Impact of Generational Commonality of Short Life Cycle Products in Manufacturing and Remanufacturing Processes

Jinju Kim
Enterprise Systems Optimization Laboratory,
Department of Industrial and Enterprise Systems Engineering,
University of Illinois at Urbana-Champaign,
Urbana, IL 61801
e-mail: jkim702@illinois.edu

Harrison M. Kim[1]
Enterprise Systems Optimization Laboratory,
Department of Industrial and Enterprise Systems Engineering,
University of Illinois at Urbana-Champaign,
Urbana, IL 61801
e-mail: hmkim@illinois.edu

Short life cycle products are frequently replaced and discarded, even though they are resource-intensive products. Technological advances and rapid changes in demand have led manufacturers to develop their innovative next-generation products quickly, which not only enables multiple generations to coexist in the market but also speeds up the technological obsolescence of products. Diversity of collected end-of-life (EoL) and rapid technological obsolescence make the effective recovery of EoL products difficult. The low utilization rate of EoL products causes serious environmental problems such as e-waste and waste of natural resources. To deal with the conflict between the technical evolution of products and the promotion of social benefits in solving environmental problems, this paper focuses on the impact of generational commonality effects on the overall production process including manufacturing and remanufacturing. Generational commonality leads to an increase in the efficiency of manufacturing due to reducing related costs. Additionally, from the remanufacturing perspective, the interchangeability between generations can help collect the EoL products needed for remanufacturing. On the other hand, it causes a weakening of the level of performance and technology evolution between generations that significantly affect the demand for short life cycle products. Therefore, this study identifies these trade-offs of generational commonality levels in both manufacturing and remanufacturing based on a quantitative approach. This study finds how different pricing strategies, production plans, and recovery costs are based on the designs of a new generation with a different degree of generational commonality. [DOI: 10.1115/1.4047092]

Keywords: life cycle analysis and design, product family design, sustainable design

1 Introduction

Rapid technological advances have accelerated the rate of global consumption and the pace of product disposal. Products that are quickly discarded or replaced have caused serious environmental pollution and wasted natural resources [1]. Primarily, short life cycle products are quickly replaced by new generations of the product due to the fast development of technology and change of trend compared to products with long life cycle products. The characteristics of the short cycle products are mainly apparent in electronic devices such as smartphones, tablet PCs, etc. These rapid changes in technological development and demand have led manufacturers to develop their innovative next-generation products quickly to satisfy their demand. It often enables multiple generations to coexist in the market at a point in time [2]. Furthermore, the speed of rapid component development advances the technological obsolescence of previously developed parts [3]. These factors make it difficult to recover their end-of-life (EoL) products, even though they are mostly resource-intensive products. Low utilization of short life cycle products has incurred severe environmental pollution, such as e-waste and waste of residual value of them. As these problems become serious, global awareness of the environment has been improved and various environmental regulations have been forced to address these issues [4,5]. These social changes have forced manufacturers and product designers to explore sustainable product designs and recovery strategies for EoL and EoU products to deal with the environmental issue.

Remanufacturing has been known to be one of the key strategies to recover EoL products [4–7]. Remanufacturing refers to the process of restoring to the original or better state functionally and aesthetically using EoL or EoU products [8]. With remanufacturing, original equipment manufacturers (OEMs) can obtain economic as well as environmental advantages. From an economic point of view, EoL products can reduce consumption of natural resources and energy needed to produce products. Additionally, besides current customers, it can target a variety of customers from eco-friendly customers to price-sensitive customers. From an environmental point of view, remanufactured products can reduce the environmental impact that may occur in the product production process. With these advantages, various brands including Samsung, Apple, Dell, and Sony are introducing new products as well as remanufactured (or refurbished) products. The obvious difference between refurbished and remanufactured products depends on the degree of an upgrade. Refurbishing means to raise the quality level to a certain level by utilizing EoL or EoU products, but remanufacturing is to bring EoL or EoU products up to like-new quality level [9].

However, as mentioned earlier, products with short life cycles have difficulties in remanufacturing due to the coexistence of different generations and the technological obsolescence. Remanufacturing requires additional processes, unlike the manufacturing process. The remanufacturing process consists of collecting EoL products, disassembling, reconditioning, procurement, and reassembling. In particular, collecting EoL products has a significant impact on the efficiency of remanufacturing, because it is a process of securing raw materials to produce remanufactured products. In this process, the coexistence of different generations leads to more uncertainties of collected products. As OEMs produce various

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[1]Corresponding author.

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products, the diversity of products that can be collected in the collection process will increase [7,10]. The diversity of these products reduces the reuse rate of parts and modules in the remanufacturing process as well as the difficulty of the remanufacturing process (i.e., a variety of disassembly and assembly techniques may be required) [7]. Besides, rapid technological obsolescence also incurs difficulties in using EoL products of previous generations. This is because using parts from EoL products may make it difficult to meet the needs of customers. Given that trends and customer requirements change quickly, it can be an obstacle for remanufacturing. Therefore, it would be helpful to quickly launch remanufactured products before technical obsolescence occurs. However, this is also difficult, considering that it takes a certain period of time to collect sufficient EoL and EoU products for remanufacturing.

Generational commonality is one of the ways to increase the efficiency of manufacturing and remanufacturing while maintaining product diversity [7]. Generational commonality represents a common set of subsystems, modules, and components between different generations of products. While many of their features change for different generations, product lines with a short life cycle tend to share similar parts. These parts are compatible with the production and repair processes, although they are of different generations. This leads to associated cost savings in the manufacturing and maintenance processes and is a factor that improves the efficiency of the manufacturing process. Additionally, it leads to reducing the uncertainty of collecting process for remanufacturing and time constraint by increasing interchangeability between generations. Nevertheless, using the same parts between generations weakens the performance gap between the two generations, which may lead to a drop in demand. Therefore, OEMs who plan to produce new and remanufactured products should have an integrated recognition of the effects of generational commonality among different generational products for the co-evolution of technology and environmental welfare.

This simultaneous consideration of manufacturing and remanufacturing is much more complex and difficult than the traditional linear-loop approach. Unfortunately, there is a lack of research regarding generational commonality from an integrated viewpoint of manufacturing and remanufacturing. Therefore, this study aims to identify trade-offs that occur with the level of generational commonality in the two processes, including manufacturing and remanufacturing, based on a quantitative approach. Several major issues are addressed in the development of this methodology: (1) The effect of generational commonality on the pricing strategy; (2) The effect of generational commonality on the revenue, cost, and profit in the manufacturing; (3) The effect of generational commonality on the revenue, cost, and profit in the remanufacturing; (4) The influence of the number of available EoL products of the new generation in the market.

Decisions regarding the commonality of products have a significant impact on not only the manufacturing and marketing processes but also recovery strategies at the EoL. Therefore, the overall life cycle and recovery strategies of the product should be considered in the initial product design phase. For short life cycle products that constrain more time to market and performance than for other types of products, more careful consideration should be needed. This study will help OEMs and product designers understand how generational commonality affects the production process in the circular production process, rather than the traditional linear production process. In addition, by identifying trade-offs of generational commonality from an integrated perspective, OEMs will gain insight that can be used in designing new generation products for economic and environmental benefits.

The rest of this paper is organized as follows. Section 2 reviews relevant prior literature on this topic. Section 3 represents a mathematical model for investigating the effect of generational commonality on manufacturing and remanufacturing processes. Section 4 presents a case study of the application of the proposed model and implementation results. Finally, conclusions and future research are discussed in Sec. 5.

2 Literature Review

2.1 Remanufacturing. As global environmental awareness and environment regulations have been strengthened, remanufacturing has gained interest in recent years to improve profitability and sustainability together. In the product design field, EoL product recovery strategies have been studied to improve sustainability throughout the product life cycle. The researches on recovery strategy have been performed to identify optimal EoL options by evaluating the different aspects of the components of the product at the EoL stage, including those by Kwak and Kim [10], Ma and Kremer [11], and Cong et al. [12]. Among the EoL options, Kwak and Kim [13] considered recycling, reuse, reconditioning, refurbishment, and cannibalization as the EoL options to maximize profitability. Ma and Krermer [11] proposed a systematic method for evaluating the EoL options (Reuse, remanufacture, primary recycle, secondary recycle, incinerated, landfills, special handling) of components considering the sustainability and subjective perception of the designer. Cong et al. [12] considered reuse, recycling, and disposal for recovery options to determine the sequence of product decomposition for minimizing recovery costs.

There are several EoL options to recover the EoL product, in particular, the remanufacturing is known as one of the most effective and efficient ways to restore the EoL product [6,14,15]. Remanufacturing is not only effective in reducing natural resources and related costs by creating new conditioned products using EoL products, but it also has the advantage of being able to target price-sensitive markets together. Following this trend, the issue of the remanufacturing process has been studied in various fields, including pricing strategy, production planning, product design, etc. Jayaraman et al. [16] and Demirel et al. [17] proposed mixed integer programming models to make logistics decision such as facility, production, and stocking for remanufacturing. Kim et al. [18] developed a general framework and mathematical model for optimal supply planning for remanufacturing. The previous models mainly considered manufacturing and remanufacturing processes separately or deal with related processes, such as production plans and price strategies, separately.

However, the process of remanufacturing and manufacturing is interrelated, and buyback prices, sales prices, and production planning should be considered in an integrated manner. A study by Kwak and Kim [13] is an exception that presents the integrated production and pricing model for a line of new and remanufactured products. This paper proposed an integrated management model, ranging from pricing policies, production plans, and marketing, while simultaneously considering new and remanufactured products. Although they proposed the integrated model, they assumed the remanufactured product has the same design as the EoL and new products. Moreover, commonality effects were also excluded from this model.

Some studies have studied the optimization of design specifications for new and remanufactured products. Aydin et al. [19] proposed a new methodology to address the simultaneous consideration of new and remanufactured products in product line design. Using the dynamic demand model and a multi-objective optimization model, the design specifications for the new and remanufactured products were selected and the timing of the release of the remanufactured products was decided. Kim and Moon [6] proposed a method to identify sustainable product family configuration. They proposed a platform strategy for a product family that considers both remanufacturing and manufacturing processes. Kwak [3] proposed a mixed integer programming model to find the optimal line design of new and remanufactured products. Although the design of new and remanufactured products was not predetermined, most studies have limitations because the cost models are limited, and multi-generations of products are not considered.

Some studies considered multiple generations of products together to apply a realistic remanufacturing process. Zhou et al. [2] developed a pricing model for short life cycle products with generation consideration. They considered the coexisting condition of a new product with the old generation and remanufactured product with the latest generation. Wang et al. [20] proposed a methodology to investigate how product diffusion dynamics in the market affect the volume of component reuse in multiple-generation product remanufacturing. Through this methodology, the expected total volume of component reuse was analyzed according to the time delay of remanufacturing. These studies, however, performed separate analyses of prices or reuse rates, which have limitations in that prices and production plans were not presented from an integrated perspective.

An important factor for the success of remanufacturing is the consumer's preferences and responses for remanufactured products. Consumers have a variety of preferences and responses for remanufactured and new products, making it difficult to make decisions [21,22]. Consumer preference for remanufactured products has been studied with consumers' willingness to pay [21,23–26], which is defined as the maximum amount consumers can pay for a remanufactured product. These studies showed that consumers are less willing to pay for remanufactured products than new ones due to the perception of remanufacturing. Although a remanufactured product has the same appearance and performance as a new product, some customers do not prefer the remanufactured product because it comes from EoL products or returned products. Abbey et al. [27] verified the existence of distinct customer segments with different preferences for new and remanufactured products through a regression model. However, previous studies have been studied in such a way as to study the patterns of customers' behavior through interviews or surveys, or to determine the price of a product or the quality of collected products through investigated behavioral patterns. Research on the impact of customer perception of the generational commonality design of products is insufficient.

2.2 The Effects of Component Commonality. The commonality of components using the same version of components in different products has been considered as a way of meeting the needs of various market segments while generating profitability through economic scale and scope in the production process. Traditionally, previous researches on commonality within a product family have been considered in the design and manufacturing stages. Most of the studies focused on what the trade-offs of commonality have [28–31]. Some researchers developed sustainable modularization algorithms based on considered sustainability factors to facilitate sharing components [32,33]. Commonality can provide benefits of reducing related material or manufacturing costs while satisfying various market segments. However, it may impede product diversity because it can limit the performance of products.

The commonality between products also has a significant impact on the remanufacturing process. It can enhance the reuse rate of EoL and EoU product family because it can provide the interchangeability between product variants. According to Kwak and Kim [10], they investigated the impact of component sharing on EoL product recovery strategies. In this study, the high sharing case generated the highest recovery profit and return on investment of materials that can be achieved. However, the effects of commonality were considered only in the EoL phase, and the effects associated with manufacturing were not analyzed. Wang et al. [7] investigated the impact of the commonality of products on cost reduction in remanufacturing, considering uncertainties of a collection process. However, they considered only the cost saving in the remanufacturing process. There are limitations to the analysis of changes in revenue and demand.

The trade-offs of commonality between manufacturing and remanufacturing are much more complex and more difficult than the relationship in manufacturing or remanufacturing. Decisions about the commonality of components that ignore remanufacturing may negatively affect the entire profitability of the company [34]. Therefore, decisions of commonality should be made by considering both manufacturing and remanufacturing. Several studies considered both manufacturing and remanufacturing simultaneously for commonality analysis. Subramanian et al. [34] analyzed how OEM's commonality decisions, which involve manufacturing and remanufacturing, affect the profitability of the company. Although they showed that the commonality decision of remanufacturing can be an obstacle to pursuing the overall profits, they did not consider the detailed remanufacturing process such as a collection of EoL products.

However, most of the previous papers were analyzed with a focus on manufacturing or remanufacturing. There is a limit that even if the focus is on remanufacturing, the detailed process for remanufacturing is not considered. Considering that commonality can affect both manufacturing and remanufacturing, this paper addresses the effect of generational commonality in the overall process of new and remanufactured products.

3 Mathematical Model

3.1 Problem Statement. This paper aims to investigate the effects of generational commonality on the entire production process of new and remanufactured products with a short life cycle. To achieve this goal, this study proposes an expanded model of an optimization model for production planning and pricing strategy presented in the previous paper [13]. Since this study deals with the characteristics of short life cycle products, the model is expanded to indicate that different generations could be collected for the remanufacturing, unlike previous models that collected the same design and used in the remanufacturing.

The model is intended for OEMs that plan to produce new and remanufactured products with a short life cycle at the same time. The proposed model is based on the following assumptions. There are several generations of products in the market simultaneously because OEMs have been quickly releasing new generation products to satisfy customers. As a recovery strategy for EoL products, it is assumed that OEMs plan to remanufacture and recycle. Although OEM use remanufacturing as their main recovery strategy, it is assumed that parts that cannot be reused due to quality problems or that remain in the remanufacturing are simply recycled as materials. Since remanufacturing is considered in this paper, it is assumed that the remanufactured product has the same quality and performance as the new product. However, the remanufactured product is cheaper than the new product due to customers who perceive them to be made from used products, even if it has the same appearance and performance as new products.

The remanufacturing consists of the collection of EoL products, disassembly, reconditioning, and reassembly and assumes that new parts can be obtained from the outside if necessary. In the process of collecting EoL products, OEMs may collect a wide range of EoL products from the latest released generations to the previously released generations. It is assumed that previous generations have more available EoL products in the market than newer ones, because of the passage of time. However, at the same time, it is assumed that more of the previous generation's EoL products are of poor quality due to component deterioration. On the other hand, for the new generation of EoL products, the EoL products are in relatively good condition, but the available quantities in the market are small.

It is assumed that the components that make up the generation products are the same (e.g., for smartphones, camera, and memory) but that the component instances (e.g., memory size 32GB, and 64GB) and product designs can vary from generation to generation. Reusable components, regardless of the generation, are assumed to be possible only when the same components are used by different generations. The commonality between generations affects the number of parts that can be used regardless of generation in the remanufacturing process. This study considers only component levels for simplicity but can also be applied to modular product designs with subassemblies. When applying

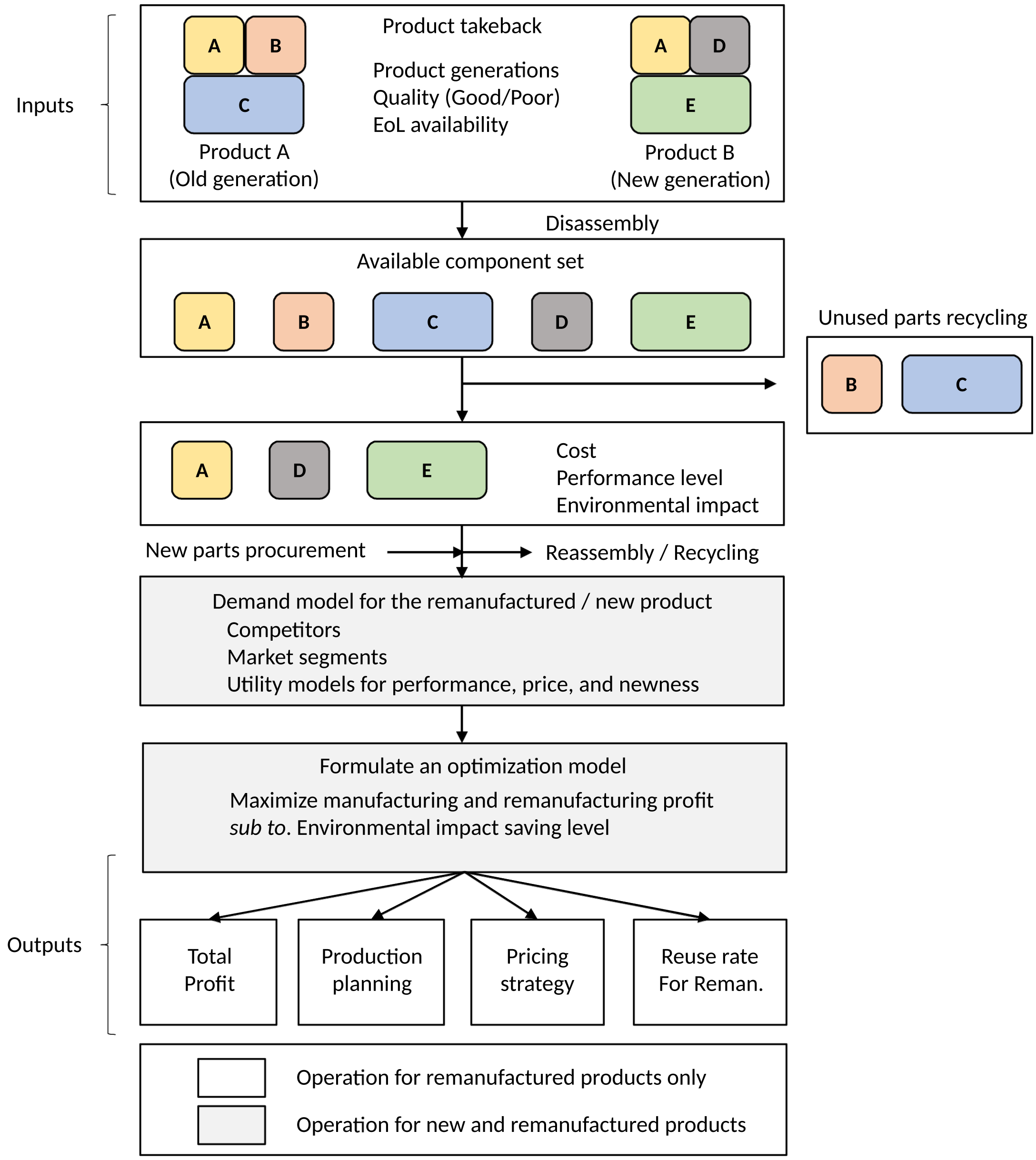

Fig. 1 The proposed methodology and production process under consideration

modular designs of the products, it is assumed that the modules used in each product are predetermined. The optimal modular design of individual products is beyond the scope of this study.

Figure 1 shows the proposed methodology, which mainly involves an expanded transition matrix for the collection process of EoL products, a demand model, and a formulation of the optimization problem. The price and production process of new products can be determined through the optimization model after demand analysis. The remanufacturing process requires additional processes such as buyback, disassembly, reconditioning, and reassembly. Buyback is a stage in the collection of EoL products from customers. At this stage, different generations of products with different qualities can be collected.

For example, in Fig. 1, product A is an old generation and product B is a new generation. Each generation of products may have differences in the available EoL quantity and quality status depending on the time of release and difference of performance. In the process of disassembling the collected product into parts (modules and/or components), an available component set can be obtained for use in the remanufacturing. If the parts for a remanufactured product and the collected parts are identical such as A, D, and E parts in Fig. 1, the parts can be used in the remanufacturing process regardless of the generation. Otherwise, other parts are recycled because they are not used in the remanufacturing (i.e., B and C parts).

Market demand in this model is derived through utility function and multinomial logit (MNL) model. By solving this problem, the results of optimal buyback planning, production planning, reuse rate, and selling prices that maximize total profit can be obtained while satisfying target environmental impact saving. By comparing and analyzing these optimal results according to different commonality levels, the effects of generational commonality can be identified.

3.2 Expanded Transition Matrix for Multi-generation of End-of-Life Products.

Transition matrix has been used to represent the remanufacturing process such as disassembly, reconditioning, reassembly, and procurement in previous studies [13,35,36]. The transition matrix has the advantage of being able to represent the remanufacturing process with a simple matrix form. This study expands the transition matrix to represent multi-generation

			Disassembly				Reconditioning			Reassembly
	Operation		1	2	3	4	5	6	7	8
Remanufactured product (2nd generation)	1	Product (ADE) (R)								1
EoL products (1st generation with k condition)	2	Product (ABC) (k = 1)	-1							
	3	Product (ABC) (k = 2)		-1						
EoL products (2nd generation with k condition)	4	Product (ADE) (k = 1)			-1					
	5	Product (ADE) (k = 2)				-1				
Available component set (W, N, R)	6	Component A (R)					1			-1
	7	Component D (R)						1		-1
	8	Component E (R)							1	-1
	9	Component A (W)	1	0.6	1	0.6	-1			
	10	Component B (W)	1	0.7						
	11	Component C (W)	1	0.3						
	12	Component D (W)			1	0.8		-1		
	13	Component E (W)			1	0.4			-1	
	14	Component A (N)		0.4		0.4				
	15	Component B (N)		0.3						
	16	Component C (N)		0.7						
	17	Component D (N)				0.4				
	18	Component E (N)				0.9				

Fig. 2 Expanded transition matrix for multi-generation EoL Products (derived from Kim and Kim [37])

of EoL products with the advantage of using design configuration and component reliability/reusability, which varies from generation to generation, in a single matrix form.

Figure 2 represents a conceptual expanded transition matrix used in this study. There are two generations of products; a previous generation ABC and a new generation ADE. The rows in the matrix represent the products, parts, and the status of them, and the columns represent the remanufacturing process. The symbol in parentheses next to the product and part indicates the current state of the product and part. The symbol of R symbolizes the remanufactured product or reconditioned components. The symbols of W and N refer to working components and non-working components, respectively.

Basically, the transition matrix is a method of expressing input and output flow within a process. Each cell (i, j) takes one of the values -1, 0, or 1. The value of -1 indicates that the product or part corresponding to i has entered the process corresponding to j. The value of 1 is used if the product or part corresponding to i is produced through the process corresponding to j. The value of 0 indicates that there is no relation between row i and column j.

The available number of parts that can be used for remanufacturing depends on the quality state of the product. Generally, a product in good condition has many parts that can be reused for remanufacturing, while a product in poor condition has fewer parts that can be reused for remanufacturing. In this study, it is assumed that the quality status of the EoL product is in good condition ($k=1$) or poor condition ($k=2$).

For good condition products, it is assumed that all components that make up the product are in operation (i.e., working condition (W)) and can be reused through a simple cleaning/reconditioning process. Each entry of good condition products takes a value of -1, 0, or 1 as in the traditional matrix expression. On the other hand, for poor condition products, not all components may be reusable in remanufacturing. To reflect this, the disassembly yield rates of components are used. Product failures are usually caused by faulty components, depending on the characteristics of the components or how the product is used. The defective components cannot be reused during remanufacturing because they are either not reusable at all or are rather costly to recover. Therefore, the value of each entry in the transition matrix for components of poor condition product is set to be less than or equal to 1.

For example, if the good condition ABC enters the remanufacturing process, components A, B, and C can all be reused without any loss (Column 1). In contrast, for poor condition ABC, each entry has a value of less than 1 as shown in column 2. Each value represents a probability of being disassembled and reused in remanufacturing, in which case part A is reusable with a 60% probability, part B is 70%, and part C is reusable with a 30% probability. The yield rates of good and poor conditions can be estimated from product failure reports. These assumptions follow assumptions from previous studies [10,13].

Moreover, it is assumed that different yield rates are present depending on the generation of products. For example, the product of ADE has a relatively high yield rate because it is a newer generation than the product of ABC. In other words, the yield rate of the product ABC is relatively lower than the product of ADE due to the aging of parts over time.

In this study, the remanufacturing process consists of disassembly, reconditioning, and reassembly, as can be seen in the columns of the matrix. During disassembly, EoL products of different generations and quality are broken down into parts (Column 1–4). The parts to be used for the remanufacturing are reconditioned through a reconditioning process (Column 5–7). Finally, the remanufactured product is produced by assembling reconditioned parts (Column 8). In order to balance the inputs entering the transition matrix with the outputs being produced, Eq. (1) is required as a constraint.

$$Input_j + \sum_{l \in L} T_{jl} \cdot Y_l = Output_j \tag{1}$$

3.3 The Model for Optimization. This study performs optimizations for product designs with different levels of commonality to compare the commonality effects across generations. The model of the previous study [13] is expanded and utilized to identify the effects of commonality on manufacturing and remanufacturing simultaneously based on the transition matrix. Equation (2) represents the optimization problem with the objective function to maximize the profits of the manufacturing and remanufacturing while meeting the target criteria for environmental impact saving (δ).

The total profits are divided into the profits from producing new products and the profits from producing remanufactured products. The cost factor of the manufacturing for the new products, C_i^n, includes all costs associated with the procurement of new parts, assembly, marketing, and distribution. However, the total cost of remanufacturing presents as separate cost factors, because the detailed cost factors are more complex than the manufacturing process: the cost of recycling, buyback, operation, procurement, marketing, and distribution.

$$
\begin{aligned}
&\underset{X,\,Y,\,Z,\,M,\,N,\,P}{\text{maximize}} \quad \sum_{i\in I}(P_i^n - C_i^n)Z_i^n + \sum_{i\in I} P_i^r Z_i^r \\
&\quad - \left(\sum_{j\in J} C_j^M M_j + \sum_{i\in I}\sum_{k\in K} P_i^k X_i^k + \sum_{l\in L} c_l Y_l + \sum_{j\in J} c_j^N N_j + \sum_{i\in I} c_d Z_i^r\right) \\
&\text{subject to} \quad g1{:}X_i^k \le A_i^k \cdot S_i^k\ (P_i^k) \\
&g2{:}Z_i^n \le \sum_{o\in O} Q_o \cdot d_{o,n,i}\ (P_i^n,\ P_i^r,\ perf,\ \beta_o) \\
&g3{:}Z_i^r \le \sum_{o\in O} Q_o \cdot d_{o,r,i}\ (P_i^n,\ P_i^r,\ perf,\ \beta_o) \\
&g4{:}\sum_{i\in I} Z_i^r \le \sum_{i\in I}\sum_{k\in K} X_i^k \\
&g5{:}\sum_{i\in I}\sum_{k\in K}(e_w - e_k)\cdot X_i^k \\
&\quad + \left(\sum_{i\in I} E_n \cdot Z_i^r - \left(\sum_{j\in J} e_j^M \cdot M_j + \sum_{l\in L} e_l \cdot Y_l + \sum_{j\in J} e_j^N \cdot N_j + \sum_{i\in I} e_d \cdot Z_i^r\right)\right) \le \delta \\
&h1{:}X_i^k + \sum_{l\in L} T_{jl}\cdot Y_l - M_j = 0\ \forall j \text{ corresponding to the EoL product } i \text{ with } k \text{ quality} \\
&h2{:}N_j + \sum_{l\in L} T_{jl}\cdot Y_l - M_j = 0\ \forall j \text{ corresponding to a part with external purchase availability} \\
&h3{:}\sum_{l\in L} T_{jl}\cdot Y_l - M_j = 0\ \forall j\ \text{ corresponding to a part without external purchase availability} \\
&h4{:}\sum_{l\in L} T_{jl}\cdot Y_l - Z_i^r = 0\,\forall j \text{ corresponding to the remanufactured product} \\
&h5{:}N_j = 0\ \forall j \notin\ \text{ part with external purchase availability} \\
&h6{:}M_j = 0\ \forall j \text{ corresponding to the remanufactured product} \\
&X_i^k,\ Y_j,\ Z_i^n,\ Z_i^r,\ M_j,\ N_j,\ P_i^n,\ P_i^r,\ P_i^k \ge 0\ (\forall i\in I,\ \forall j\in J,\ \forall k\in K,\ \forall l\in L)
\end{aligned}
\tag{2}
$$

The constraints $g1$ through $g5$ represent inequality constraints. The constraint $g1$ represents that the number of buyback products that can be collected from customers is determined by the availability of EoL products and buyback price. The constraints $g2$ and $g3$ represent the production quantities of the new products and the remanufactured products. It is assumed that the production quantities of new and remanufactured products cannot exceed the demand in the market. The constraint $g4$ indicates the production quantity of remanufactured products cannot exceed the total number of EoL products collected from customers. The constraint $g5$ represents the goal of environmental impact saving that OEMs need to achieve. The environmental impact saving may occur when the environmental impact of reusing components from EoL products is less than the environmental impact of producing the same products using the new equivalent components. The left-hand side represents the environmental impact saving from two sources. The first term means saved environmental impact by using EoL products that are intended to be discarded, and the second term indicates the difference between the environmental impact of making the new products in the same amount as the remanufactured products and the environmental impact of remanufacturing. The right-hand side represents the target value of environmental impact saving that is often set by the regulators (δ).

The constraints $h1$ through $h6$ represent the equality constraints related to input-output material flow balance in the expanded transition matrix (Eq. (1)). The constraint $h1$ indicates that the collected EoL products may be used for material recycling or remanufacturing depending on the state of the EoL products and the design configuration of the remanufactured product. For a component that can be procured from an external market, the constraint $h2$ represents that the part can be discarded or used for remanufacturing, and that part can be procured from outside if necessary. Otherwise, in the case of a part that cannot be procured from the external market, the $h3$ constraint indicates that it is only available for recycling or for remanufacturing. The constraint $h4$ defines that the remanufactured products should be produced as much as Z_i^r through the remanufacturing. The constraint $h5$ excludes the external procurement if it cannot be procured from the external market. The constraint $h6$ is used to control the unrealistic situation of producing remanufactured products and then using them for recycling. The last constraint assumes the non-negativity of all decision variables.

4 Case Illustration and Discussion

4.1 Case Study: Smartphones. Smartphones are resource-intensive products with a short life cycle. The technology of smartphones is rapidly evolving, and a new generation of products is coming out fast to capture market demands. Many customers are fascinated by the new features and performance and abandon their existing products to buy new ones. Unfortunately, most of the products are thrown away without recovering them even though they still have residual value. This take-make-waste flow model is causing severe environmental problems such as e-waste and waste of natural resources. According to a Greenpeace report [38], the number of waste electronics was estimated to be around 65.4 million metric tons, enough to bury the entire 14-feet-deep San Francisco every year. But despite the huge amount, only 15.5 percent were estimated to be recycled. Given the growing number of people using smartphones, researches are needed on how to reuse EoL or EoU smartphones in terms of economic and environmental benefits.

4.2 Problem Description and Basic Assumptions. In the scenario, OEMs have so far produced only new products but have a plan to produce new and remanufactured products of a new generation to cope with enhanced environmental regulations and various customers. To produce a remanufactured product, it is necessary to collect the EoL products. In this process, OEMs can capture a wide range of products, from defective or returned products that can occur in the manufacturing of new generation products to EoL products that were previously sold. The EoL products of the previous generation may be easier to obtain than those of the new generation. However, there is a high probability of having a relatively poor condition, and there may be no parts available to produce. For the new generation of products, the condition of the parts is relatively good and the probability of being utilized is high. However, it is not easy to obtain enough quantities of the EoL products needed for remanufacturing.

To address these difficulties, OEMs focus on generational commonality. If the previous generation and the new generation of products are designed to share some modules (or components), the modules separated from the previous generation could be used for the new generation remanufactured product. It can increase the reusability of EoL products of the previous generation and reduce related remanufacturing costs. However, it has a risk of weakening performance differentiation from the previous generation. It leads to a reduction in the appeal of new generation products to their customers. Given this trade-off of generational commonality, OEMs would like to explore the impact of the level of generational commonality on the manufacturing and remanufacturing processes. To answer this question, this study analyzes this issue based on the quantitative approach. This study identifies how different price strategies, production plans, profits, and recovery costs are based on a new generation of designs with different degrees of generational commonality design. The optimal results of the following scenarios are compared:

(1) Baseline scenario (no commonality case): In this scenario, there is no shared part between the generations. Therefore, the EoL products of the old generation cannot be used for remanufacturing of the new generation.
(2) Sharing cases (different commonality cases): There are scenarios in which a certain portion of parts is shared between the generations. OEMs can use parts from EoL products of the old generation for new generation remanufacturing. The available number of parts may vary depending on the degree of commonality between generations.

In this case study, the smartphone is assumed to consist of eight modules based on the online smartphone analysis site (teardown.com), and the price of each module is based on the estimation data provided by the site. It is assumed that modules that make up the product of generations are the same, but the module instance can be different with respect to generations; each module maybe not upgraded or upgraded when developing a new generation of products. If a module becomes an upgrade, a different module instance is generated, which may cause a difference in performance between generations. It is assumed that intergenerational compatibility is difficult for different module instances. Therefore, the generational commonality defined here is based on the assumption that the same module instance is used between generations.

Since this study assumes that the modules and price of modules for the previous generation of the product are predetermined, the estimated data are set to the module price of the previous generation product. When developing the new generation of products, it is necessary to decide whether to upgrade each module. According to Han et al. [39], a high-quality level of product usually leads to high production costs and vice versa. In this study, the upgrade of a module follows the general wisdom that it is costly to develop and produce the module. On the other hand, if a module is not developed and modules of the previous generation are used, the cost associated with the module can be discounted because it is an old technology rather than a new technology (i.e., technological obsolescence). Therefore, it is assumed that when using a new module, it increases by 20% from the price of the existing module, and when using a module of the previous generation, it decreases by 20% from the price of the existing module.

The other detailed parameters are assumed based on the researches of Kwak and Kim [10,13], because these studies also use smartphones as an example, as can be seen in Tables 5 and 6. Table 5 shows the parameter setting for cost and impact parameters regarding part procurement and material recovery. For the environmental impact parameters, greenhouse gas emissions are considered, which is measured by carbon emissions to the air in the unit of metric tons of carbon dioxide equivalent (kg CO_2 equivalent). Table 6 represents the expanded transition matrix of this case study. The rows represent each product, module, and status of them, and the columns represent the operations required for remanufacturing. In addition, the unit cost of remanufacturing operations and environmental impacts are provided in Table 6. The study assumes that the product can be broken down directly into individual modules for ease of expression. However, it may have a structural form in which individual modules of the product are combined to form another module. If necessary, it may even include the structural form of the product.

4.3 Assumptions on the Supply of End-of-Life Products. EoL products used in remanufacturing include a variety of products from different generations and qualities. In particular, for products with short life cycles, this uncertainty in the collection process is high because of the diversity of generations that coexist in the market. It is assumed that the EoL products of the previous generation may be easier to obtain than those of the new generation. However, there is a high probability of having a relatively poor condition, and there may be no parts available to produce the remanufactured product. As can be seen in Table 1, the availability of EoL products in the market has more products from the previous generation than from the new generation, but EoL products from the previous generation have more products in poor condition. For EoL products of the new generation, there is less availability in the market, but there are relatively many of them in good condition.

A return response function is used to determine the number of EoL products in the market to be collected for remanufacturing. This function is used to define the relationship between the return rate of EoL products (S_i^k) and the buyback price (P_i^k) in previous studies [,13,40], assuming a linear relationship between them. It assumes that the return rates of EoL products increase linearly below a certain level of critical buyback price ($\bar{P}_i^k$). In the critical buyback price, the return rate remains constant at maximum, even if the buyback price increases further. The critical prices are set differently depending on the generation and quality of products. As can be seen in Table 2, the critical price assumes that the new generation of products is set higher than the previous one and that the products are in good condition ($k=1$) are higher than those in poor condition ($k=2$). Equation (3) shows the return response function. Based on this, the optimum buyback price that OEMs need to pay to collect the optimum buyback quantities for remanufacturing can be obtained.

$$S_i^k(P_i^k) = \begin{cases} P_i^k/\bar{P}_i^k, & \text{if } 0 \le P_i^k < \bar{P}_i^k \\ 1, & \text{if } P_i^k \ge \bar{P}_i^k \end{cases} \tag{3}$$

Table 1 Parameters for EoL products

Product	Quality	Critical price ($\bar{P}_i^k$)	Availability
Product 1 (Gen 1)	Good ($k=1$)	\$80	2000
	Poor ($k=2$)	\$30	4000
Product 2 (Gen 2)	Good ($k=1$)	\$120	1500
	Poor ($k=2$)	\$80	500

Table 2 Targeted market segments

	Size	Critical price	Utility discount factor (β_o)
Segment 1	5000 units	\$1000	0.3
Segment 2	5000 units	\$800	0.5
Segment 3	5000 units	\$600	0.7

Table 3 Competing products in the target market

	Performance	Price	Newness
Competitor 1	0.8	\$800	New
Competitor 2	0.5	\$500	New
Competitor 3	0.8	\$400	Remanufactured

4.4 Assumptions on Demand Model. Detailed information of customers in the target market and competitors is predetermined. Tables 2 and 3 indicate the parameter settings required for the demand model. Table 2 represents the assumptions of customers in the target market. The market is divided into three market segments according to different characteristics of the customer. Segment 1 is a group of performance-sensitive customers who value the performance of products, are relatively less price-sensitive, and have a negative perception of the remanufactured product. Segment 3 is a group of price-sensitive customers who are relatively performance insensitive and have a positive perception of the remanufactured product than others. Segment 2 is a group of customers in the middle of segment 1 and segment 3. They value a new product more than the customers in segment 3 do, but desire a reasonable price more than those in segment 1 do. Each market segment size is 5000.

Table 3 shows the information of competitors in the market. It is assumed three competitors exist in the market. Competitor 1 produces new high-spec smartphones that are expensive. Competitor 2 produces new low-spec smartphones at low prices. Competitor 3 produces remanufactured high-spec smartphones but sells them at relatively low prices due to customers' perception of remanufactured products.

This model assumes that the market share is determined by the customers' utility of performance, selling price, and newness (i.e., a tendency to prefer new products to remanufactured due to customers' perception) of the product. The utilities for performance, selling price, and newness are calculated as follows. Under the common wisdom that high levels of performance form a higher cost, the newly upgraded module assumes that the unit cost is more expensive but provides higher performance than the old module [39]. Therefore, the upgraded performance level of the new generation can be calculated as a percentage of how much the price of modules has increased compared to the previous generation. Equation (4) shows how the new generation performance level is obtained based on the value of each module and the performance of the previous generation ($perf_{old}$). The pi_{new}, pi_{old} represent the module i's money value of new and old generations, respectively. It is assumed that the sum of the performance of the module represents the performance of the product.

$$perf_{new} = \sum_{k=1}^{N} \left(\frac{p_{i,new}}{\sum_{k=1}^{N} p_{i,old}} \right) \times perf_{old} \tag{4}$$

The utility for the selling price is determined based on the customer segment by the critical price ($\bar{P}_o$) and sales price. The utility function of the selling price assumes that customers in that market segment will not purchase the product if the price of the product is set above the critical price ($\bar{P}_o$) of the market segment. The utility of newness refers to the discount factors (β_o) in the customers' perception that depends on whether the part of the product comes from a new component or a used component. For new products, the value of 1 is applied and no discount is given. However, for remanufactured products, different discount factors are applied depending on the customer segments.

$$u_{product_{s,o}} = u_{s,perf,o} \times u_{s,price,o} \times u_{s,new,o}$$

where

$$u_{s,perf,o} = \begin{cases} \exp(perf_s)^2, & \text{for the market segment 1} \\ \exp(perf_s), & \text{for the market segment 2} \\ \sqrt{\exp(perf_s)}, & \text{for the market segment 3} \end{cases}$$

$$u_{s,price,o} = \max\left(0,\, 1 - \frac{P_s}{\bar{P}_o}\right)$$

$$u_{s,new,o} = \begin{cases} 1, & \text{if choice } s \text{ is a new product} \\ \beta_o, & \text{else choice } s \text{ is a remanufactured product} \end{cases}$$

$$d_{o,n,i}(P_i^n, P_i^r, perf, \beta_o) = \frac{u_{o,n,i}}{\sum_{s\in S} u_{s,o}}, \quad d_{o,r}(P_i^n, P_i^r, perf, \beta_o) = \frac{u_{o,r,i}}{\sum_{s\in S} u_{s,o}} \tag{5}$$

Based on the information, the customer's utility for the product is calculated as in Eq. (5), where S is the indices for the choice set ($s \in S$). The choice set (S) includes new products and remanufactured products of OEM, and competitors' products. $u_{s,perf,o}$, $u_{s,price,o}$, $u_{s,new,o}$ is the utility of product s in market segment o with respect to performance, price, and newness, respectively.

Total utility for the product is calculated by multiplying the utility for performance, the utility for price, and the utility for newness. For the performance utility, different utility functions are applied depending on the sensitivity of performance in each segment. The design of a demand model is beyond the scope of the study. This study follows the framework of the demand model of the previous study [13]. However, it can be changed for other demand models desired by users.

4.5 Optimization Results and Discussion. This section shows the optimal results of applying the assumptions and scenarios described above to the model. By solving the optimization problems, decision variables such as selling prices, production quantities, and remanufacturing operations are derived for each generational commonality scenario. Through the comparison of optimal results obtained for each scenario, this study analyzes how overall profit, production planning, and pricing strategies change with intergenerational module sharing.

This problem is a non-convex optimization problem dealing with an integrated management model that includes pricing strategies, production planning, and marketing. In this research, Analytic Solver Platform "Large-Scale SQP Solver Engine" is applied to solve this problem, since this solver engine can deal with high dimensional and more difficult non-linear optimization problems [13]. This solver engine provides optimal (or near-optimal) solutions to non-convex/non-linear problems.

4.5.1 Generational Commonalty Effect on Pricing Strategy. The generational commonality affects the selling price of new and remanufactured products. Based on the optimal results, lower generational commonality cases generate higher selling prices for both new and remanufactured products. This is because low generational commonality means that using newly developed modules instead of the same modules with the older generation, which leads to performance differences between generations. The large performance gap between these generations leads to higher selling prices for new and remanufactured products.

Figure 3 shows the difference in the selling prices concerning the commonality level. The x-axis represents the commonality level, which is calculated as the ratio of the number of shared modules

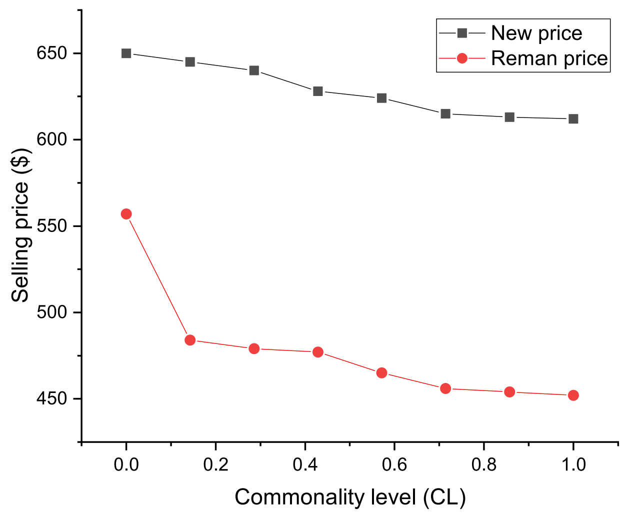

Fig. 3 Differences in the selling price according to the commonality level

to the entire modules for ease of expression. The *y*-axis represents the selling price of new and remanufactured products. As can be seen in Fig. 3, the results show that the selling price increases as the level of commonality decreases. From these results, this study shows that the performance of the new generation of products can vary depending on the generational commonality, and the difference between these performance affects the selling price for new and remanufactured products.

4.5.2 Generational Commonality Effect on Revenue, Cost, and Profit in Manufacturing Process. Although the results are optimized for both manufacturing and remanufacturing, the results of manufacturing and remanufacturing are presented separately to identify the effects of commonality in each production process. This section indicates that the generational commonality in manufacturing to produce the new products affects the revenue, cost, and profit.

Figure 4(*a*) shows the differences in the revenue, cost, and profit in manufacturing. In terms of revenue for new products, no/lower generational commonality cases generate more revenue. This is because performance upgrades not only result in high selling prices (Fig. 3) but also a high demand for new products. Figure 4(*b*) represents the change in demand for new products according to the level of commonality. These results show that for new products, demand decreases as the degree of commonality increases, vice versa.

In terms of cost, no/lower sharing cases incur more costs because they use more expensive modules. The no/lower sharing cases mean that all/most modules use newly developed modules, not previously developed ones. According to the assumption, newly developed modules have a higher unit cost. Therefore, no/lower commonality levels incur more costs in developing and producing new products, as can be seen in Fig. 4(*a*).

In terms of profit, no/lower sharing cases generate more profits compared to high commonality cases. This is because no/lower level of commonality costs high, but the revenues from it are greater. The results show that the smaller the degree of commonality, the greater the profit of the new product. The optimal results from the manufacturing process illustrate the trade-offs of general commonality. High commonality can reduce associated costs, but at the same time, it can reduce performance differences (i.e., similar performance between new and old generations), affecting demand and the selling price.

4.5.3 Generational Commonality Effect on Revenue, Cost, and Profit in Remanufacturing Process. This section shows that the generational commonality in remanufacturing to produce the remanufactured products affects the revenue, cost, and profit. Figure 5(*a*) represents the differences in the revenue, cost, and profit in remanufacturing. On the revenue side, lower commonality cases generate more revenue, except where there is no commonality case. The lower commonality cases increase the utilization of newly developed modules, which in turn leads to the higher selling price of both remanufactured products and new products.

Figure 5(*b*) represents the change in demand for remanufactured products according to the level of commonality. An interesting result is that there has been no significant change in demand due to changes in the commonality level, except in cases where there is no commonality (i.e., CL = 0). This is because of the reduction in performance and the decrease in price occurs simultaneously. A decrease in performance levels reduces demand for performance-sensitive customer segments, but a corresponding drop in prices is a factor in increasing demand for price-sensitive customer segments. Compared to changes in demand for new products that are highly

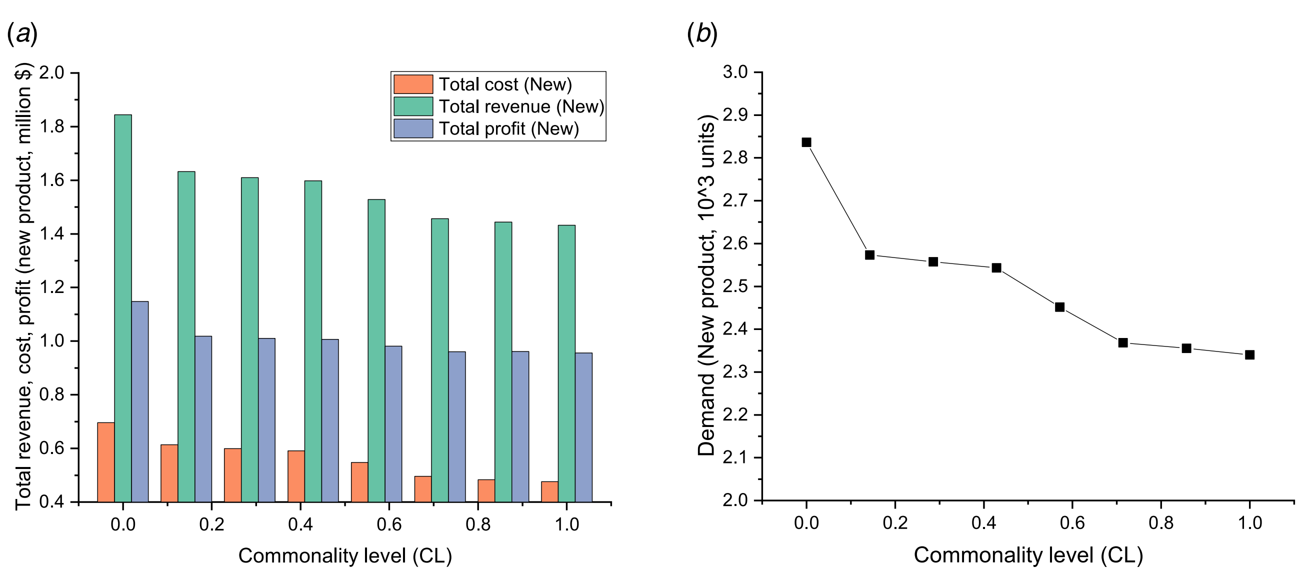

Fig. 4 (*a*) Differences in the revenue, cost, and profit according to the commonality level (manufacturing) and (*b*) differences in demand of new products

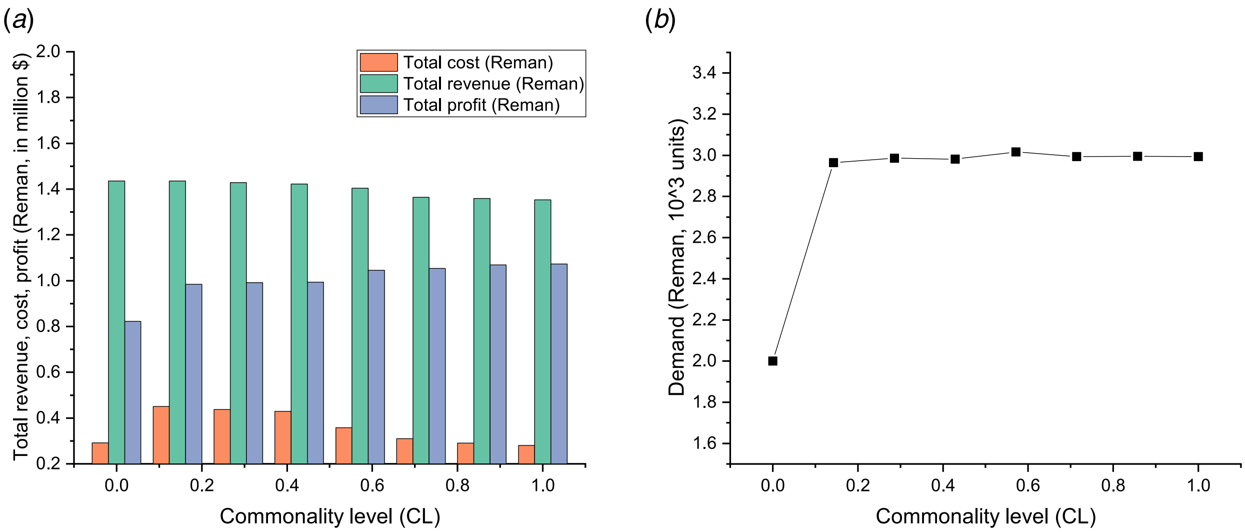

Fig. 5 (*a*) Differences in the revenue, cost, and profit according to the commonality level (remanufacturing) and (*b*) differences in demand of remanufactured products

performance-impacted, the demand for remanufactured products is shown to be heavily influenced by prices as well.

In terms of cost, higher commonality cases generate lower costs. In the process of remanufacturing, there are additional costs, unlike the manufacturing process. The study considers the costs of the buyback, procurement, recycling, and marketing as recovery costs. These cost factors related to the efficiency of the remanufacturing process, such as the utilization rates of EoL products and modules. An analysis of detailed costs will be presented in the next subsection, but a high level of sharing lowers the costs of the remanufacturing process by increasing the utilization rate of products and modules from the previous generation.

In terms of profit, remanufacturing profit is the highest in the high commonality case. This is because the high commonality case is less profitable, but less costly to remanufacture. Figure 5(*a*) shows that the higher the degree of commonality, the greater the profit of the remanufactured product.

However, the resulting value for the remanufacturing process has a different exception from the other optimal results flow. That is a case of no commonality between generations (i.e., CL = 0). Since there are no modules shared between generations, only the new generation of EoL products can be used for remanufacturing. In other words, the previous generation of EoL products that do not have the same parts as the remanufactured products mean that they cannot be used in the remanufacturing process. Therefore, the collected EoL products of the new generation can limit the number of remanufactured products that can be made. Even though it has a high performance, OEMs do not produce as much they need because they lack the EoL products needed for remanufacturing. Therefore, there is lower revenue, cost, and profit in the no commonality case. The optimal results from the remanufacturing process are completely different from those in the manufacturing process. The most profitable commonality strategy (i.e., CL = 0) in the manufacturing process may be an obstacle in the remanufacturing process.

Table 4 summarizes the results mentioned earlier and shows how the trend of outcomes varies as the level of generational commonality increases.

Table 4 Results comparison as commonality level increases

		As CL increases
Manufacturing	New product price	Decrease
	New product demand	Decrease
	Revenue (New product)	Decrease
	Cost (New product)	Decrease
	Profit (New product)	Decrease
Remanufacturing	Reman product price	Decrease
	Reman product demand	Insignificant
	Revenue (Reman product)	Decrease
	Cost (Reman product)	Decrease
	Profit (Reman product)	Increase

4.5.4 Generational Commonality Effect on Unit Cost for Remanufacturing. Generational commonality has a significant effect on reducing related unit costs in the remanufacturing process, especially, buyback and procurement costs. Actually, there is an impact on the unit costs of recycling and marketing, but there is relatively little change compared to buyback and procurement costs. Figure 6(*a*) represents the unit buyback and procurement costs per the remanufactured product. Figure 6(*b*) shows the optimal buyback price according to generation and quality. In terms of buyback cost, lower commonality cases have a higher buyback cost, as can be seen in Fig. 6(*b*). This is because more of the new generation of EoL products need to be collected in the process of collecting for remanufacturing. The new generation of EoL products has a higher critical buyback price for customers than the previous generation. In other words, it means that OEMs have to pay higher prices to customers to collect the desired number of EoL products of the new generation. On the other hand, the higher commonality of P1 and P2, the higher the use of relatively inexpensive EoL products of the previous generation, resulting in reduced buyback cost.

In terms of procurement cost, higher commonality cases have lower procurement cost. This is because the higher the degree of commonality, the more modules can be utilized from different generations. On the other hand, a lower degree of commonality between generations would reduce the number of available modules coming from the previous generation, which would mean that those modules would have to be purchased from the external market. However, the no commonality case between generations incurs the lowest external procurement cost exceptionally, as can be seen in Fig. 6(*a*).

No commonality case uses only EoL products of the new generation for remanufacturing. This means that the modules of the EoL product and the remanufactured product are the same, so there are relatively few modules that must be acquired from the outside. In conclusion, generational commonality affects the buyback and

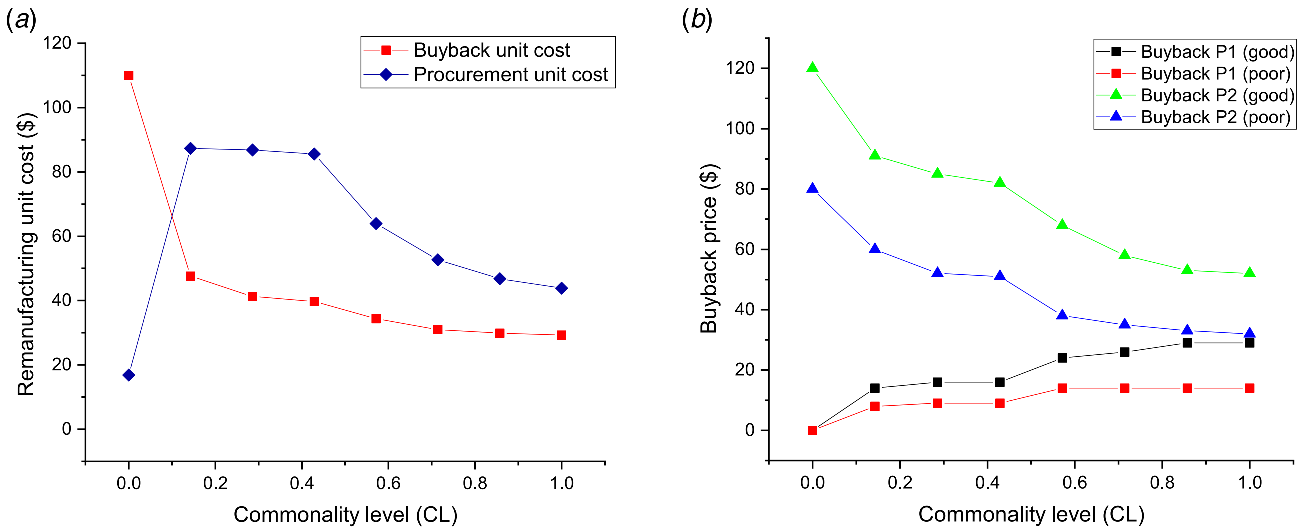

Fig. 6 (*a*) Differences in the unit costs for remanufacturing according to the commonality level and (*b*) differences in buyback prices

procurement costs that occur during the remanufacturing process. The reduction in these costs results in a reduction in the total cost of remanufacturing.

4.6 Sensitivity Analysis. This section provides sensitivity analysis results that show changes in the results according to the various settings of the parameters: (1) effect of the number of available EoL products of the new generation, (2) the effect of customer perception for the remanufactured product (i.e., discount factors, β_o), and (3) the effects of critical price of the customer (i.e., critical price, $\bar{P}_o$).

4.6.1 Effect of the Number of Available EoL Products of New Generation. Through the analysis of optimal results, the effect of generational commonality on manufacturing and remanufacturing is found. The optimal results show that the low level of commonality is advantageous for the sales of the new products, and the higher degree of commonality is advantageous for the sales of the remanufactured products. When there is no commonality among generations, the optimal results show that no commonality design is the most profitable for manufacturing. For remanufacturing, on the other hand, no commonality design limits the production quantity of the remanufactured products to the number of EoL products of the new generation that could be collected.

As a result, no commonality case has the best performance, but does not make the highest profit in remanufacturing. This indicates that the results of the remanufacturing may be limited depending on the collectability of the new generation of EoL products. In this subsection, this study identifies how the results can vary with the change in the number of EoL products of the new generation. The new generation of EOL products is analyzed by applying fewer (80% A_i, $i = new$) and more (200% A_i, $i = new$) than expected to the model.

Figure 7 shows the differences in the revenue, cost, and profit in manufacturing derived from 80 percent and 200 percent levels of available EoL products of the new generation. It shows a pattern of outcomes similar to those seen in the manufacturing process of the basic scenario, both of which produce higher profits in manufacturing due to increased selling prices and demand in the no/lower sharing cases. Costs also increase as the level of commonality decreases, due to the increased use of expensive newly developed modules. In terms of profit, no/lower sharing cases generate a higher profit in both cases.

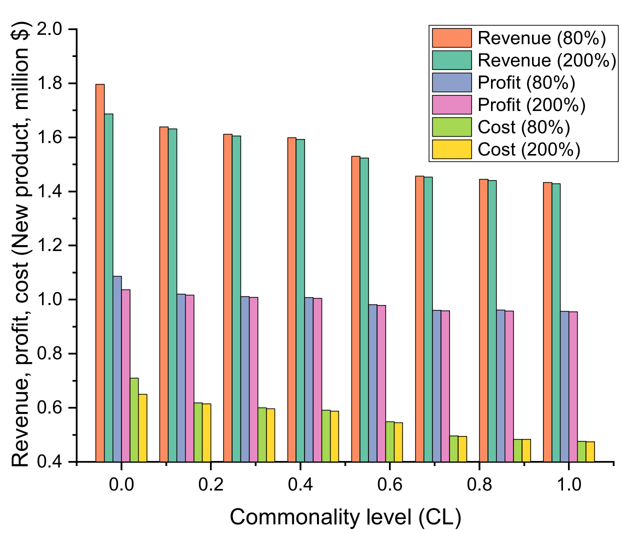

Fig. 7 Differences in the revenue, cost, and profit in manufacturing (80%, 200%)

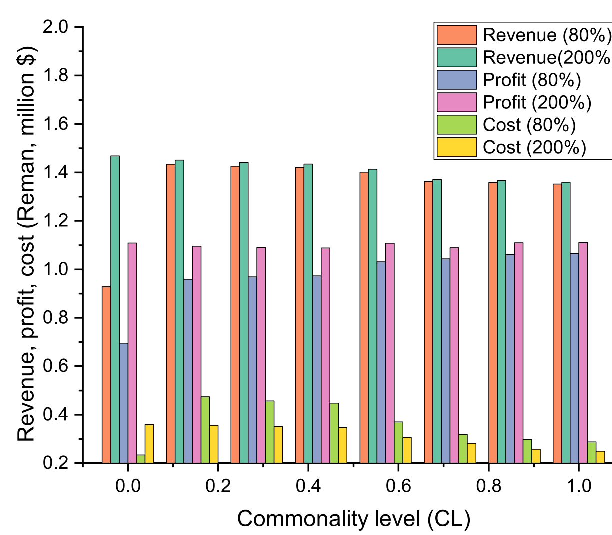

Fig. 8 Differences in the revenue, cost, and profit in remanufacturing (80%, 200%)

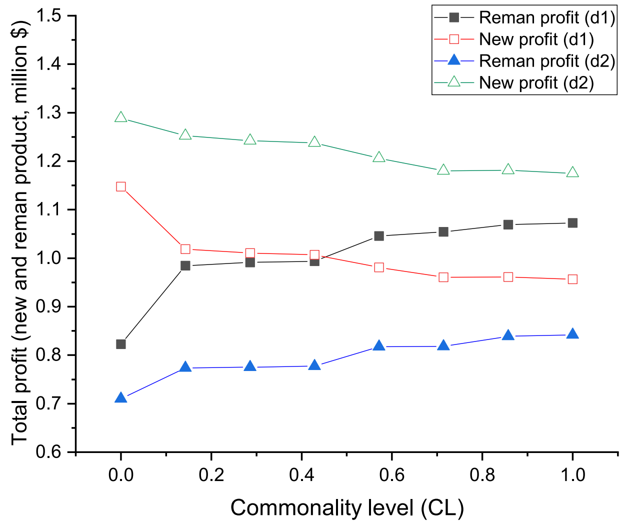

Fig. 9 Change in profit: the effect of discount factor

However, the optimal results of remanufacturing vary significantly with the availability of the new generation of EoL products. Figure 8 shows the differences in the revenue, cost, and profit in remanufacturing derived from 80 percent and 200 percent levels of available EoL products of the new generation. When available return EoL products of the new generation are less than the expected level (80%), the optimal results have a result pattern like that derived from the basic model. Lower commonality cases generate higher revenue and cost but lower profit. If there is no commonality between the two generations, the number of remanufactured products that can be produced is limited by available EOL products from the new generation. On the other hand, if new generation EoL products are enough, the availability of new generation EOL products will not limit the production of remanufactured products, allowing OEMs to generate revenue. In this case, although no/lower sharing cases generate higher revenue and cost, there are insignificant differences in profit concerning generational commonality.

Through these results, it is understandable that it is important for the overall profit to collect relevant EoL products that can be used to produce the remanufactured product. Considering the case of products in a short life cycle, the rapid generation of replacements and changes in demand do not allow enough time to collect the EoL products of that generation. On the contrary, if there is a high chance that EoL products from the previous generations will be collected, and OEMs should consider how to use them. In this case, generational commonality can be of great help to remanufacturing in terms of increasing generational interchangeability.

However, the increase in intergenerational commonality is not necessarily good. This is because the design for generational commonality affects not only remanufactured products but also new products. High commonality can reduce associated costs in the manufacturing, but at the same time, it can reduce performance differences, affecting demand and the selling price negatively. Therefore, understanding of generational commonality is necessary from the design stage. The lack of understanding regarding generational commonality in remanufacturing will present an important challenge for industries seeking to adopt a remanufacturing process.

4.6.2 The Effect of Customer Perception for the Remanufactured Product. The study assumes that the target market consists of three market segments according to customer preference (Table 2). Each market segment has a different utility discount factor and critical price. In particular, the discount factor is a measure of the customer's perception of the remanufactured product and has a significant effect on the utility of the remanufactured product. It analyzes how the results change if the customer's perception of the product is changed in a negative direction compared to the original scenario. The new parameters ($d2$) are set to decrease by 0.2 for each segment from the basic model discount factor ($d1$) (Table 2), which means a market is not a remanufacturing-friendly environment than the basic model scenario.

Figure 9 shows the optimization results comparing the original scenario($d1$) with the changed scenario ($d2$). It shows a pattern of results similar to the optimal results of the basic model. One difference is that in the new scenario, the optimal result is that the profits of the new product increase, while the profits of the remanufactured product decrease than the original results. As expected, the market segments for the new scenario have a negative perception of remanufactured products; therefore, sales of new products rather than remanufactured ones are marked. Differences in these results mean that strategies of commonality can be applied differently depending on the characteristics of the market. When targeting markets with negative perceptions of the remanufactured products, generational commonality negatively affects the performance level and technological development of the new generation, affecting the sales of new products. On the other hand, for markets with positive perceptions, the positive impact of commonality on the interchangeability and collection process of used components is greater than the

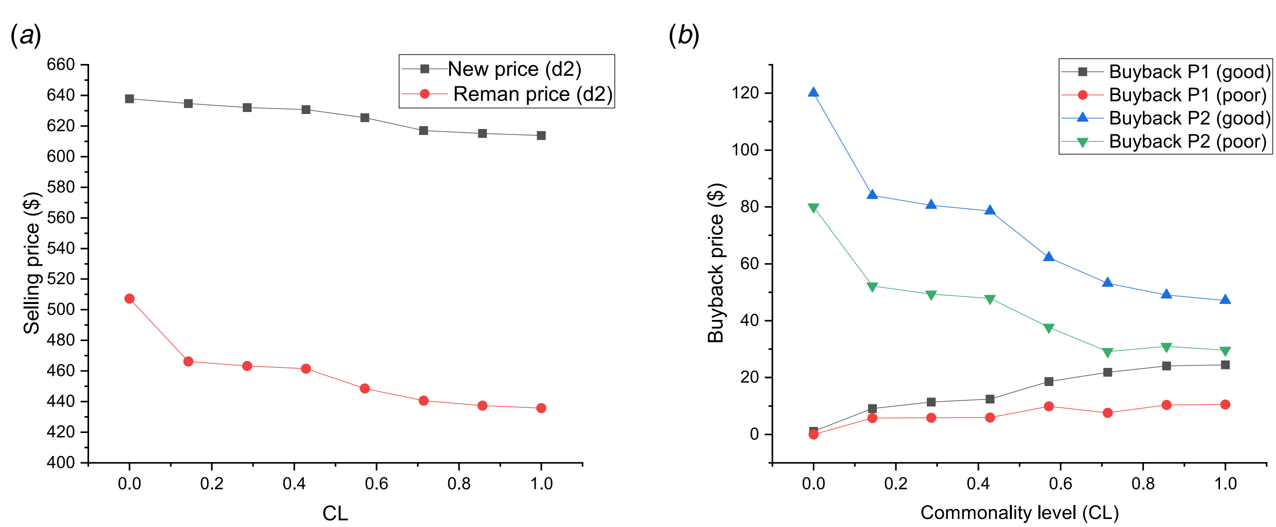

Fig. 10 (a) Differences in the selling price according to the commonality level and (b) differences in buyback prices

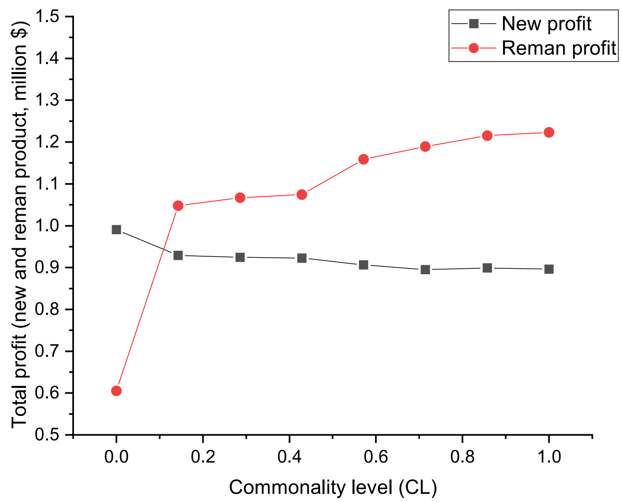

Fig. 11 Change in profit: the effect of critical price

negative impact on the sales of the new product. Figures 10(*a*) and 10(*b*) show changes in the selling prices for new and remanufactured products and buyback prices, respectively.

4.6.3 The Effect of the Critical Price of Customer. The final sensitivity analysis considers the effect of the critical price of the customer. This study assumes that each market segment has a different critical price. The critical price represents the maximum price that consumers in the segment are willing to pay for the product. This affects market sharing and product pricing in the problem. To examine the effect of the critical price, a new scenario for the critical price is setup and tested in this section. The new critical prices are set to decrease by 100 for each segment from the previous critical price (Table 2). This means that the new market segment prefers products with lower prices compared to the previous market segment.

Figure 11 shows the results of a profit analysis on manufacturing and remanufacturing according to the commonality level. As the level of commonality increased, profits for new products decrease and profits for remanufactured products increase. However, the profit growth rate of remanufactured products increases steeply. Since price-sensitive customers are attracted to low-priced remanufactured products and demand increases. Figures 12(*a*) and 12(*b*) show changes in the selling prices for new and remanufactured products and buyback prices, respectively.

5 Conclusion

It is important for OEMs who produce products with a short life cycle to quickly develop and sell innovative new products to meet the needs of their targeted market. At the same time, however, strategies on how to use the products they have sold are also important to address issues related to enhanced environmental regulations and environmental pollution. For products with short life cycles, many difficulties exist in the remanufacturing due to the rapid pace of technological obsolescence as well as the coexistence of different generations of products in the same market. To deal with these challenges, this paper addresses the issue of generational commonality, which means sharing the same modules or parts between different generations.

Sharing the same parts between generations has a significant impact on the manufacturing process and the remanufacturing process. In the manufacturing process, generational commonality reduces the cost of developing and producing a new generation of modules, but when too many modules are shared, the differentiation between products may be reduced. In the remanufacturing process, the sharing of modules between generations increases the compatibility of components between generations at the stage of collecting EoL products but also reduces the differentiation of remanufactured products from the previous generations. As such, commonality decisions should be made carefully, as it affects not only economic but also environmental benefits.

To understand the impact of generational commonality on the entire production process, including manufacturing and remanufacturing, this paper finds out through a quantitative model what changes are made to production planning, pricing strategies, and remanufacturing process, depending on different levels of commonality. The comparison of optimal results can be used as a quantitative measure to assess the impact of generational commonality on the entire life cycle of a product.

Smartphones, one of the short life cycle products, are used as a case study to explain the model and analyze the impact of its generational commonality on manufacturing and remanufacturing. This study confirms that commonality among generations has a significant impact on the manufacturing process as well as on the remanufacturing process.

First, generational commonality has a significant effect on the selling price of new and remanufactured products. The low commonality between generations means that it improves product performance of the new generation as it utilizes upgraded modules compared to previous products. This improvement in performance/quality helps to increase the selling prices of new or remanufactured products. Next, generational commonality affects the production process of new and remanufactured products. In the manufacturing, designs with lower commonality generate high

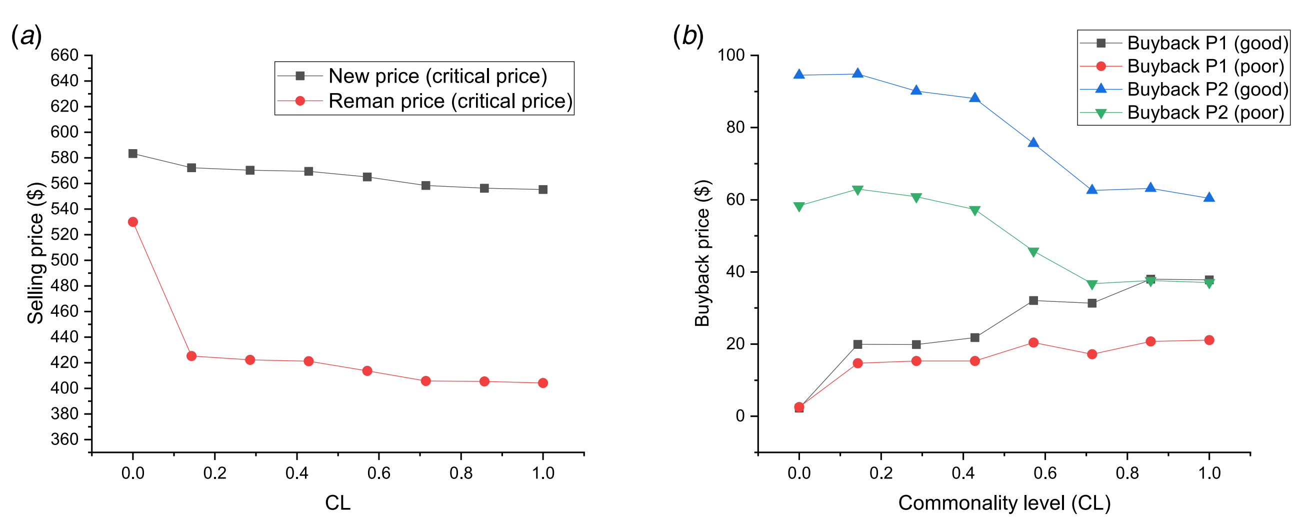

Fig. 12 (*a*) Differences in the selling price according to the commonality level and (*b*) differences in buyback prices

revenues due to higher selling prices and high demand, but high costs due to upgraded modules. As a result, lower sharing cases generate more profits compared to high commonality cases. On the contrary, in the remanufacturing, designs with lower commonality generate higher revenues due to higher selling prices, but high additional costs due to low compatibility of modules. Generational compatibility has a significant impact on the costs for remanufacturing, especially the buyback and procurement costs. Lower module compatibility limits the type and quantity of products that can be collected during the remanufacturing process and results in expensive unit costs in the production of the remanufacturing product.

Sensitivity analysis was used to understand changes in the results according to the various settings of the parameters. Particularly, effect of the number of available EoL products of the new generation showed how optimal results differ when new generation EoL products are insufficient or sufficient at the collection stage. Where it is difficult to collect a sufficient number of new generation EoL products in the process of remanufacturing, such as short life cycle products, some level of generational commonality can help increase the efficiency of remanufacturing. However, if sufficient EoL products can be collected for remanufacturing, generational commonality does not have a significant impact.

The main contribution of this study is that: Based on the need for remanufacturing of products with a short life cycle and their difficulties in the process, the impact on the manufacturing and remanufacturing process is analyzed, focusing on issues of commonality among generations. Through this study, various trade-offs that may occur in generational commonality are identified through quantitative analysis. An understanding of these trade-offs will provide insight into generational commonality between products for OEMs considering the economic success and product sustainability.

This research may be extended by considering uncertainties in the remanufacturing process. Various parameters are predetermined in the current model, but the parameters associated with remanufacturing have uncertainty in the real world. Probabilistic models can be applied in various areas, such as the process of collecting EoL products or the part reusability after disassembly. Additionally, the current study focuses on the quantity of modules shared; in other words, "how many components should be common (i.e., what is the level of commonality (CL))?". The issue can be further complicated into a question of "what components should be shared between families when we consider manufacturing and remanufacturing together (i.e., which one to share)?". It can also be expanded into issues about how to design product architecture to make sharing easier within a product family.

Nomenclature

I = index set for generation of products (old/new), $i \in I$
J = index set for items (include parts and products), $j \in J$
K = index set for qualities of EoL products, $k \in K$
L = index set for remanufacturing operations, $l \in L$
O = index set for market segments, $o \in O$
e_d = per-unit environmental impact of an EoL product discarded by customer
e_k = per-unit environmental impact of collecting an EoL product with quality k
M_j = number of part j to be recycled
N_j = number of part j to purchase additionally
Q_o = size of market segment
T_{jl} = expanded transition matrix
Y_l = number of times operation l is performed
A_i^k = amount of EoL product i availability with k condition
P_i^k = buyback price of collected EoL product i with quality k
P_i^n = selling price of a new product i
P_i^r = selling price of a remanufactured product i
S_i^k = return rate of EoL product i with k condition
X_i^k = number of collected EoL product i with quality k
Z_i^n = production quantity of a new product i
Z_i^r = production quantity of a remanufactured products i
c_d, e_d = per-unit cost and environmental impact for marketing, respectively
c_l, e_l = per-unit cost and environmental impact for operation l, respectively
$d_{o,n,i}\ (P_i^n, P_i^r, perf_i, \beta_o)$ = market share of a new product i in segment o with selling price (P_i^n, P_i^r), performance level ($perf_i$), and discount factor for remanufactured product (β_o)
$d_{o,r,i}\ (P_i^n, P_i^r, perf_i, \beta_o)$ = market share of a remanufactured product i in segment o with selling price $= (P_i^n, P_i^r)$, performance level ($perf_i$), and discount factor for remanufactured product (β_o)
c_j^M, e_j^M = per-unit cost and environmental impact for recycling a part j, respectively
c_j^N, e_j^N = per-unit cost and environmental impact for purchasing a new component j, respectively
C_i^n, E_n = per-unit total cost and environmental impact for producing a new product i, respectively
δ = target for the environmental impact saving

Appendix

Table 5 Cost and environmental impact parameters regarding new part procurement and material recovery

		New procurement		Material recovery	
		Cost ($)	Impact (kg CO_2 equivalent)	Cost ($)	Impact (kg COs_2 equivalent)
1	Phone R	N/A	N/A	−0.74	0.55
2	Display_R	5.40	4.75	−0.10	0.04
3	Battery_R	5.40	6.18	−0.08	0.06
4	Camera_R	20.90	1.24	−0.03	0.01
5	Sensors_R	13.00	1.19	−0.02	0.01
6	NAND_R	12.20	5.59	−0.23	0.05
7	DRAM_R	6.50	4.75	−0.10	0.04
8	Processor_R	43.70	4.75	−0.23	0.04
9	BB + XCR_R	27.50	1.19	−0.02	0.01

Table 6 Transition matrix (Smartphones)

		Disassembly		Reconditioning	Reassembly									
		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Phone R	−1												
2	Phone_old_(EoL, $k=1$)		−1											
3	Phone_old_(EoL, $k=2$)			−1										
4	Phone_new_(EoL, $k=1$)				−1									
5	Phone_new_(EoL, $k=2$)					1								−1
6	Display_R						1							−1
7	Battery_R							1						−1
8	Camera_R								1					−1
9	Sensors_R									1				−1
10	NAND_R										1			−1
11	DRAM_R											1		−1
12	Processor_R												1	−1
13	BB+XCR_R													
14	Display_W			1	0.6	−1								
15	Battery_W	1	0.6	1	0.792									
16	Camera_W	1	0.5	1	0.787		−1							
17	Sensors_W	1	0.4	1	0.5									
18	NAND_W	1	0.4	1	0.7			−1						
19	DRAM_W	1	0.5	1	0.6									
20	Processor_W	1	0.793	1	0.6				−1					
21	BB+XCR_W	1	0.5	1	0.5					−1				
22	Display_N				0.4						−1			
23	Battery_N		0.4		0.208									
24	Camera_N		0.5		0.213							−1		
25	Sensors_N		0.6		0.5									
26	NAND_N		0.6		0.3								−1	
27	DRAM_N		0.5		0.4									
28	Processor_N		0.207		0.4									
29	$BB+XCR_N		0.5		0.5									
	Cost ($)	3	3	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	2
	Env. Impact (kg CO_2e)	2.40	2.40	0.47	0.12	0.56	0.12	0.47	0.12	0.12	0.12	0.47	0.12	0.01

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