(C_{i,\text{target}}^{new}(t)-C_i^{recond}(t)-V_i^{matl}(t)\right)\cdot f_i(n,t)\right], \quad (13)$$

$$\beta_{RS-NR}^{*}=1-(1/P_N)\cdot\sum_{i\in I}\left[w_i(t)\cdot\left\{\begin{aligned}&\sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)}\left(C_{i,\text{target}}^{new}(t)-C_i^{recond}(t)\right)\cdot f_i(n,t)\\&+\sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty}V_i^{resale}(t)\cdot f_i(n,t)-V_i^{matl}(t)\end{aligned}\right\}\right]. \quad (14)$$

5 ILLUSTRATIVE EXAMPLE: DESKTOP PC

This section illustrates the implementation of the proposed model by using a fictional case study of a desktop PC. The product information is assumed based on Schau et al. (2012), Painton and Campbell (1995), and Kwak and Kim (2013) as shown in Table 1. All the cost and impact values are measured in US dollar ($) and kilogram of carbon dioxide equivalent (kg CO2e), respectively. An LCA was conducted to obtain the environmental-impact information.

Table 1. Product Information on the Desktop PC: Cost and Environmental Impact

Part	λ_i	μ_i	ϕ_i	$\delta_i^{\text{target}}(t)$	$C_{i,latest}^{new}(t)$	$C_i^{new}(t)$	$V_i^{matl}(t)$	$E_i^{new}(t)$	$E_i^{recond}(t)$	$E_i^{matl}(t)$
CPU	0.5	0.67	0.67	2	175	45.52	5	5.92	1.18	0.005
RAM	0.5	0.50	0.84	1	50	21.63	5	7.59	1.52	0.001
Motherboard	1	0.67	0.67	2	150	39.02	5	169.00	33.80	0.004
Hard drive	1	1.00	0.17	3	120	71.69	4.5	12.30	2.46	0.004
Graphic card	1	1.00	0.29	3	100	42.11	4.5	50.20	10.04	0.003
Optical drive	2	0.40	0.81	2	80	15.87	3	17.10	3.42	0.002
Chassis	1	0.20	0.15	0	75	75.00	3	56.20	11.24	0.002

In addition, the following assumptions were made:

- The initial generational difference of the PC is $\boldsymbol{\delta}_{\mathbf{i}}(0)=\mathbf{0}$.

- The physical reusability $w_i(t)$ is defined by Equation (15) where λ_i (10^{-5}/hour) denotes the constant failure rate for part *i*. If the product returns for remanufacturing at year *t*, the disassembled part is approved to be reusable when the part is expected to survive at least *t* more years.
- $f_i(n,t)$ is defined as Equation (16), where *n* is assumed to be a Poisson process having rate μ_i, and μ_i denotes the average frequency per year with which a new generation of part *i* is released.
- $V_i^{resale}(t)$ is defined as Equation (17), where $C_{i,latest}^{new}(t)$ denotes the market value of the latest, cutting-edge part *i* and α_i is the ratio of market-value degradation for used part *i*. Also, it is assumed that $E_i^{resale}(t) = E_i^{recond}(t)$ $(i \in I)$. Other parameters are assumed as follows: $C^{reverse}(t) = 28.5$; $C^{forward}(t) = 35; C_i^{recond}(t) = 5; E^{disposal}(t) = 1.488; E^{reverse}(t) = 0.658; E^{forward}(t) = 0.658.$
- The price for the brand-new PC is assumed to be 1.5 times the total part cost, i.e., \$518.76.
- To convert monetary values to present value at *t*=0, a 3% interest rate with continuous compounding is applied.

$$w_i(t) = e^{-\lambda_i \cdot 10^{-5} \cdot 2t \cdot 250 \cdot 8} \quad (15)$$

$$f_i(n,t) = e^{-\mu_i t}(\mu_i t)^n / n! \quad (16)$$

$$V_i^{resale}(t) = \alpha_i \cdot C_{i,latest}^{new}(t) \cdot e^{-\phi_i(n+\delta_i(0))} \quad (17)$$

Figure 1(a) illustrates the cost advantage of the remanufacture PC resulting from the model. When remanufacturing is conducted in year 1, the unit production cost for the brand-new product is \$334 (in present value at *t* = 0), while that of the remanufactured product is \$120 (36% of the brand-new cost) and \$113 (34%) under RR and RS scenarios, respectively. In other words, the cost advantage of remanufacturing is \$214 (64%) and \$221 (66%), respectively. However, this cost advantage rapidly

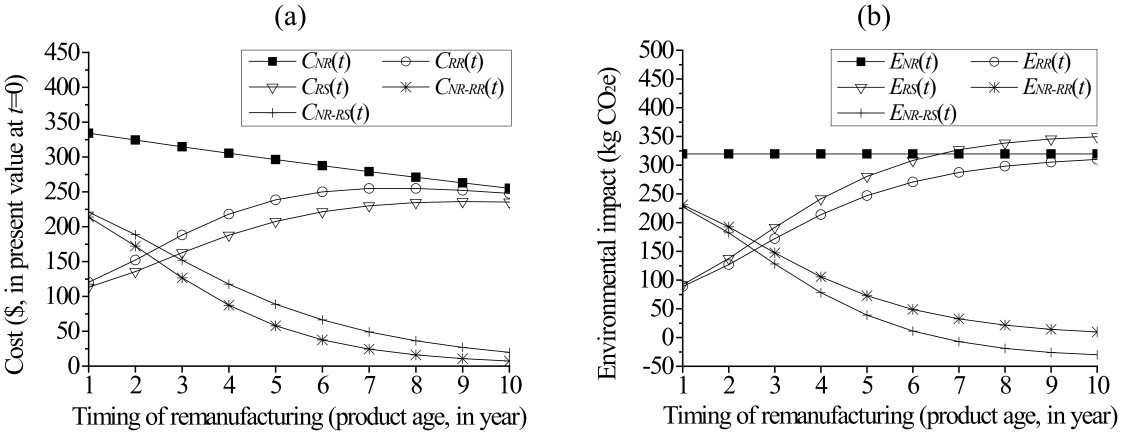

Figure 1. Advantages of remanufacturing: (a) Unit production cost, (b) Environmental impact

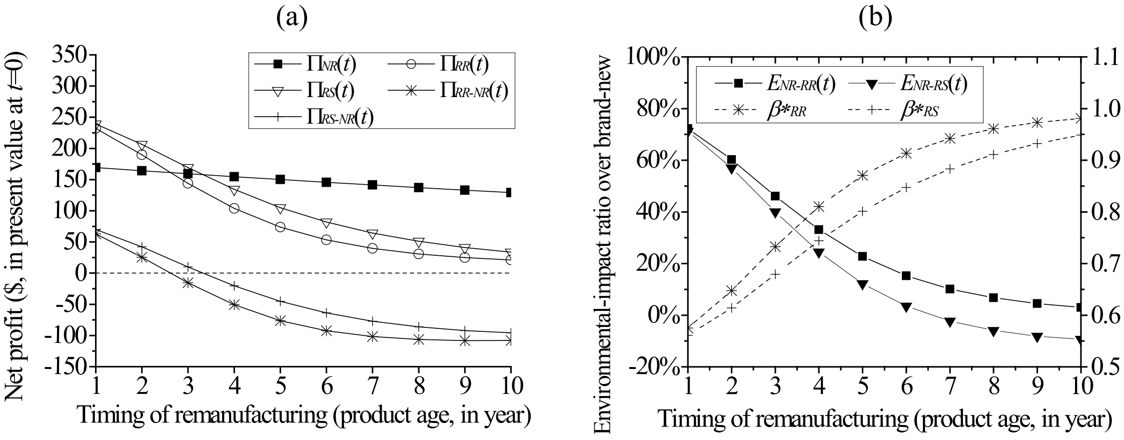

Figure 2. Advantages of remanufacturing: (a) Net profit (β=0.7), (b) β where the remanufactured and brand-new PCs are equally profitable*

decreases with time as the product ages. If remanufacturing is conducted at year 10, the unit production cost of the remanufactured PC becomes \$248 (RR) and \$235 (RS) which is almost the same as the brand-new cost of \$255. The advantage is estimated to be only \$7 (3%) and \$20 (8%).

Figure 1(b) shows the environmental advantage of remanufacturing. The figure compares the unit production impact of the remanufactured and brand-new PCs. (Note that it is assumed that both PCs will have the same usage impact during its second life, so the usage impact is excluded from the consideration.) Similar to Figure 1(a), Figure 1(b) implies that remanufacturing has a significant environmental advantage over producing the brand-new product, but the advantage will quickly disappear. When part resale is considered (i.e., RS scenario), the impact of remanufacturing even exceeds that of the brand-new production in year 7 due to the impact from reselling used parts. In other words, the upper limit of the year when remanufacturing can maintain its advantage is year 6.

From a net profit perspective, the upper limit becomes even lower. Figure 2(a) compares the net profit of remanufactured and brand-new PCs, given that β is assumed to be 0.7, that is, customers are willing to pay as much as 70% of the new product price for the remanufactured PC when its environmental advantage is known as Figure 1(b). Figure 2(a) shows that the remanufactured PC outperforms the brand-new until $t = 2$ (RR scenario; $t = 3$ for RS scenario); its profit advantage disappears.

Considering that the average lifetime of a desktop PC is generally known to be four years or more (Kwak et al., 2011(b); Microsoft, 2008), Figures 1(b) and 2(a) imply that PC remanufacturing may be a green business but not a profitable one. To achieve a profitable business, remanufacturing should be conducted within 2-3 years, or the β value in the market should be raised. Figure 2(b) suggests how much the β value should be raised to in order to make remanufacturing more profitable than producing a brand-new PC. For instance, if a four-year-old PC is remanufactured, a β greater than 81% is required in RR scenario. In RS scenario, the β^* value decreases to 74% as remanufacturing can recover more economic value from part resale. If customers are willing to pay more than 81% of the brand-new product's price, it is reasonable to remanufacture the product; part resale can be considered if the β in the market is greater than 74%; otherwise, producing a brand-new product is recommended.

6 DISCUSSION AND CONCLUSION

This paper proposes a value-assessment model that clarifies the link between product nature (its design and lifetime characteristics) with the advantage of remanufacturing. The model focuses on the fact that the time when the remanufacturing is conducted greatly influences the advantages of remanufacturing and proposes quantitative methods to estimate time-varying economic and environmental values.

The developed model enables remanufacturers to make more informed and effective business decisions. First, it helps remanufacturers to assess their business plans from the design stage. The model provides a quantitative performance measure to evaluate product alternatives from a remanufacturing perspective. Using the model, remanufacturers can clarify which alternative is more suitable for remanufacturing and how much better it is than others with respect to production cost, environmental impact, and net profit.

The model is also expected to assist in strategic planning for remanufacturing. It helps to evaluate and compare different remanufacturing strategies in terms of their expected production cost, environmental impact, and net profit. By considering multiple criteria at the same time, remanufacturers can investigate the best remanufacturing strategy including whether or not to remanufacture a product, when to remanufacture their end-of-life products, whether or not to resell disassembled parts, and what price should be set for the remanufactured product.

One potential research opportunity would be to apply the model to a wider range of products. The desktop PC in Section 5 exemplified a case where the net profit becomes the main driver in deciding whether or not to remanufacture. The profit advantage of remanufacturing disappears first before the environmental advantage does. Profit determines the upper limit of the year when remanufacturing can maintain its advantages and be justified. There can be other type of products, however, whose environmental impact poses a lower upper limit than the net profit (e.g., products that require part conditioning and upgrades causing significant environmental impact). In such cases, profit-driven decision will not be justified all the time. By applying the model to a diverse range of products, one can obtain better understanding and insights into what products are suitable for remanufacturing under what conditions and how β^* values differ by the type of product.

One limitation of the model, however, is that it requires a few input parameters that characterize the product and customers in the market, which may bring about additional challenges in estimation and prediction. Although these factors were beyond the scope of this study, estimation and prediction models need to be developed in the future.

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