

Modeling the Time-Varying Advantages of a Remanufactured Product: Is “Reman” Better Than “Brand New”?¹

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In order for remanufacturers to succeed in the market, it is important for them to be 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. This paper provides an approach to estimate the economic and environmental advantages of a remanufactured product. 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 the remanufacturing, this paper proposes a model for assessing the time-varying advantages of remanufacturing a given product. The model provides an objective, quantitative method to compare a remanufactured product with an equivalent brand-new version of the product. Focus is placed on three perspectives: unit production cost, environmental impact, and net profit. By providing a multidimensional assessment tool for measuring product remanufacturability, the model is expected to assist remanufacturers make informed and effective decisions concerning product planning. It also helps marketing activities by supporting an effective sustainability communication with customers. Two versions of the model are presented, each of which targets a specific product type: (1) a product with only physical deterioration and (2) a product with both physical deterioration and technological obsolescence. Each version of the model is illustrated by utilizing an automotive alternator and a desktop computer, respectively. [DOI: 10.1115/1.4032808]

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1 Introduction

Remanufacturing is the process of restoring discarded or traded-in used products (i.e., end-of-life products) to a like-new condition, giving them another life [1–4]. In remanufacturing, end-of-life products are taken back and disassembled; parts that are still functioning and in good condition are harvested for reuse. After being cleaned and reconditioned, the parts are reassembled into a remanufactured product that provides the same quality and performance as a brand-new product.

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 a small fraction of the original production costs [5]. Adverse environmental impacts of the products (e.g., greenhouse gases emissions, natural resource depletion, and air and water pollution) can be avoided as well, as the amount of waste is reduced and less energy and materials are consumed in the production process.

One concern is that the advantages of remanufacturing over producing brand-new products may not always exist, and even if they do, the advantages may change over time. Many previous

studies have indicated that remanufacturing is not always profitable [6–8] or environmentally friendly [9–11]. One possible explanation is that the *nature of the product*, including its design and lifetime characteristics, has a major influence on the time-varying value of remanufacturing. To be more specific, the rate at which its parts become obsolete and deteriorate, the production costs for the parts, the ease of the disassembly and reassembly of the product, and many other factors affect the value of remanufacturing. Accordingly, some products are suitable for remanufacturing, while others are not. Even if a product seems suitable at first, the suitability may change, depending on the time in which the product is remanufactured; in general, the advantages of remanufacturing decrease over time as the product suffers from wear and tear and technological obsolescence.

This paper addresses the methods for estimating the time-varying value of remanufacturing; in other words, *the time-varying advantage of a remanufactured product over a brand-new product*. 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 values than an equivalent brand-new product at the moment of remanufacturing. To this end, a product evaluation model is needed which establishes a quantitative link between the nature of the product (e.g., product specifications, physical and technological characteristics of each part, production costs) and the time-varying value of remanufacturing from the remanufacturer’s perspective. Figure 1 presents an overview of the proposed model and its potential applications.

The model proposed in this paper assesses the time-varying advantages of remanufacturing for a given product. It focuses on

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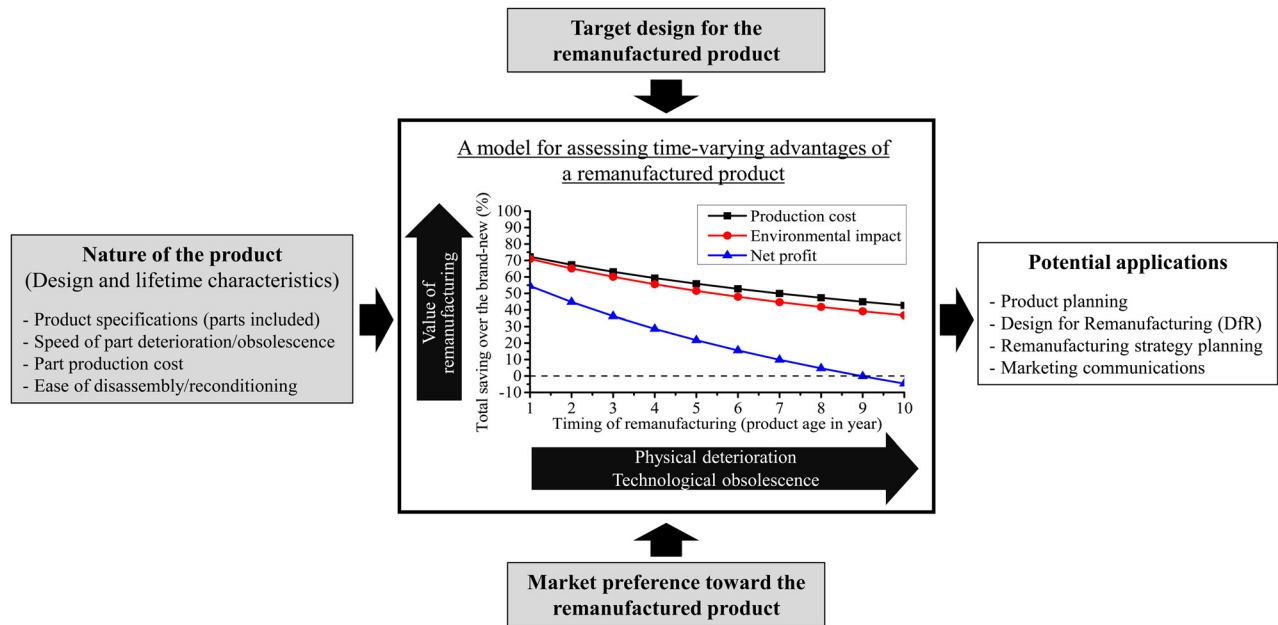


Fig. 1 Overview of the proposed model

estimating how much value can be asserted to be achieved by a unit of remanufactured product by avoiding new product production. A one-to-one comparison is conducted between the remanufactured and equivalent brand-new versions of a product from three perspectives: unit production cost, environmental impact, and net profit. 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. Two time-dependent factors are incorporated: physical deterioration and the technological obsolescence of the constituent parts. The results provide answers to the following questions: Is a remanufactured product better than a brand-new version of the product? How does the timing of remanufacturing affect the advantages of a remanufactured product? How do market conditions (e.g., market preferences toward a remanufactured product and customer requirements on product specifications) influence any advantages from remanufacturing?

The proposed model has two versions, i.e., *Model I* and *Model II*. Each model is developed for a specific type of product. Model I targets a product that experiences only physical deterioration over its lifetime (e.g., water pump, alternator) without any technological obsolescence of the design. Such products usually have a long life cycle in the market and sufficient demand for the original specifications. Thus, the products maintain their original design during remanufacturing. As such, exactly the same products are produced. Model II, on the other hand, targets products that suffer from both physical deterioration and technological obsolescence (e.g., computer, network equipment). To attract customers who want more advanced specifications, such products may need technological upgrades provided by adopting new parts during the remanufacturing process.

Remanufacturers are facing the need to validate and improve the economic and environmental sustainability of their business. The proposed model can serve this need by providing a multidimensional (i.e., production cost, environmental impact, and net profit) assessment tool for measuring product remanufacturability. To be more specific, it helps clarify whether or not a product is suitable for remanufacturing; if multiple candidate products are given, it investigates which product is more suitable and how much better it is than others. Marketing activities can be supported as well, as the model enables product declaration and supports effective sustainability communication with customers. For original equipment manufacturers (OEMs) who also conduct

remanufacturing (e.g., Xerox, Caterpillar, and John Deere), Design for Remanufacturing (DfR) can be another application of the model. The model helps assess the influence of design decisions on product remanufacturability, which is critical in design improvement and optimization.

The rest of this paper is organized as follows. Section 2 reviews the relevant literature and discusses the major contributions of this work. Section 3 describes the remanufacturing process and the key assumptions under consideration in this paper. Sections 4 and 5 propose Models I and II, respectively, with illustrations of the models using the examples of an alternator and a personal computer (PC), respectively. Section 6 discusses the implications of the case examples and potential applications of the proposed model. Section 7 concludes the paper with future research directions.

2 Relevant Literature and Contribution

2.1 DfR. In order for remanufacturing to be successful, it is critical to know whether the design and the key nature of the product incorporate features that are favorable to remanufacturing. In the area of DfR, a number of studies have been presented with the aim of supporting remanufacturing operations (i.e., transportation, disassembly, sorting, cleaning, refurbishment, reassembly, and testing) by means of design evaluation and enhancement.

Much of the DfR research has involved the presentation of design principles to guide DfR with an aim to reduce the cost of remanufacturing and increase profits. Lund [12] presented a set of conditions for a product that need to be fulfilled to ensure the ease of remanufacturing, or remanufacturability. According to Guide [13], the conditions encompass the following features: "(1) the product is a durable good, (2) the product fails functionally, (3) the product is standardized and the parts are interchangeable, (4) the remaining value-added is high, (5) the cost to obtain the failed product is low compared to its remaining value, (6) the product technology is stable, and (7) the consumer is aware that the remanufactured products are available." Amezcua et al. [14] characterized the remanufacturability of a product and suggested DfR guidelines, including the ease of disassembly, ease of cleaning, ease of parts replacement, and the standardization of parts, fasteners, and interfaces. Hammond and Bras [15] presented quantitative metrics for assessing the ease of remanufacturing. Shu and

Flowers [16] investigated the effects of the designs of fasteners and joints on the profit from remanufacturing. Zwolinski and Brisaud [17] generated profiles of products with higher remanufacturability by analyzing past products that had been remanufactured successfully in terms of their external (i.e., market life cycle, technology cycle, and wear-out life) and internal characteristics (i.e., number of parts, modularity, and number and types of fasteners). Du et al. [18] developed an integrated model for assessing the remanufacturability of used machine tools. Three criteria were used in the assessment: technical feasibility, economic feasibility, and environmental benefits. Fang et al. [19] proposed a CAD-based model for remanufacturability assessment. Xing and Luong [20] presented a model for estimating a product's potential to serve an extended life considering its functional, physical, and structural characteristics. Many factors were incorporated, including the elapsed lifetime of the product, reliability of the component, the design cycle (the frequency for new designs to be released), and the current functional level of the component.

Some studies have selected remanufacturing profit as an evaluation criterion and developed models to obtain the profit value by finding an optimal remanufacturing plan. Ishii [21] emphasized that incorporating optimal remanufacturing plans in product design is important for improving and selecting appropriate design options. Kwak and Kim [22] introduced a framework for analyzing how product design affects product recovery and what architectural characteristics are desirable for higher recovery profits. Extending their research, Kwak and Kim [23] developed a framework for evaluating the design of a product family (i.e., multiple products that share a set of common components and have overlapping end-of-life stages).

One difficulty in remanufacturing is that the product and its parts can easily become obsolete or outdated [24]. A few models have been developed regarding the value depreciation of a product and its impact on remanufacturing. Kumar et al. [25] proposed a model to characterize how value is created, consumed, and reclaimed over a product's life cycle. They emphasized that the value perceived by the consumer affects the optimal recovery option for the product end-of-life treatment. Rachaniotis and Pappis [26] formulated the performance value of a product as the weighted sum of the performance values of its constituent parts, where the part value was represented as a function of time. Pandey and Thurston [27] proposed a method for evaluating the time-dependent performance of a remanufactured product. To determine the performance function, a customer's or an expert's assessment was coupled with the reliability of that component.

Unlike the previous models using nonmonetary terms, some researchers have researched how the market value of a product depreciates over time. Guide et al. [28] presented an exponential value decay function (i.e., $V(t) = V(0) \cdot e^{-at}$) to model the time-dependent market value of returned commercial products. The parameter a was used to represent the speed at which technological advances occur. Ferrer [29] defined the value of a remanufactured PC as a linear function of time and its components' market value. The value of each component was defined as a decreasing function of time (i.e., $V(t) = V(0) \cdot t^{-a}$), where a is the component-specific parameter obtained by a regression analysis of the retail prices of the new components [26]. Kwak and Kim [3] presented a quantitative model for estimating the market value of an end-of-life product in the second-hand market. Their model estimated the expected residual value of a product by considering two major depreciation factors, the physical deterioration of constituent parts and the technological obsolescence of specifications.

Product upgrading, conducted by adding modules to a product or replacing modules in a product, can be an effective means to overcome the obsolescence issues in remanufacturing. In this regard, *Design for Upgrading* is a line of design principles that has a close relationship with DfR. Xing and Luong [20] proposed quantitative measures for product upgradability and developed an evaluation model that can be applied at the design stage. Ishigami et al. [30] proposed a design method to enhance the upgradability

of a product over multiple generations; when an upgrade plan is given, the method helps determine the optimal product structure that best fits the plan.

2.2 Environmental Assessment of Remanufacturing.

Remanufacturing is generally claimed as being more environmentally friendly than producing new products, but some researchers [9–11] have underlined the possibility that this may not always be true. They have argued that some remanufactured products might actually cause more environmental damage than brand-new products, in most part due to their lower energy efficiency. This leads to the need for scientific methods that evaluate and validate the environmental benefit of remanufacturing. A life cycle assessment (LCA) can be an effective tool for this purpose. It examines all stages of the product life cycle (i.e., manufacturing, use, maintenance, and end-of-life) and quantifies the total environmental impact associated with the product from the “cradle to the grave” [31]. (For more detail about LCA, refer to Ref. [32].)

With an aim to evaluate the environmental benefit of remanufacturing, many LCA studies have been conducted to investigate a variety of products (e.g., consumer electronics, appliances, engines, and transmissions). Smith and Keoleian [33] conducted an LCA on a midsize automotive gasoline engine and illustrated that remanufacturing the engines has significant environmental advantages over manufacturing new engines. Goldey et al. [34] provided the results from LCA studies on telecommunication equipment remanufacturing and demonstrated that remanufacturing can avoid approximately 30–40% of the global warming potential (GWP). Boustani et al. [10] evaluated the energy savings of appliance remanufacturing. The authors highlighted that remanufacturing may lead to higher energy consumption, as compared to purchasing a new product. Although remanufacturing can save energy and raw materials during production processes, the energy savings can be offset by the technological obsolescence of a remanufactured unit. Gutowski et al. [11] reported on 25 case studies, including studies on engines, furniture, clothing, computers, electric motors, toner cartridges, and tires. The authors demonstrated that remanufacturing may not always bring about an environmental benefit, especially if the product generates most of its life-cycle impact at the use phase and if the use phase energy has a decreasing trend due to efficiency improvements in new products.

2.3 Management of Remanufacturing. Remanufacturing is only possible when there exist both the supply of end-of-life products and the demand for remanufactured products [8,35]. The imbalance in quantity between returns of end-of-life products and demands for remanufactured products is one of the major factors that impede remanufacturing business [13,36]. For OEMs, remanufacturing raises an additional concern, namely, the effect of remanufacturing on new product sales. The threat of cannibalization by remanufactured products has been highlighted as a major barrier preventing OEMs from implementing remanufacturing [37–39].

Understanding how the customer evaluates remanufactured products is critical to addressing the balancing and cannibalization issues. With an aim to increase the understanding, several empirical studies have been presented to date. Guide and Li [37] used auctions to investigate consumers' willingness to pay (WTP) for new and remanufactured products. Their results revealed that the WTP is affected by both the condition (i.e., new or remanufactured) and type (i.e., consumer or commercial) of the product. Abbey et al. [40] examined how the attractiveness of remanufactured products is determined in the consumer goods market. Various factors were studied, including price discounting, brand equity, negative perception due to prior ownership, greenness of remanufactured products, and the existence of green segment consumers. Ovchinnikov [41] and Ovchinnikov et al. [42] conducted behavioral studies to better understand consumers' choice

between new and remanufactured products and construct demand functions.

Proper pricing for end-of-life and/or remanufactured products also plays a central role in optimal remanufacturing. Optimizing the buy-back price of end-of-life products (i.e., a financial incentive paid to end-users for returning an end-of-life product) can be an effective means for controlling the quantity and quality of returns [43]. A few models have been developed for the optimal pricing of end-of-life products, including Klausner and Hendrickson [44] and Liang et al. [45]. The pricing of remanufactured products has been examined as an effective strategy to control demand. Vadde et al. [46] and Mitra [47] presented optimal pricing models for remanufactured products. Kwak and Kim [48] proposed a model that optimizes both the selling price and design specifications of a remanufactured product. Recently, pricing models that simultaneously optimize the price of both end-of-life and remanufactured products have been also presented, including those of Guide et al. [8] and Vadde et al. [49].

Ferguson and Toktay [39], Vorasayan and Ryan [50], Atasu et al. [51], Ovchinnikov [41], and Ovchinnikov et al. [42] developed pricing models to help manufacturers who produce both new and remanufactured products. The selling price and production quantity of the new and remanufactured products were jointly optimized to maximize the total profit, while reducing the negative impact of demand cannibalization. Profitability conditions were also identified for various situations, which can help answer the question of whether or not to conduct remanufacturing. Some researchers have also incorporated the impact of product design. Debo et al. [52], Abbey et al. [40], and Wu [53] among others investigated the impact of product durability, modularity, and disassemblability, respectively.

Unlike the previous studies focusing on optimal pricing, many studies in the engineering domain (e.g., Refs. [22] and [54–56]) have actively examined production planning (i.e., how to optimize the remanufacturing operations including disassembly, part reconditioning, and reassembly). These models have been aimed at optimizing decision variables such as (1) the quantity of the end-of-life products to take back, (2) the plans for product disassembly and part reconditioning, (3) the quantity and type of parts to externally procure, and (4) the quantity and type of remanufactured products to produce.

2.4 Contributions of the Proposed Model. The proposed model is a new contribution that is distinct in the following ways:

- (1) The current model estimates the relative advantage of a remanufactured product, as compared to an equivalent brand-new product, which can be used as an index of its suitability (feasibility and appropriateness) for remanufacturing, or remanufacturability. Although previous DfR studies (Sec. 2.1) have provided an excellent base for analyzing whether a product supports remanufacturing, they have paid little attention to whether the remanufactured product will surpass a brand-new version. By quantifying the competitive advantages of a remanufactured product, the model enables remanufacturers to discern if their business will be regarded as feasible and appropriate and to explore ways to maximize their advantage over a brand-new product.
- (2) The model provides a multidimensional assessment tool for measuring product 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. By using monetary terms and well-known impact measures (e.g., GWP in kilograms of carbon dioxide), the model can facilitate internal and external sustainability communications. The model offers more useful insights and implications that can be directly fed into business decision-making and product declarations for marketing purposes.

- (3) The current model clarifies how the nature of the product (e.g., product specifications, physical and technological characteristics of each part, production costs) and the timing of remanufacturing influence the economic and environmental advantages of remanufacturing. Researchers have agreed that the advantages change over time (in most cases, they decrease as the product ages), but many of them, especially those in the field of environmental assessment (Sec. 2.2), have conducted evaluations for a static condition (e.g., product of an average age). Some (e.g., Refs. [28] and [29]) 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 by modeling how the product nature changes with time, and then estimates their influences on the value of remanufacturing. This approach provides an answer for how the value of remanufacturing differs by the nature of the product, as well as by the timing of the remanufacturing.
- (4) Regarding the nature of the product, the model distinguishes two types of products: one with only physical deterioration and the other with both physical deterioration and technological obsolescence. It provides a customized model for each type. Each model can serve as a base for variations, which will be discussed further in Sec. 7. The inclusion of technological obsolescence is one of the major differences from the previous studies. The model proposes a new approach to quantifying the impact of technological obsolescence by adopting the concept of a *generational difference*, which was first suggested by the authors [3].
- (5) The model can complement the existing models in the field of remanufacturing management (Sec. 2.3) that aim to optimize remanufacturing strategies (i.e., prices and production quantities) at the system level. (Their objective is to maximize the total profit of the remanufacturing system.) Different from the existing models, the goal of the current model is to evaluate a remanufacturing system under a predetermined remanufacturing strategy, especially at the single-product level. The results provide another set of performance measures for the remanufacturing system (i.e., cost per unit, environmental impact per unit, and profit per unit that can be asserted to be achieved by a remanufactured product by avoiding new-product production), which helps to investigate the remanufacturing system from a different angle.

3 Remanufacturing Process and Assumptions

Remanufacturing is “a series of manufacturing steps acting on an end-of-life part or product in order to return it to like-new or better performance [57].” The remanufacturing process under consideration in this paper starts with the disassembly of the end-of-life products into parts. (Here, the term “part” refers to any decomposable component of a product.) The resulting parts are sorted by type, and a determination is made as to whether or not they are reusable [58]. Reusable parts are fed back into production for reuse, while nonreusable parts are sent to third-party recyclers to be recovered as raw materials.

After being reconditioned (e.g., cleaning, remachining, testing), 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. As can be seen in the description above, 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. Upgrading is also possible by including more up-to-date parts.

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 central processing units (CPUs) 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., CD-ROM, DVD drive) are relatively less reliable, but they change less frequently from a technological perspective. Thus, depending on the required levels of physical reliability and technological performance, some parts will be reusable, whereas others will not.

To represent a part's technological specification and the level of obsolescence, the model proposed in this paper adopts the concept of a generational difference, which was first suggested by Kwak and Kim [3]. As product technology advances, the cutting-edge parts of a new generation appear on the market. The generational difference is a relative measure that indicates how much obsolete an existing part is (in terms of the technology), as compared to the latest cutting-edge part. Let the newer part corresponds to the greater number of generation, and the latest cutting-edge part corresponds to the maximum generation. Then, the generational difference of a part refers to the gap between its generation and that of the current cutting-edge part (i.e., maximum generation). For instance, presume that part i is an l th generation part at time 0; the cutting-edge part is an m th generation part ($l \leq m$). Then, the generational difference of part i at time 0 is $\delta_i(0) = m - l$. With this definition, the generational difference of the cutting-edge part (of a particular moment) is zero, while that of the very next former cutting-edge part becomes one. Now, suppose that time proceeds and a new generation appears on the market (i.e., an $(m + 1)$ th generation part). The generational difference of part i then increases by one to $(m - l + 1)$. If n more successive generations of part i are released in the market from time 0 to t , the generational difference of part i at time t will become $\delta_i(t) = \delta_i(0) + n$, which is $(m - l + n)$. Likewise, the

generational difference of a part increases by time and is affected by the speed of the technological advancement.

Table 1 describes the notations used in the model. For simplicity's sake, the proposed model is based on the following assumptions. The first four assumptions are applied to both Model I (Sec. 4) and Model II (Sec. 5); the rest are applied only to Model II:

- Remanufacturing has a negligible lead time. Considering the scale of the entire lifetime of a product, remanufacturing is conducted in a relatively short period of time. Product take-back, remanufacturing, and the sale of the remanufactured product occur at almost the same time; parts experience no additional deterioration or obsolescence during remanufacturing.
- Reselling the disassembled parts to the second-hand market is not considered. All nonreusable parts that cannot pass either physical or technological requirements are recycled for material recovery.
- When considering the production of brand-new products, the remanufacturer can choose from two scenarios: (1) no take-back is conducted and the end-of-life product is treated at the customer side without causing any cost to the manufacturer (scenario NO); (2) the end-of-life product is taken back to the original manufacturer for responsible recycling (scenario NR). When the take-back happens, the end-of-life product is assumed to be disassembled, and the resulting parts are sold to third-party recyclers for material recovery. This means that both scenarios NR and RR assume the same reverse logistics and disassembly process.
- The models assume a "waste-stream system [43]" for product take-back. No financial incentives are given for returning end-of-life products, and the remanufacturer passively accepts returns. Relaxing the assumption and utilizing financial incentives (or, buy-back prices) for early take-back is discussed later in Sec. 6.
- Both brand-new and remanufactured products are produced under the same conditions and environment. All scenarios,

Table 1 Mathematical notation

t	Timing of remanufacturing, or, the age of the end-of-life product
i	Index for part ($i \in I$)
NO	Index for the scenario of producing a brand-new product without any take-back
NR	Index for the scenario of producing a brand-new product with responsible recycling
RR	Index for the scenario of remanufacturing the end-of-life product
$C_{NO}(t), E_{NO}(t), \Pi_{NO}(t)$	Unit production cost, environmental impact, and net profit under the NO scenario at t
$C_{NR}(t), E_{NR}(t), \Pi_{NR}(t)$	Unit production cost, environmental impact, and net profit under the NR scenario at t
$C_{RR}(t), E_{RR}(t), \Pi_{RR}(t)$	Unit production cost, environmental impact, and net profit under the RR scenario at t
$C_i^{new}(t), E_i^{new}(t)$	Unit cost and impact of purchasing (or producing) new part i at t
$C_{i,target}^{new}(t), E_{i,target}^{new}(t)$	Unit cost and impact of purchasing new, target-level part i for remanufacturing at t
$C_i^{part}(t), E_i^{part}(t)$	Total cost and impact of preparing part i for remanufacturing a product at t
$I_i^{recycle}(t), E_i^{recycle}(t)$	Total income from and impact of recycling part i from an end-of-life product 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 disassembled part i to recyclers at t
$C^{forward}(t), E^{forward}(t)$	Unit cost and impact of assembling, distributing, and marketing a product for sale at t
$C^{reverse}(t), E^{reverse}(t)$	Unit cost and impact of taking back and disassembling a product at t
$E^{dispose}(t)$	Unit impact of disposing a product at the customer side at t
$w_i(t)$	Probability that a disassembled part i is determined as a physically reusable at t
P_N, P_R	Sale price of the brand-new and remanufactured product, respectively
β	Price ratio of the remanufactured product to the equivalent brand-new ($P_R = \beta \cdot P_N$) that maintains the same demand level (or, choice probability in the market)
λ_i	Constant failure rate of part i
$\delta_i^{target}(t)$	Target generational difference for part i
$\delta_i(t)$	Generational difference of disassembled part i at t
$f_i(n, t)$	Probability that the number of successive generations of part i being newly released in the market for $[0, t]$ is n

therefore, share the same values for $C_i^{\text{reverse}}(t)$, $E_i^{\text{reverse}}(t)$, $C_i^{\text{new}}(t)$, $E_i^{\text{new}}(t)$, $V_i^{\text{matl}}(t)$, $E_i^{\text{matl}}(t)$, $C_i^{\text{forward}}(t)$, and $E_i^{\text{forward}}(t)$. If necessary, the assumption can be easily relaxed by assuming separate parameters for each of the scenarios.

- 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 the same, 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; only the part that conforms to the target can be reused in remanufacturing [59]. In other words, a remanufactured product can include both a part with the target specification and one with an above-target (i.e., newer generation). This means that a part’s generational difference should be lower than, or equal to, the target generational difference (i.e., $\delta_i(t) \leq \delta_i^{\text{target}}(t)$, $\forall i$). 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 midlevel product in the manufacturing stage, the remanufactured product can be positioned either as a midlevel or a low-end product. In other words, the target generational difference of the remanufactured product (at time t) cannot be lower than that of the original product at the manufacturing stage (at time 0) (i.e., $\delta_i^{\text{target}}(t) \geq \delta_i(0)$, $\forall i$). This may not be always true, but it is a realistic assumption [60]. If necessary, this assumption can be relaxed, which will be discussed in Sec. 5.1.

4 Model I: Product With Physical Deterioration Only

Model I considers a product that only experiences physical deterioration. Since the product does not suffer from technological obsolescence, the end-of-life product can be remanufactured to be the same product without any change in the design. This means that all the parts whose physical condition is approved as reusable will be input into the remanufacturing process.

To estimate the value of remanufacturing, the model compares the remanufactured product with its equivalent brand-new version by considering three scenarios: NO, NR, and RR. NO and NR both represent a case where a brand-new product is produced; the only difference is whether the end-of-life product is taken back for responsible recycling. RR represents a case where the remanufactured product is produced. Note that the remanufacturing accompanies recycling to deal with nonreusable or leftover parts.

4.1 Unit Production Cost and Environmental Impact.

Equations (1) and (2) show the unit production cost under the NO and NR scenarios, respectively. In the NO scenario, new parts are purchased and assembled into a product. In the NR scenario, the responsible recycling incurs an additional cost $C_i^{\text{reverse}}(t)$ due to take-back and disassembly activities. However, this cost can be compensated for by the income from recycling $I_i^{\text{recycle}}(t)$, as the end-of-life parts are sold to third-party recyclers

$$C_{\text{NO}}(t) = \sum_{i \in I} C_i^{\text{new}}(t) + C^{\text{forward}}(t) \quad (1)$$

$$C_{\text{NR}}(t) = C^{\text{reverse}}(t) + \sum_{i \in I} C_i^{\text{new}}(t) + C^{\text{forward}}(t) - \sum_{i \in I} I_i^{\text{recycle}}(t)$$

$$\text{where } I_i^{\text{recycle}}(t) = V_i^{\text{matl}}(t) \quad (2)$$

Equation (3) formulates the unit production cost under the RR scenario. Here, $C_i^{\text{part}}(t)$ denotes the cost of preparing part i in need

to remanufacture a unit of product. Part i from the end-of-life product is reusable with the probability of $w_i(t)$, and each reusable part requires a reconditioning process that costs $C_i^{\text{recond}}(t)$. ($w_i(t)$ can be calculated using a reliability distribution such as the exponential and Weibull distributions.) Since $w_i(t) \leq 1$, part i is in short supply for remanufacturing, and a new part is purchased with the probability of $(1 - w_i(t))$

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

where

$$C_i^{\text{part}}(t) = w_i(t) \cdot C_i^{\text{recond}}(t) + (1 - w_i(t)) \cdot C_i^{\text{new}}(t)$$

$$I_i^{\text{recycle}}(t) = (1 - w_i(t)) \cdot V_i^{\text{matl}}(t) \quad (3)$$

From Eqs. (1)–(3), the advantage of remanufacturing from the production-cost perspective can easily be obtained. Proposition 1 details the cost advantages (i.e., $C_{\text{NO-RR}}(t) (= C_{\text{NO}}(t) - C_{\text{RR}}(t))$ and $C_{\text{NR-RR}}(t) (= C_{\text{NR}}(t) - C_{\text{RR}}(t))$) by comparing the NO and RR scenarios and the NR and RR scenarios, respectively; only simple deductions are required, so no proof is provided here.

PROPOSITION 1. *The cost advantage of remanufacturing over producing the equivalent brand-new product is formulated in Eq. (4). If responsible recycling is assumed for the brand-new product, the cost advantage is given as Eq. (5)*

$$C_{\text{NO-RR}}(t) = \sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t)) + (1 - w_i(t)) \cdot V_i^{\text{matl}}(t)] - C^{\text{reverse}}(t) \quad (4)$$

$$C_{\text{NR-RR}}(t) = \sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t))] \quad (5)$$

Equations (6) and (7) measure the per-unit environmental impact under the NO and NR scenarios, respectively. They measure how much of an environmental impact is caused by, and attributable to, producing a unit of the brand-new product. The calculation is similar to Eqs. (1) and (2); one difference is that the end-of-life product discarded on the customer side causes environmental impact $E^{\text{dispose}}(t)$. Equation (8) presents the environmental impact of the remanufactured product under the RR scenario. Similar to Eq. (3), the impact is greatly influenced by a part’s reusability w_i

$$E_{\text{NO}}(t) = E^{\text{dispose}}(t) + \sum_{i \in I} E_i^{\text{new}}(t) + E^{\text{forward}}(t) \quad (6)$$

$$E_{\text{NR}}(t) = E^{\text{reverse}}(t) + \sum_{i \in I} E_i^{\text{new}}(t) + E^{\text{forward}}(t) + \sum_{i \in I} E_i^{\text{recycle}}(t)$$

$$\text{where } E_i^{\text{recycle}}(t) = E_i^{\text{matl}}(t) \quad (7)$$

$$E_{\text{RR}}(t) = E^{\text{reverse}}(t) + \sum_{i \in I} E_i^{\text{part}}(t) + E^{\text{forward}}(t) + \sum_{i \in I} E_i^{\text{recycle}}(t)$$

where

$$E_i^{\text{part}}(t) = w_i(t) \cdot E_i^{\text{recond}}(t) + (1 - w_i(t)) \cdot E_i^{\text{new}}(t)$$

$$E_i^{\text{recycle}}(t) = (1 - w_i(t)) \cdot E_i^{\text{matl}}(t) \quad (8)$$

The environmental advantage of remanufacturing can be defined as how much of an environmental impact can be avoided by producing a remanufactured product, in comparison to

producing a brand-new product. This can be easily obtained by deducing the environmental impact of the RR scenario from those of the NO and NR scenarios. Proposition 2 provides the results.

PROPOSITION 2. *The environmental advantage of a remanufactured product over its equivalent brand-new product is formulated in Eq. (9). If responsible recycling is assumed for the brand-new product, the environmental advantage is given as Eq. (10)*

$$E_{\text{NO-RR}}(t) = E^{\text{dispose}}(t) + \sum_{i \in I} [w_i(t) \cdot (E_i^{\text{new}}(t) - E_i^{\text{recond}}(t)) - (1 - w_i(t)) \cdot E_i^{\text{matl}}(t)] - E^{\text{reverse}}(t) \quad (9)$$

$$E_{\text{NR-RR}}(t) = \sum_{i \in I} [w_i(t) \cdot (E_i^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t))] \quad (10)$$

4.2 Net Profit. The expected net profit from the remanufactured product can be defined as $\Pi_{\text{RR}}(t) = P_R - C_{\text{RR}}$. Similarly, the net profit from the brand-new product can be defined as $\Pi_{\text{NO}}(t) = P_N - C_{\text{NO}}$ and $\Pi_{\text{NR}}(t) = P_N - C_{\text{NR}}$. Proposition 3 is then derived based on Eqs. (1)–(3) and (6)–(8), as follows:

PROPOSITION 3. *Given that the environmental advantage of the remanufactured product is $E_{\text{NO-RR}}(t)$ and $E_{\text{NR-RR}}(t)$, respectively, let β be the price ratio of the remanufactured product to the equivalent brand-new product (i.e., $P^R = \beta \cdot P^N$) that maintains the same demand level. Consequently, the advantage of remanufacturing from the net-profit perspective is given in Eqs. (11) and (12), respectively,*

$$\begin{aligned} \Pi_{\text{RR-NO}}(t) &= \Pi_{\text{RR}}(t) - \Pi_{\text{NO}}(t) \\ &= (P_R - C_{\text{RR}}) - (P_N - C_{\text{NO}}) \\ &= (\beta - 1) \cdot P_N + \sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t)) \\ &\quad + (1 - w_i(t)) \cdot V_i^{\text{matl}}(t)] - C^{\text{reverse}}(t) \end{aligned} \quad (11)$$

$$\begin{aligned} \Pi_{\text{RR-NR}}(t) &= \Pi_{\text{RR}}(t) - \Pi_{\text{NR}}(t) \\ &= (P_R - C_{\text{RR}}) - (P_N - C_{\text{NR}}) \\ &= (\beta - 1) \cdot P_N + \sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t)) \\ &\quad - V_i^{\text{matl}}(t)] \end{aligned} \quad (12)$$

In Proposition 3, the β value implies that customers are willing to pay as much as β of the new-product price for the remanufactured product. It is one of the key factors determining the profit advantage of the remanufactured product. Thus, many researchers have tried to find the real β value in the market through empirical studies, as discussed in Sec. 2.3. Given that the real β value is available, a point of interest might be the range of β for which the remanufactured product is expected to be more profitable than the brand-new product. Corollaries 1 and 2 from Proposition 3 can provide the answer. By comparing the range with the real β in the market, one can quickly assess if the product is suitable for a remanufacturing business.

COROLLARY 1. *When no responsible recycling is assumed for the production of the brand-new product (NO scenario), the range of β where the remanufactured product becomes more profitable than the brand-new product is $\beta \geq \beta^*$, where β^* is*

$$\beta^* = 1 - \frac{\sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t)) + (1 - w_i(t)) \cdot V_i^{\text{matl}}(t)] - C^{\text{reverse}}(t)}{P_N} \quad (13)$$

COROLLARY 2. *If responsible recycling is assumed for the production of the brand-new product (NR scenario), the range of β where the remanufactured product becomes more profitable than the brand-new product is $\beta \geq \beta^*$, where β^* is*

$$\beta^* = 1 - \frac{\sum_{i \in I} [w_i(t) \cdot (C_i^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t))]}{P_N} \quad (14)$$

4.3 Illustrative Example: Alternator. To illustrate the use of Model I, this section presents a fictional case study of an automotive alternator. The alternator information was derived from multiple data sources. The product design of the alternator, including its parts, weight, material composition, and reliability, was assumed based on Refs. [61] and [62]; Cost parameters were assumed based on multiple sources, including the national survey on labor cost [63] and various e-commerce websites dedicated to mechanical parts. As for the environmental-impact parameters, an LCA was conducted based on the product design information. *SimaPro* (Version 7.3,³) a well-known software product for conducting LCA, was used for the impact estimation. *Ecoinvent* (Version 2.2,⁴) was mainly used as the source for the life cycle inventory (LCI) data; when appropriate data was unavailable, other LCI databases (e.g., USLCI 1.6 and ELCD 2.0) were

referred to. Note that the way in which to perform the LCA is beyond the scope of this study, so the detailed procedure is not illustrated here. For more details about LCA, refer to Ref. [32].

Table 2 shows the assumed alternator information. All the cost and impact values are measured in U.S. dollars (\$) and kilograms of carbon dioxide equivalent (kg CO₂e), respectively. In Table 2, the reconditioning cost for a reusable part is assumed to be 10% of the new part cost. Alongside Table 2, other parameter values are set as follows: $C^{\text{reverse}}(t) = 2.479$; $C^{\text{forward}}(t) = 5.479$; $E^{\text{disposal}}(t) = 1.092$; $E^{\text{reverse}}(t) = 0.232$; $E^{\text{forward}}(t) = 1.047$. The price for the brand-new alternator is assumed to be 1.5 times of the total part cost (i.e., \$105.72). In addition to the parameter values, further assumptions were made as follows:

- The alternator is remanufactured into the same product without any changes in the design.
- When analyzing the equivalent brand-new product, the NO scenario is assumed; responsible recycling is not considered, and no take-back is performed.
- Fans, bearings and rings are not reusable regardless of their condition. Other parts pass through reusability testing. For a part's physical condition to be approved as reusable, the part should be expected to survive at least t more years. As Anityasari and Kaebnick [62] pointed out, the reusability of a part must be determined based on the probability of its survival during the second life. When the product returns in year t for remanufacturing (i.e., the product is t years old), the minimum mean-time-to-failure required for the disassembled part is also t years (i.e., the part should last t more

³www.pre-sustainability.com/simapro

⁴www.ecoinvent.org

Table 2 Product information on the alternator

Part	λ_i	$C_i^{new}(t)$	$C_i^{recond}(t)$	$V_i^{matl}(t)$	$E_i^{new}(t)$	$E_i^{recond}(t)$	$E_i^{matl}(t)$
Measuring unit	—	\$	\$	\$	kg CO ₂ e	kg CO ₂ e	kg CO ₂ e
Stator	0.0223	20	2	0.034	2.720	0.544	0.0025
Rotor coil	0.0248	5	0.5	0.097	0.434	0.087	0.0010
Rotor	0.0211	15	1.5	0.048	4.360	0.872	0.0012
Drive shaft	0.0105	5	0.5	0.012	0.921	0.184	0.0005
Belt fitting	0.1386	5	0.5	0.135	2.140	0.428	0.0007
Fan	Not reusable	5	0	0.000	0.053	0.011	0.0005
Spacer	0.0693	3	0.3	0.002	0.036	0.007	0.0001
Housing	0.0511	5	0.5	0.718	11.400	2.280	0.0007
Bearing, rings	Not reusable	2	0	0.000	0.430	0.086	0.0004

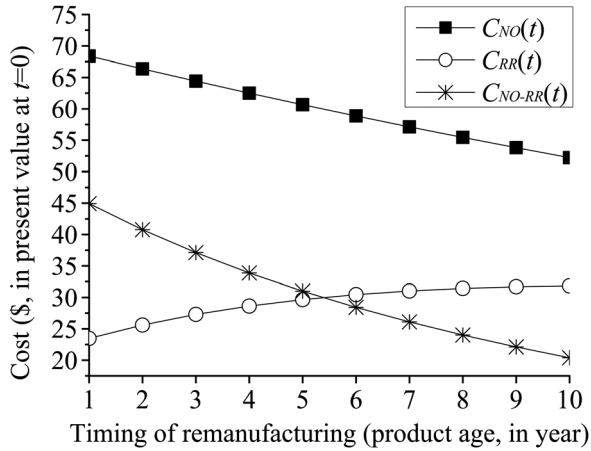


Fig. 2 The cost advantage of the remanufactured alternator

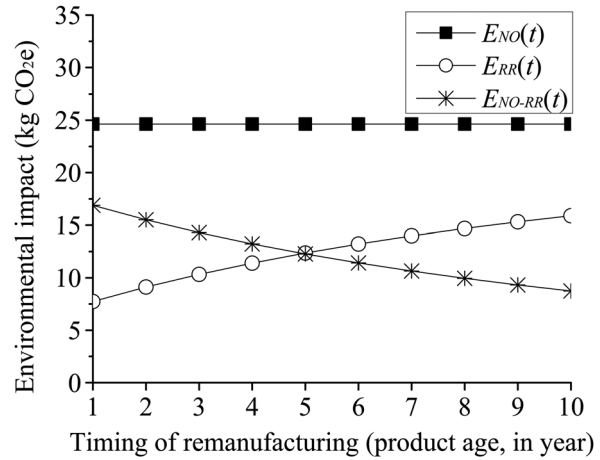


Fig. 3 The environmental advantage of the remanufactured alternator

years). In this case study, a constant failure rate λ_i is assumed for part i . (An increasing failure rate can be a more realistic representation, but a constant failure rate was assumed for illustrative purposes due to a lack of data.) The physical reusability $w_i(t)$ is defined in the following equation:

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

- When converting costs and net profits to the present value at $t=0$, a 3% interest rate with continuous compounding is applied.

As described in Sec. 4.1, Model I can quantify the time-varying advantages of the remanufactured product. Figures 2 and 3 illustrate the estimated cost and environmental advantages of the remanufactured alternator, respectively, and how they change over time depending on when the remanufacturing happens (i.e., the age of the end-of-life alternator). (Note that “time value of money” was considered in Fig. 2. This is why the cost function of NO strategy shows a decreasing trend.) Both figures indicate that the remanufactured product has significant advantages over the brand-new product. When the one-year-old alternator is remanufactured, the remanufacturer can assert that the product can save approximately \$45 of the production cost and 17 kg CO₂e of the environmental impact, as compared to the brand-new product; this corresponds to 66% and 69% of the cost and impact of the brand-new product, respectively. However, as the figures illustrate, the advantages decrease with time as the end-of-life alternator returns with more physical deterioration. Model I estimates that the advantages will decrease to \$20 (39% of the brand-new product) and 9 kg CO₂e (35%), if remanufacturing is conducted at $t=10$. Once the details about the cost and environmental advantages are obtained, Model I can also quantify the expected profit advantage.

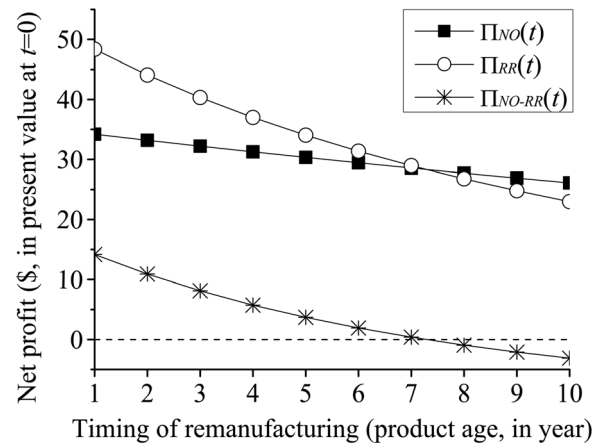


Fig. 4 The net profit advantage of the remanufactured alternator ($\beta = 0.7$)

Suppose that customers are willing to pay as much as 70% of the new product price for the remanufactured alternator when its environmental advantage is known; in other words, $\beta = 0.7$. Figure 4 shows the results from Model I. It illustrates that the remanufactured alternator can bring greater profit than its equivalent brand-new product until $t=7$. The net profit advantage is gone at $t=8$ and afterward, so producing the brand-new alternator seems more reasonable than remanufacturing.

Figure 5 shows the threshold β^* values obtained from Eq. (13). As described in Sec. 4.2, remanufacturing can lead to a larger

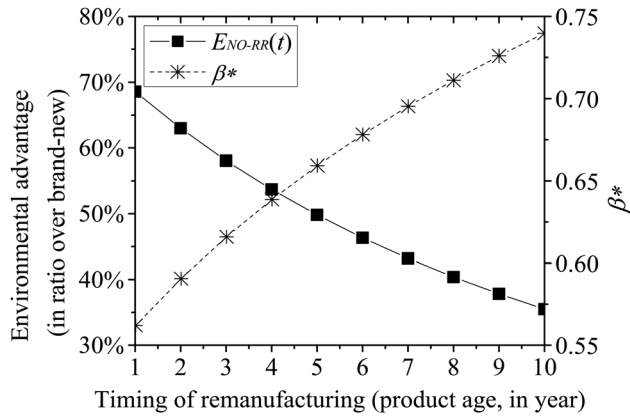


Fig. 5 β^* where the remanufactured and brand-new alternators are equally profitable

profit only if customers are willing to pay for the remanufactured product at more than β^* of the brand-new product's price; if the β of the market is lower than β^* , producing the brand-new version is more profitable than remanufacturing. Figure 5 indicates that the β^* values vary depending on the timing of the remanufacturing; they have an increasing trend with t . (Table 3) When the one-year-old alternator is remanufactured, it can outperform the brand-new product if the customers are willing to pay more than 56% of the new product price (when they know the remanufactured alternator can save 69% of the environmental impact). However, it becomes increasingly difficult to outperform the brand-new product as t increases. If remanufacturing happens at $t=5$, the threshold increases to 66%, and at $t=10$, the threshold increases to 74%; the environmental advantage of the remanufactured product decreases, which makes it more difficult to appeal to customers.

5 Model II: Product With Both Physical Deterioration and Technological Obsolescence

Model II is developed for a product that suffers from both physical deterioration and technological obsolescence. Here, technological obsolescence means that the product is too outdated (even though it may still be in good working order) to attract customers who prefer more advanced technologies and performance. When the product is no longer wanted in the market with its original specifications, a part upgrade is needed in remanufacturing; parts from end-of-life products should be selectively reassembled with new ones to offer more advanced specifications [48].

As described in Sec. 3, Model II assumes that there exist target specifications and that 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, a part upgrade should be conducted by adopting a new, target-level part.

5.1 Unit Production Cost and Environmental Impact. Similar to Model I in Sec. 4, Model II compares two pairs of scenarios: NO vs. RR and NR vs. RR. Equations (16) and (17) illustrate the unit production cost under the NO and NR scenarios, while Eq. (18) shows the unit cost under the RR scenarios. In the NO and NR scenarios, 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

$$C_{NO}(t) = \sum_{i \in I} C_{i, \text{target}}^{\text{new}}(t) + C^{\text{forward}}(t) \quad (16)$$

$$C_{NR}(t) = C^{\text{reverse}}(t) + \sum_{i \in I} C_{i, \text{target}}^{\text{new}}(t) + C^{\text{forward}}(t) - \sum_{i \in I} I_i^{\text{recycle}}(t) \quad (17)$$

where $I_i^{\text{recycle}}(t) = V_i^{\text{matl}}(t)$

In remanufacturing, first note that the target generational difference is set to greater than or equal to the original generational difference (i.e., $\delta_i^{\text{target}}(t) \geq \delta_i(0)$) as assumed in Sec. 3. If not, part i can never satisfy the target specification and always needs to be replaced with a newer part, which means $C_i^{\text{part}}(t) = C_{i, \text{target}}^{\text{new}}(t)$ in Eq. (18). Given that all parts satisfy $\delta_i^{\text{target}}(t) \geq \delta_i(0)$, the reusability of a part is determined by its degree of obsolescence as well as the physical condition. Among the parts in good working condition, only the part that conforms to the target specification (i.e., $\delta_i(t) \leq \delta_i^{\text{target}}(t)$) can be reused in remanufacturing. To put it in another way, the maximum increase in the generational difference allowed for part i for t years is $\delta_i^{\text{target}}(t) - \delta_i(0)$; accordingly, n (i.e., the number of successive generations of part i being newly released in the market for $[0, t]$; $\delta_i(t) = \delta_i(0) + n$) should satisfy $n \leq \delta_i^{\text{target}}(t) - \delta_i(0)$. 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 $f_i(n, t)$ is the probability of n that follows a distribution (e.g., Poisson distribution)

Table 3 β^* depending on the timing of the remanufacturing t

t (year)	β^*	t (year)	β^*	t (year)	β^*
1.00	0.5620	4.25	0.6440	7.50	0.7034
1.25	0.5695	4.50	0.6492	7.75	0.7074
1.50	0.5767	4.75	0.6543	8.00	0.7112
1.75	0.5837	5.00	0.6593	8.25	0.7150
2.00	0.5905	5.25	0.6642	8.50	0.7188
2.25	0.5972	5.50	0.6689	8.75	0.7224
2.50	0.6036	5.75	0.6735	9.00	0.7260
2.75	0.6098	6.00	0.6781	9.25	0.7295
3.00	0.6159	6.25	0.6825	9.50	0.7330
3.25	0.6218	6.50	0.6869	9.75	0.7364
3.50	0.6276	6.75	0.6912	10.00	0.7397
3.75	0.6332	7.00	0.6953		
4.00	0.6387	7.25	0.6994		

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

where

$$\begin{aligned}
C_i^{\text{part}}(t) &= \begin{cases} w_i(t) \cdot C_i^{\text{recond}}(t) + (1 - w_i(t)) \cdot C_{i,\text{target}}^{\text{new}}(t) & \text{if } \delta_i(t) \leq \delta_i^{\text{target}}(t) \\ C_{i,\text{target}}^{\text{new}}(t) & \text{else} \end{cases} \\
&= \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} (C_{i,\text{target}}^{\text{new}}(t) \cdot f_i(n, t)) - \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} [(w_i(t) \cdot C_i^{\text{recond}}(t) + (1 - w_i(t)) \cdot C_{i,\text{target}}^{\text{new}}(t)) \cdot f_i(n, t)] \\
&= \sum_{n=\delta_i^{\text{target}}-\delta_i(0)+1}^{\infty} (C_{i,\text{target}}^{\text{new}}(t) \cdot f_i(n, t)) + \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} (C_{i,\text{target}}^{\text{new}}(t) \cdot f_i(n, t)) \\
&\quad - \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} [w_i(t) \cdot (C_{i,\text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t)) \cdot f_i(n, t)] \\
&= C_{i,\text{target}}^{\text{new}}(t) - \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} [w_i(t) \cdot (C_{i,\text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t)) \cdot f_i(n, t)] \\
&= C_{i,\text{target}}^{\text{new}}(t) - w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n, t) \cdot (C_{i,\text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t)) \\
I_i^{\text{recycle}}(t) &= \begin{cases} (1 - w_i(t)) \cdot V_i^{\text{matl}}(t) & \text{if } \delta_i(t) \leq \delta_i^{\text{target}}(t) \\ V_i^{\text{matl}}(t) & \text{else} \end{cases} \\
&= V_i^{\text{matl}}(t) - \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} (w_i(t) \cdot V_i^{\text{matl}}(t) \cdot f_i(n, t)) \\
&= V_i^{\text{matl}}(t) \cdot (1 - w_i(t)) \cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n, t)
\end{aligned} \tag{18}$$

Equations (16)–(18) lead to Proposition 4, where the cost advantage of remanufacturing is given by comparing the NO and RR scenarios and the NR and RR scenarios, respectively. Deductions are conducted, (i.e., $C_{\text{NO-RR}}(t) (= C_{\text{NO}}(t) - C_{\text{RR}}(t))$ and $C_{\text{NR-RR}}(t) (= C_{\text{NR}}(t) - C_{\text{RR}}(t))$); no proof is provided here.

PROPOSITION 4. *The cost advantage of remanufacturing over producing the equivalent brand-new product is formulated as Eq. (19). If responsible recycling is assumed for the brand-new product, the cost advantage is given as Eq. (20)*

$$C_{\text{NO-RR}}(t) = \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n, t) \cdot (C_{i,\text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t)) \right] + \sum_{i \in I} V_i^{\text{matl}}(t) - C^{\text{reverse}}(t) \tag{19}$$

$$C_{\text{NR-RR}}(t) = \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}}-\delta_i(0)} f_i(n, t) \cdot (C_{i,\text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t)) \right] \tag{20}$$

Equations (21) and (22) quantify the environmental impact of producing a unit of product under the NO, NR, and RR scenarios, respectively. The calculation is similar to Eqs. (16)–(18), except that the product is disposed of by the customer and causes environmental impact $E^{\text{dispose}}(t)$

$$E_{\text{NO}}(t) = E^{\text{dispose}}(t) + \sum_{i \in I} E_{i,\text{target}}^{\text{new}}(t) + E^{\text{forward}}(t) \tag{21}$$

$$E_{\text{NR}}(t) = E^{\text{reverse}}(t) + \sum_{i \in I} E_{i,\text{target}}^{\text{new}}(t) + E^{\text{forward}}(t) + \sum_{i \in I} E_i^{\text{recycle}}(t) \tag{22}$$

$$\text{where } E_i^{\text{recycle}}(t) = E_i^{\text{matl}}(t)$$

$$E_{RR}(t) = E^{\text{reverse}}(t) + \sum_{i \in I} E_i^{\text{part}}(t) + E^{\text{forward}}(t) + \sum_{i \in I} E_i^{\text{recycle}}(t)$$

where

$$\begin{aligned} E_i^{\text{part}}(t) &= \begin{cases} w_i(t) \cdot E_i^{\text{recond}}(t) + (1 - w_i(t)) \cdot E_{i,\text{target}}^{\text{new}}(t) & \text{if } \delta_i(t) \leq \delta_i^{\text{target}}(t) \\ E_{i,\text{target}}^{\text{new}}(t) & \text{else} \end{cases} \\ &= E_{i,\text{target}}^{\text{new}}(t) - \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} [w_i(t) \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t)) \cdot f_i(n, t)] \\ &= E_{i,\text{target}}^{\text{new}}(t) - w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t)) \\ E_i^{\text{recycle}}(t) &= \begin{cases} (1 - w_i(t)) \cdot E_i^{\text{matl}}(t) & \text{if } \delta_i(t) \leq \delta_i^{\text{target}}(t) \\ E_i^{\text{matl}}(t) & \text{else} \end{cases} \\ &= E_i^{\text{matl}}(t) \cdot (1 - w_i(t)) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \end{aligned} \quad (23)$$

Proposition 5 provides a formula for calculating the environmental advantage of the remanufactured product by subtracting the environmental impact of RR scenario from those of NO and NR scenarios.

PROPOSITION 5. *The environmental advantage of a remanufactured product over its equivalent brand-new product is formulated as Eq. (24). If responsible recycling is assumed for the brand-new product (NR scenario), the environmental advantage is given as Eq. (25)*

process, the total usage impact of the remanufactured product should lie between the impact of the brand-new $E^{\text{use}}(t)$ and that of the end-of-life product $(1 + \alpha) \cdot E^{\text{use}}(t)$. If we conservatively assume that the total usage impact of the remanufactured product is $(1 + \alpha) \cdot E^{\text{use}}(t)$ (same as the end-of-life product), then its environmental advantage will be at least as follows, as illustrated in Eqs. (26) and (27)

$$\begin{aligned} E_{\text{NO-RR}}(t) &= E^{\text{dispose}}(t) + \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t)) \right] \\ &\quad - \sum_{i \in I} E_i^{\text{matl}}(t) - E^{\text{reverse}}(t) \end{aligned} \quad (24)$$

$$\begin{aligned} E_{\text{NO-RR}}(t) &= E^{\text{dispose}}(t) + \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t)) \right] \\ &\quad - \sum_{i \in I} E_i^{\text{matl}}(t) - E^{\text{reverse}}(t) - \alpha \cdot E^{\text{use}}(t) \end{aligned} \quad (26)$$

$$\begin{aligned} E_{\text{NR-RR}}(t) &= \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t)) \right] \end{aligned} \quad (25)$$

$$\begin{aligned} E_{\text{NR-RR}}(t) &= \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t)) \right] - \alpha \cdot E^{\text{use}}(t) \end{aligned} \quad (27)$$

Note that Proposition 5 assumes that the remanufactured and brand-new products have no impact difference at the usage stage, as both products are constrained to meet the same target specifications, and thus, have almost the same energy efficiency. If that is not the case, however, it is also possible to release the assumption. Now suppose that both products might have different energy efficiency at the usage stage. Then, the following can be established as Corollary 1.

COROLLARY 1. *Let $E^{\text{use}}(t)$ be the total usage impact of the brand-new product manufactured at time t . Considering the advanced energy efficiency of the newer products, let the total usage impact of the brand-new product manufactured at time 0 be $E^{\text{use}}(0) = (1 + \alpha) \cdot E^{\text{use}}(t)$ for $\alpha \geq 0$. Due to the possibility of a part upgrade and replacement during the remanufacturing*

Corollary 1 implies that $E_{\text{NO-RR}}(t) \geq 0$ or $E_{\text{NR-RR}}(t) \geq 0$ should be satisfied for the remanufactured product to be “greener” than a brand-new product. Corollary 2 presents the conditions for α values for which remanufacturing can hold its environmental advantage by satisfying $E_{\text{NO-RR}}(t) \geq 0$ and $E_{\text{NR-RR}}(t) \geq 0$, respectively.

COROLLARY 2. *A remanufactured product can maintain its environmental advantage over the equivalent brand-new product, if $\alpha \leq \alpha^*$, where α^* is defined as Eqs. (28) (when NO scenario is assumed for the brand-new product) and (29) (when NR scenario is assumed)*

$$\alpha^* = \frac{\left(E^{\text{dispose}}(t) + \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \cdot (E_{i,\text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t)) \right] - \sum_{i \in I} E_i^{\text{matl}}(t) - E^{\text{reverse}}(t) \right)}{E^{\text{use}}(t)} \quad (28)$$

$$\alpha^* = \frac{\sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \cdot \left(E_{i, \text{target}}^{\text{new}}(t) - E_i^{\text{recond}}(t) + E_i^{\text{matl}}(t) \right) \right]}{E^{\text{use}}(t)} \quad (29)$$

Now, let γ (≥ 0) be the average annual change over t years in the total usage impact. The relationship between $E^{\text{use}}(0)$ and $E^{\text{use}}(t)$ can then be rewritten as $E^{\text{use}}(0) \cdot (1 - \gamma \cdot t) = E^{\text{use}}(t)$ which leads to $\alpha = 1/(1 - \gamma \cdot t) - 1$. Accordingly, Corollary 3 is established from Corollary 2, as follows:

COROLLARY 3. A remanufactured product can maintain its environmental advantage over the equivalent brand-new product, if $\gamma \leq \gamma^*$, where γ^* is defined as follows:

$$\gamma^* = \frac{1}{t} \cdot \left(1 - \frac{1}{1 + \alpha^*} \right) \quad (30)$$

5.2 Net Profit. Proposition 6 presents the net profit advantage of the remanufactured product, followed by its corollaries showing the condition for β , where the remanufactured product can provide greater profits than its equivalent brand-new product.

PROPOSITION 6. 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 $E_{\text{NO-RR}}(t)$ and $E_{\text{NR-RR}}(t)$, respectively. Then, the advantage of remanufacturing from the net-profit perspective is given as Eqs. (31) and (32), respectively,

$$\begin{aligned} \Pi_{\text{RR-NO}}(t) &= \Pi_{\text{RR}}(t) - \Pi_{\text{NO}}(t) \\ &= (P_R - C_{\text{RR}}) - (P_N - C_{\text{NO}}) \\ &= (\beta - 1) \cdot P_N + \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (C_{i, \text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t)) \right] \\ &\quad + \sum_{i \in I} V_i^{\text{matl}}(t) - C^{\text{reverse}}(t) \end{aligned} \quad (31)$$

$$\begin{aligned} \Pi_{\text{RR-NR}}(t) &= \Pi_{\text{RR}}(t) - \Pi_{\text{NR}}(t) \\ &= (P_R - C_{\text{RR}}) - (P_N - C_{\text{NR}}) \\ &= (\beta - 1) \cdot P_N + \sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \right. \\ &\quad \left. \cdot (C_{i, \text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t)) \right] \end{aligned} \quad (32)$$

COROLLARY 1. When no responsible recycling is assumed for the production of the brand-new product (NO scenario) and the target generational difference of $\delta_i^{\text{target}}(t) (\geq \delta_i(0), \forall i)$ is given, the range of β where the remanufactured product becomes more profitable than the brand-new product is $\beta \geq \beta^*$, where β^* is

$$\beta^* = 1 - \frac{\left(\sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \cdot \left(C_{i, \text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t) \right) \right] + \sum_{i \in I} V_i^{\text{matl}}(t) - C^{\text{reverse}}(t) \right)}{P_N} \quad (33)$$

COROLLARY 2. If responsible recycling is assumed for the production of the brand-new product (NR scenario) and the target generational difference of $\delta_i^{\text{target}}(t) (\geq \delta_i(0), \forall i)$ is given, the range of β where the remanufactured product becomes more profitable than the brand-new product is $\beta \geq \beta^*$, where β^* is

$$\beta^* = 1 - \frac{\sum_{i \in I} \left[w_i(t) \cdot \sum_{n=0}^{\delta_i^{\text{target}} - \delta_i(0)} f_i(n, t) \cdot \left(C_{i, \text{target}}^{\text{new}}(t) - C_i^{\text{recond}}(t) - V_i^{\text{matl}}(t) \right) \right]}{P_N} \quad (34)$$

5.3 Illustrative Example: Desktop PC. This section illustrates the implementation of Model II by using a fictional case study of a desktop PC. The design of the PC and cost parameter values were adopted from Refs. [48,64], and [65], while the environmental-impact information was obtained by an LCA study. In the LCA, *SimaPro* (version 7.3) and *Ecoinvent* (version 2.2) were used for the impact assessment. Table 4 illustrates the product information on the desktop PC. Other parameter values are set as follows: $C^{\text{reverse}}(t) = 28.5$; $C^{\text{forward}}(t) = 35$; $E^{\text{disposal}}(t) = 1.488$; $E^{\text{reverse}}(t) = 0.660$; and $E^{\text{forward}}(t) = 2.288$. The price for the brand-new PC is assumed to be 1.5 times the total part cost (i.e., \$518.76). In addition, the following assumptions were made:

- When analyzing the equivalent brand-new product, the NR scenario is assumed; responsible recycling is performed, and

the end-of-life product is taken-back to the original manufacturer for material recovery.

- The initial generational difference of the PC is $\delta_i(0) = 0$. In other words, the PC was originally positioned as a high-end product. The target generational difference for the remanufactured PC (i.e., $\delta_i^{\text{target}}(t)$) is given in Table 4. It implies that the market position for the remanufactured product is set at lower than its original position (i.e., $\delta_i^{\text{target}}(t) \geq \delta_i(0), \forall i$).
- When calculating $f_i(n, t)$ (i.e., the probability that a total of n generations of part i will appear in the market for $[0, t]$), n is assumed to be a Poisson process having rate μ_i , where μ_i denotes the average frequency per year with which a successive generation of part i is newly released. $f_i(n, t)$ can then be defined as in the following equation:

Table 4 Product information on the desktop PC: cost and environmental impact

Part	λ_i	μ_i	$\delta_i^{\text{target}}(t)$	$C_i^{\text{new}}(t)$	$C_i^{\text{recond}}(t)$	$V_i^{\text{matl}}(t)$	$E_i^{\text{new}}(t)$	$E_i^{\text{recond}}(t)$	$E_i^{\text{matl}}(t)$
Measuring unit	—	—	—	\$	\$	\$	kg CO ₂ e	kg CO ₂ e	kg CO ₂ e
CPU	0.5	0.67	2	45.52	5	5	5.920	1.184	0.005
RAM	0.5	0.50	1	21.63	5	5	7.590	1.518	0.001
Motherboard	1	0.67	2	39.02	5	5	169.000	33.800	0.004
Hard drive	1	1.00	3	71.69	5	4.5	12.300	2.460	0.004
Graphic card	1	1.00	3	42.11	5	4.5	50.200	10.040	0.003
Optical drive	2	0.40	2	15.87	5	3	17.100	3.420	0.002
Chassis	1	0.20	0	75.00	5	3	56.200	11.240	0.002

$$f_i(n, t) = \frac{e^{-\mu_i t} (\mu_i t)^n}{n!} \tag{35}$$

- During the second life, both the remanufactured and brand-new products are assumed to follow the same usage scenario: 250 working days per annum and 8 hrs of use per day. The annual energy used and the per-unit environmental impact are assumed to be 238.93 kWh and 0.594 kg CO₂e/kWh, respectively [66].
- The physical reusability $w_i(t)$ is defined by Eq. (36), where λ_i denotes the constant failure rate (10⁻⁵/hour) for part i [64]. 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

$$w_i(t) = e^{-\lambda_i \cdot 10^{-5} \cdot 2r \cdot 250 \cdot 8} \tag{36}$$

- To convert monetary values to the present value at $t=0$, a 3% interest rate with continuous compounding is applied.

Figure 6 illustrates the cost advantage of the remanufactured PC resulting from Model II. 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). In other words, the cost advantage of remanufacturing is \$214 (64%). However, this cost advantage rapidly decreases with time as the product ages. If remanufacturing is conducted at year 10, the unit production cost of the remanufactured PC becomes \$248, which is almost the same as the brand-new cost of \$255. The advantage is estimated to be only \$7 (3%).

Figure 6 shows the time-varying 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 Fig. 6, Fig. 7 implies that remanufacturing has a significant

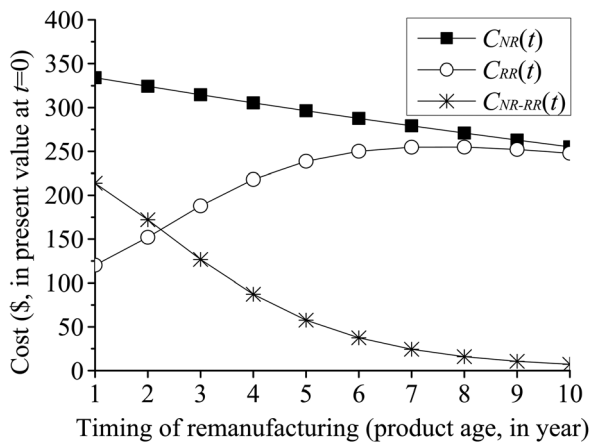


Fig. 6 The cost advantage of the remanufactured PC

environmental advantage over producing the brand-new product; however, the advantage quickly disappears. When the remanufacturing is conducted in year 1, the unit production impacts for the brand-new and remanufactured PCs are 321 kg CO₂e and 90 kg CO₂e, respectively. This means that remanufacturing can save more than 72% of the environmental impact from production. If remanufacturing is conducted in year 10, however, the unit production impacts become 321 kg CO₂e (brand-new) and 311 kg CO₂e (remanufactured), respectively. Thus, the advantage is estimated to be less than 10 kg CO₂e (3%).

If the usage impact is involved, the environmental advantage becomes even smaller. Figure 8 implies that the environmental advantage may not always exist if a significant amount of an energy-efficiency increase is expected for the brand-new product

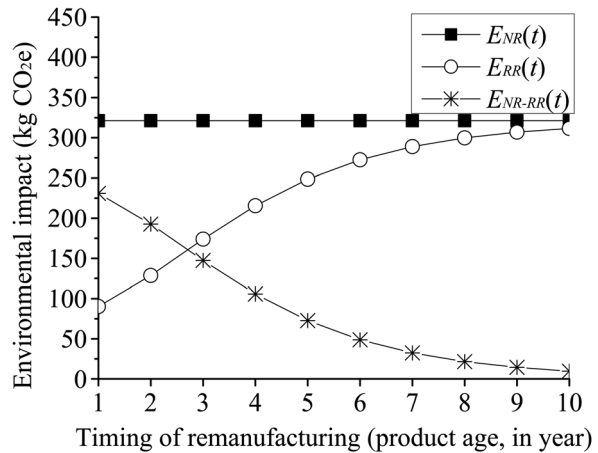


Fig. 7 The environmental advantage of the remanufactured PC

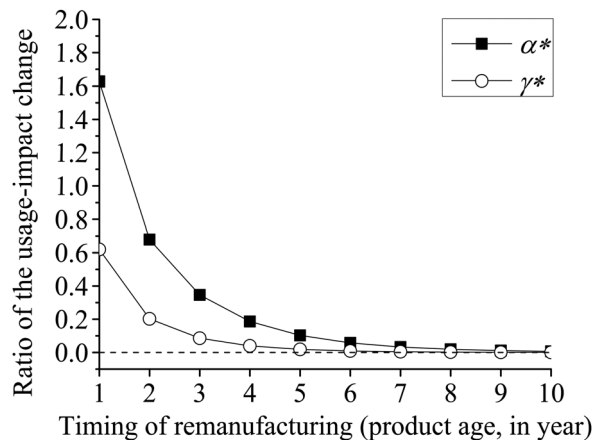


Fig. 8 α^* and γ^* where the remanufactured and brand-new PCs are equally green

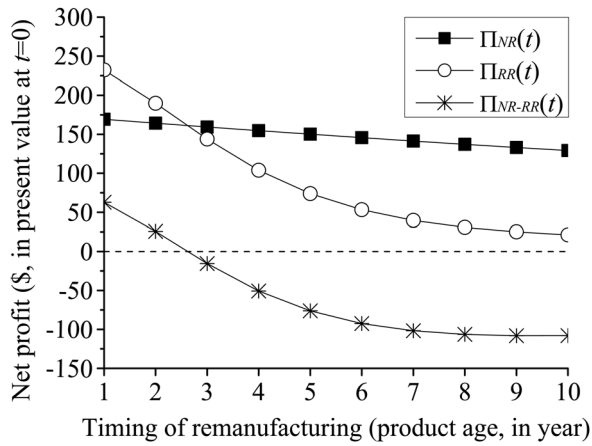


Fig. 9 The net profit advantage of the remanufactured PC ($\beta = 0.7$)

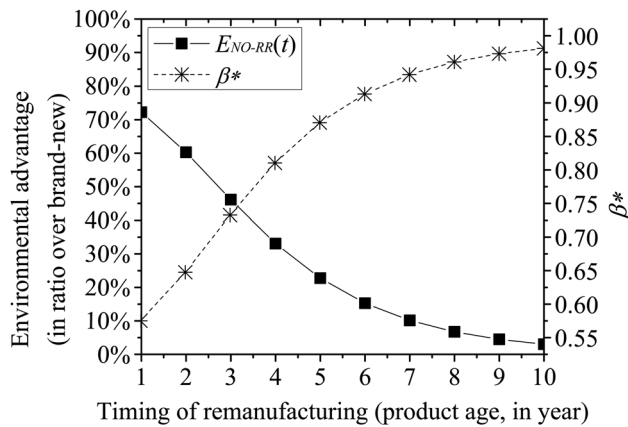


Fig. 10 β^* where the remanufactured and brand-new PCs are equally profitable

(i.e., $\alpha \geq \alpha^*$ or $\gamma \geq \gamma^*$). The brand-new product now has a significant environmental advantage in the usage phase; it offsets the advantage of remanufacturing in the production phase. instance, suppose that the total usage impact for a brand-new product is expected to decrease by 5% on average, every year (i.e., $\gamma = 0.05$). Remanufacturing the PC until year 3 will have an environmental advantage. However, from year 4, where γ becomes greater than γ^* , producing the brand-new product is greener than remanufacturing. Figure 9 compares the remanufactured and brand-new PCs from the net-profit perspective. When $\beta = 0.7$ (i.e., 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 Fig. 7), the remanufactured PC outperforms the brand-new product until $t = 2$. From $t = 3$, however, its profit advantage disappears and the brand-new PC is expected to bring greater profit. This implies that remanufacturing may not be a promising business, considering that the average lifetime of a desktop PC is 4 years or more [65,67]. To achieve a viable business, remanufacturing should be conducted within 2 years, or the β value should be increased.

Figure 10 and Table 5 suggest how much the β value should be raised 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. If customers are willing to pay more than 81% of the brand-new product's price, it is reasonable to remanufacture the product; otherwise, producing a brand-new product is recommended, considering its higher profit.

Table 5 β^* depending on the timing of the remanufacturing t

t (year)	β^*	t (year)	β^*	t (year)	β^*
1.00	0.5751	4.25	0.8272	7.50	0.9525
1.25	0.5909	4.50	0.8429	7.75	0.9569
1.50	0.6084	4.75	0.8574	8.00	0.9608
1.75	0.6274	5.00	0.8707	8.25	0.9644
2.00	0.6476	5.25	0.8829	8.50	0.9676
2.25	0.6686	5.50	0.8941	8.75	0.9705
2.50	0.6900	5.75	0.9042	9.00	0.9731
2.75	0.7115	6.00	0.9134	9.25	0.9754
3.00	0.7328	6.25	0.9217	9.50	0.9775
3.25	0.7535	6.50	0.9292	9.75	0.9794
3.50	0.7734	6.75	0.9360	10.00	0.9811
3.75	0.7924	7.00	0.9421		
4.00	0.8104	7.25	0.9475		

6 Discussion

The results from the two case studies imply that remanufacturability differs by product and some products are more suitable for remanufacturing. In the previous cases, the alternator illustrates a greater potential than the desktop PC. When β is set to be 0.7, the remanufactured alternator maintains the net-profit advantage until $t = 7$, while the remanufactured PC does until $t = 2$. In terms of β^* , the alternator requires a lower threshold (i.e., from 0.56 in year 1 to 0.74 in year 10) than that for the PC (i.e., from 0.58 in year 1 to 0.98 in year 10). Admittedly, the results were obtained based on a single set of parameter values. However, a sensitivity analysis also confirms that such a difference between the two products is also valid in a wider variety of cases.

Figure 11 shows the results from the sensitivity analysis which varied three key parameter values: (1) part cost, C_i^{new} , (2) reconditioning cost, C_i^{recond} , and (3) take-back and disassembly cost, C^{reverse} . Each parameter was varied in two levels: 50% and 200% of the current value. Figure 11 plots how β^* changes according to different parameter settings and compares the results with the previous ones in Tables 3 and 5 (noted as the "baseline" in the figure).

In both cases, the threshold β^* increases when the part cost C_i^{new} decreases, which means reduced remanufacturability of the product. When the part cost C_i^{new} increases, the β^* decreases accordingly, indicating increased remanufacturability. This makes sense, because the cost-saving effect of reusing parts is proportional to the new part cost. In contrast, the β^* is inversely proportional to C_i^{recond} and C^{reverse} , which is more straightforward, as only remanufacturing involves these two cost elements.

Of interest here is the difference between the alternator and the PC. In general, the β^* of the PC is higher than that of the alternator. The results also illustrate that the β^* of the PC increases more rapidly, meaning that the PC loses its remanufacturability faster than the alternator does. In a nutshell, the current results indicate that, in this particular case, the remanufacturability of a PC may not be profitable enough to pursue remanufacturing. To support the remanufacturing of such products, additional actions are needed.

Buying back end-of-life products for early take-back can be one possible solution for increased remanufacturability. Suppose that the remanufacturer changes their take-back strategy and decides to buy back end-of-life products in year t' ($t' < t$). To advance the take-back from year t to year t' , the remanufacturer should pay a unit buy-back price of $\zeta(t')$ in year t' . The net profit of the RR scenario then changes to $\Pi_{RR}(t) - \zeta(t')$. The counterpart NR scenario is also redefined. An equivalent new product is produced in year t' , while responsible recycling happens in year t . Accordingly, the net profit advantage of remanufacturing with the buy-back strategy is given as Eq. (37) (in a present value at $t = 0$), where r denotes the interest rate with continuous compounding. If $\Pi_{RR-NR}^{\text{Buyback}}(t)$ is positive and greater than $\Pi_{RR-NR}(t)$ (i.e., net profit

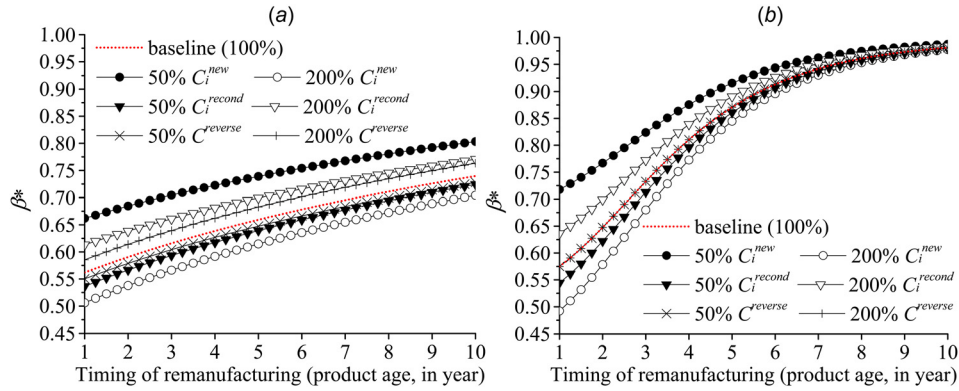


Fig. 11 Sensitivity analysis: change of β^* under varied settings for cost parameters

Table 6 Upper limit of buy-back prices (\$) for the net profit advantage of remanufacturing ($\beta = 0.7$)

	Timing of remanufacturing under waste-stream system, t	Timing of remanufacturing with buy-back, t'			
		1	2	3	4
	3	66.56	52.86	–	–
	4	67.39	52.97	6.31	–
	5	68.21	53.07	6.33	–55.23
	6	68.99	53.17	6.35	–55.22
	7	69.75	53.26	6.37	–55.20
	8	70.50	53.35	6.39	–55.19
	9	71.21	53.43	6.40	–55.17
	10	71.91	53.50	6.42	–55.16

advantage without buy-back; Eq. (32)), the buy-back of the product is recommended

$$\begin{aligned}
 \Pi_{RR-NR}^{\text{Buyback}}(t') &= (\Pi_{RR}(t') - \zeta(t')) \cdot e^{-r \cdot t'} - \left\{ \left(\Pi_{NR}(t') \right. \right. \\
 &\quad \left. \left. - \sum_{i \in I} V_i^{\text{matl}}(t') \right) \cdot e^{-r \cdot t'} + \sum_{i \in I} V_i^{\text{matl}}(t) \cdot e^{-r \cdot t} \right\} \\
 &= \left(\Pi_{RR-NR}(t') - \zeta(t') + \sum_{i \in I} V_i^{\text{matl}}(t') \right) \cdot e^{-r \cdot t'} \\
 &\quad - \sum_{i \in I} V_i^{\text{matl}}(t) \cdot e^{-r \cdot t} \text{ (in a present value at } t = 0)
 \end{aligned} \quad (37)$$

Equation (37) also defines an upper limit of the buy-back price $\zeta(t')$. To make the remanufactured product more profitable than the brand-new product (i.e., $\Pi_{RR-NR}^{\text{Buyback}}(t') \geq 0$), $\zeta(t')$ should satisfy the constraint in Eq. (38). If the market requires buy-back prices greater than the limit, the buy-back is not recommended

$$\zeta(t') \leq \Pi_{RR-NR}(t') + \sum_{i \in I} V_i^{\text{matl}}(t') - \sum_{i \in I} V_i^{\text{matl}}(t) \cdot e^{-r \cdot (t-t')} \quad (38)$$

Table 6 shows the upper limit of the buy-back price $\zeta(t')$ calculated for the desktop PC assuming various combinations of t and t' . For instance, presume that the remanufacturer pays less than \$52.86 and can buy back an end-of-life product that was supposed to be returned in year 3 one year earlier in year 2 (i.e., $t = 3$; $t' = 2$). The net profit advantage $\Pi_{RR-NR}^{\text{Buyback}}(2)$ then becomes positive, and the remanufactured product becomes more profitable than the brand-new product. Considering that $\Pi_{RR-NR}(3)$ was negative in Fig. 9, it is better to buy back the product. This

illustrates that a buy-back can be one potential way to increase the value of remanufacturing.

When the remanufacturability of a product needs to be improved, the DfR can be another possible solution, especially for OEM remanufacturers. The proposed model can assist in making design decisions for the DfR. It helps designers investigate how their design decisions will affect remanufacturing at the end-of-life stage.

For instance, OEM remanufacturers may consider improving the reliability of parts so as to increase part reusability and reduce new part purchases. Suppose that design solutions are available to increase the physical reusability (i.e., $w_i(t)$) of each part by 5% points and designers want to decide which ones to adopt. The proposed model can help make the decision by showing how much of an increase in remanufacturability is expected by each solution. Figures 12 and 13 illustrate the expected increases in the cost and environmental advantages, respectively. The figures reveal that each solution has different economic and environmental implications. For example, if remanufacturing is performed in year 3 and a design solution for the hard drive is developed, the cost and environmental advantages are expected to increase by \$1.84 and 0.29 kg CO₂e, respectively. If a design solution for the motherboard is developed, the advantages are expected to increase by \$0.9 and 4.18 kg CO₂e, respectively. To make any conclusion, the cost for adopting each design solution should be considered together later, but the current results demonstrate that the proposed model can provide useful inputs for the decision making process. If designers are interested in increasing the cost advantage, the solution for the hard drive seems most promising; the solution for the chassis is the next most promising solution. If the environmental advantage is of interest, however, the solution for the motherboard would be the best, and the solutions for the graphic card and chassis are next.

Figures 12 and 13 also imply that the design solutions have different implications, depending on the timing of the

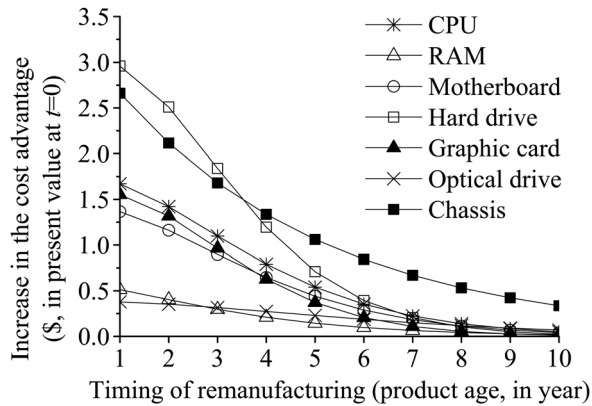


Fig. 12 Increase in the cost advantage when the part physical reusability is improved by 5% point

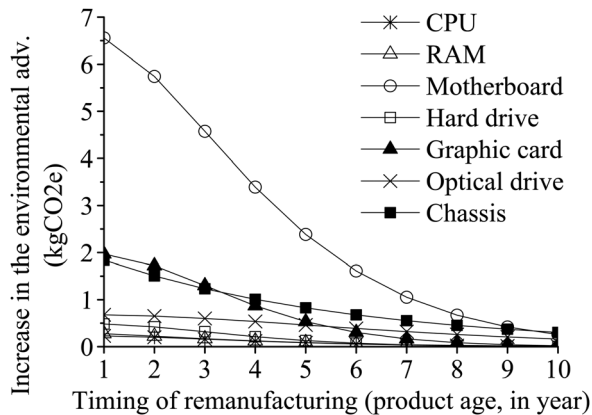


Fig. 13 Increase in the environmental advantage when the part physical reusability is improved by 5% point

remanufacturing (or, the product age). Since the reusability of parts is also constrained by technological obsolescence, the benefit of increased reliability decreases over time, and more importantly, at different speeds by the part type. Therefore, designers should make different decisions depending upon the expected timing of the remanufacturing. For instance, if remanufacturing is conducted in year 5, the leveraging effect of an improved hard drive will decrease to \$0.71 and 0.11 kg CO₂e, respectively. If all other conditions are the same, improving the chassis seems to be a better option than improving the hard drive, which will bring more increases in both the cost and environmental advantages. Changing the design of the remanufactured product (i.e., target specifications) can be another option to consider in improving remanufacturability. In Table 4, the target specifications for the remanufactured PC were $\delta_i^{\text{target}}(t) = \{2, 1, 2, 3, 3, 2, 0\}$ (baseline) in terms of the generational difference. What if the designers lower the specifications and change the specifications to $\{3, 2, 3, 4, 4, 3, 1\}$ ("low spec")? Lowering the target specifications will reduce the part cost. However, at the same time, the selling price of the brand-new and remanufactured PCs will drop from \$518.76 and \$363.13 to \$376.56 and \$263.59, respectively.

In Fig. 14, the proposed model compares the cost, net profit, and environmental advantages of the two scenarios. As more parts can be reused with the new specifications, it becomes clearer that the environmental advantage is increased in the low spec scenario. Interesting results are illustrated in the cost and net profit advantages. With the increased part reusability, the low spec results in more cost and profit advantages when remanufacturing is executed in later years and the product is of an older age. However, if

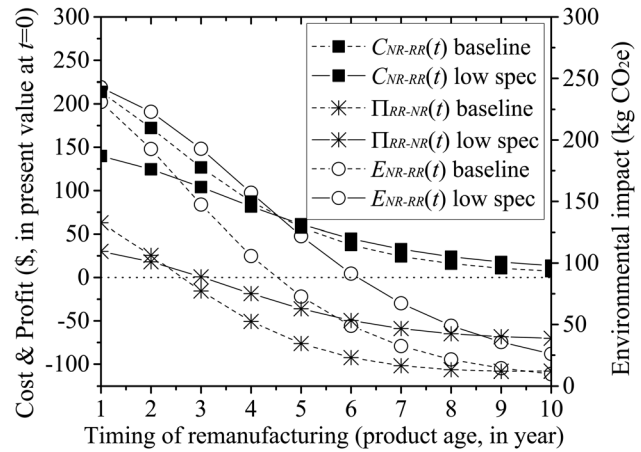


Fig. 14 Effect of changing the target specifications for the remanufactured product

early remanufacturing within year 2 is possible, it seems that it is better to maintain the current specifications. In the earlier years, parts are less affected by technological obsolescence, so the loss from the reduced selling price outweighs the benefit from the marginally increased reusability. This result implies that the competitive advantages of remanufactured products get stronger at a lower-level market position if late end-of-life returns are anticipated.

7 Conclusions

For remanufacturing to be successful, it is critical to know in advance whether the design of a given product incorporates features that will facilitate the remanufacturing process or not. Considering its competition with brand-new products, the remanufactured product should possess a significant economic and/or environmental advantage over the brand-new product.

Although a remanufactured product is commonly accepted as an economical and environmentally friendly alternative to a brand-new product, it is also known that more consideration is necessary before supporting the case for remanufacturing. To validate the advantages of remanufacturing, assessment models are needed to quantify the economic and environmental advantages of a remanufactured product. With an aim to serve the need, 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 especially focuses on the fact that the time when the remanufacturing is conducted greatly influences the advantages of remanufacturing, and thus, the model proposes quantitative methods to estimate time-varying economic and environmental values. "How much value can be asserted to be achieved by a unit of a remanufactured product by avoiding new product production" is quantified by means of a one-to-one comparison between the remanufactured and equivalent brand-new versions of a product. The quantification of technological obsolescence and simultaneous evaluation of cost, environmental impact, and net profit can be taken as the major contribution of the paper.

The developed model enables remanufacturers to make more informed and effective business decisions concerning product planning and remanufacturing strategy planning (e.g., whether or not to remanufacture a product, which products to remanufacture, and when to take back the end-of-life product). It provides quantitative performance measures to evaluate the product and remanufacturing strategy alternatives. Using the model, remanufacturers can clarify which alternative is more suitable and how much better it is than others with respect to the unit production cost, environmental impact, and net profit. OEM remanufacturers (e.g., Xerox, Caterpillar, and John Deere) can also use the model for the DfR

at the design stage. By applying the model to multiple design alternatives, they can evaluate product remanufacturability and use the results in the design selection process. The model also assists in design improvement and optimization by informing designers about the impact of their decisions on product remanufacturability.

With environmental regulations and in the presence of strong consumer pressure, remanufacturers are facing the need to validate the economic and environmental sustainability of their products. The proposed model is also expected to help the effective marketing of remanufactured products along this line. It enables product declaration from both economic and environmental perspectives. The results can be used in communication with customers to show them how good a product is and to strengthen the brand reputation.

The proposed model is generic and applicable to a wide range of products. Two versions of the model allow for the consideration of different product types: products with only physical deterioration and products with both physical deterioration and technological obsolescence. Taking the model as a base, variant models can be developed that are customized for a specific case or a particular remanufacturing scenario. For instance, the current model assumes that there is no resale of used parts to the secondary market, but a variant model can be derived to incorporate the resale of used parts [2].

The current model requires a few input parameters that characterize the products and the customers in the market (e.g., cost, part reusability, β value). One limitation is that this may bring about additional challenges in the estimations and predictions. Considering the variable and uncertain conditions of the end-of-life products, a significant variance is expected for the parameters. Although these factors were beyond the scope of this study, estimation and prediction models need to be developed in the future. Predictive data mining, time-series analysis, and an empirical market study (e.g., Refs. [37,40–42], and [68–71]) would provide promising solutions to the challenge.

In the future, one potentially productive line of research would be to extend the proposed model to design optimization models. In the current model, product design is a key input, and the model evaluates the given design from a remanufacturer's point of view. With the understanding of the relationship between the design and the value of remanufacturing, more proactive approaches can be developed. The product design can be optimized to attain improved remanufacturability at the end-of-life stage; for instance, product specifications or part reliability can be optimized for maximum remanufacturability. The target design for the remanufactured product can be also optimized. In the current model, the target design was assumed to be the same as the end-of-life product (Model I) or was predefined and given by the decision maker (Model II). By optimizing the target design, remanufacturers can explore additional opportunities to maximize their competitive advantages.

Future work can also include applying the model to a wider range of products to obtain insights into how β^* values differ by the type of product and what products are suitable for remanufacturing. Finally, the current model assesses the value of a remanufactured product from a remanufacturer's perspective. Another research opportunity would be to integrate this company-perspective model with a consumer-perspective model.

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