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Planning Demand- and Legislation-Driven Remanufacturing for a Product Family: A Model for Maximizing Economic and Environmental Potential

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ABSTRACT

Remanufacturing used, end-of-life products is a complex problem involving multiple types of products that may share common parts. Recovery targets assigned by market demand and environmental legislation add more difficulty to the problem. Manufacturers now need to achieve specified take-back and recovery rates while fulfilling demands for remanufactured products. To assists in the demand- and legislation-driven remanufacturing of a family of products (i.e., multiple products that share common parts), this paper introduces a bi-objective mixed integer linear programming (MILP) model for optimizing remanufacturing. The model identifies optimal remanufacturing plans for a product family, whereby, the remanufacturer can achieve demand and recovery targets more profitably and in an environmentally-friendly manner. The model can also be used to quantify and justify the economic and environmental benefits of a product family from a remanufacturing perspective. A case study is presented for remanufacturing an alternator-family of products.

Keywords: Product Family Design, End-of-Life Recovery, Remanufacturing, Life Cycle Assessment (LCA)

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1. INTRODUCTION

In the manufacturing industry, remanufacturing end-of-life products after customer use is emerging as a promising business opportunity that can support in both economic and environmental values (Guo *et al*., 2010; Iwao and Kusukawa, 2014). In remanufacturing, used, discarded end-of-life products are taken back and reprocessed so that they can live a second (or third, or fourth) life (Hauser and Lund, 2003). Since remanufacturing allows for reuse of parts and materials from end-of-life products, it reduces waste disposal and enables manufacturers to comply with waste-treatment environmental legislation, such as the Extended Producer Responsibility (EPR) act and the Waste Electrical and Electronic Equipment Directive (WEEE). Remanufacturing also allows manufacturers to satisfy market demand for cheaper and more environmentally-sustainable products. Manufacturers can produce the same product at only a small fraction of the original production costs (Fleischmann *et al*., 1997), while causing less adverse environmental impact (e.g., greenhouse gas emissions, energy and resource depletion).

As more companies are pursuing remanufacturing (e.g., Caterpillar, John Deere, Hewlett-Packard, Apple, and Xerox), decision-support tools for managing the remanufacturing process are in increasing demand. One challenge of remanufacturing is that it involves multiple types of end-of-life products that may share some common parts (Kwak and Kim, 2011). In other words, both individual product designs as well as the interactions between designs, i.e., the commonality of parts across product variants, greatly influence the remanufacturing process and economic and environmental performance. Recovery targets assigned by market demand and environmental legislation add more difficulty to the problem. Manufacturers need to achieve specified take-back and recovery rates while fulfilling orders for remanufactured products (Kwak and Kim, 2012). As such, a systematic approach is needed to find a more profitable, environmentally-friendly way to achieve these demands and legislative targets.

To assists in the demand- and legislation-driven remanufacturing of a family of products (i.e., multiple products that share common parts), this paper introduces a mixed-integer linear programming (MILP) model for optimizing remanufacturing. In many studies in the field of product family design (e.g., Simpson, 2004; Jiao *et al*., 2007), a product is defined as a group of close products that share a set of common design elements, processes, technologies, and/or other assets, and this is called a product platform. In this paper, a product family is spe-cifically defined as a group of products (1) whose pro-duct variants are anticipated to simultaneously reach end-of-life stages, and (2) that have common parts shared by some or all of product variants. The proposed model focuses on the fact that the design of a product family (or, part interchangeability among product variants) influences the profitability and environmental sustainability of remanufacturing. Reflecting the degree of part interchangeability, the model identifies an optimal remanufacturing strategy for a product family, whereby the manufacturer can achieve demand and legislative targets (i.e., take-back and recovery rates and order quantity) more profitably and in an environmentally-friendly manner. To assist in multi-objective decision-making, two objective functions are used: maximizing net profit and maximizing environmental-impact saving (i.e., the avoided environmental impact in comparison to producing equivalent new products).

In addition to providing an optimal strategy for product-family remanufacturing, the model can also be used to evaluate the economic and environmental potential of a product family design from a remanufacturing perspective. Manufacturers must carefully make commonality decisions in product family design (i.e., what parts to share) to improve the profitability and environmental sustainability of remanufacturing. Most previous studies in product family design, however, have not focused on the end-of-life stage; only a few studies (e.g., Simpson, 1998; Perera *et al*., 1999; Bras, 2007) have simply stated that cost reduction in the recovery process is another possible advantage of a product family and provided little justification. Kwak and Kim (2011) is an exception, and they attempted to quantify the effects of part sharing on the end-of-life stage, but their study was limited in that it only aimed at maximizing profit without considering environmental benefit. Incorporating both economic and environmental aspects together, this paper proposes a model aimed at providing more informed guidance as to which product family design is better and why from a remanufacturing perspective.

The rest of the paper is organized as follows. Relevant literature is reviewed in Section 2. The problem statement and mathematical formulation are proposed in Section 3, while a case study of an alternator family is presented in Section 4. Section 5 presents the conclusion and future research directions.

2. PREVIOUS RELATED WORK

In this section, three streams of research that are closely related to the current study are discussed: (1) disassembly-to-order (DTO), (2) remanufacturing optimization for a product family, and (3) life cycle assessment (LCA) on remanufactured products.

2.1 Disassembly-To-Order (DTO)

Research in the arena of DTO focuses on disassembly activities during remanufacturing. The main objective is to fulfill the demand for remanufactured products at minimum cost. To acquire a sufficient number of parts to meet demand, the disassembly plan is optimized, including the amount and type of end-of-life products to disassemble and the amount and type of new parts to externally procure. In general, multiple types of end-of-life products are considered, and deterministic targets for part supply (in other words, production target for parts) are given at the beginning.

Taleb and Gupta (1997) addressed the problem of scheduling the disassembly of multiple products that share common parts or materials. They presented a set of algorithms to find an ordering and disassembly schedule that fulfills the demand for parts while minimizing disassembly cost. Meacham *et al*. (1999) proposed an optimization model to determine a revenue-maximizing disassembly plan. Partial, selective disassembly to recover subassemblies was also incorporated in the model. Ferrer and Whybark (2001) suggested a more advanced approach that incorporates multiple factors including multiple periods, core trade-ins, and disassembly yield rates. Imtanavanich and Gupta (2005) and Kongar and Gupta (2006) presented a multi-criteria optimization model for DTO under uncertainty. Considering stochastic disassembly yield rates, their goal programming models determined the optimal number of products to take back as well as the number of items to reuse, recycle, store, and dispose. Kim *et al*. (2006) developed a mathematical model to optimize part supplies in the manufacturing. They compared two alternatives for supplying parts (i.e., purchasing the required parts from external suppliers or harvesting used parts by overhauling returned products in remanufacturing facilities) and provided an optimal part-supply plan for maximizing the total cost saving from remanufacturing. Jayaraman (2006) developed a linear-programming model for production planning in remanufacturing. The goal was to minimize the remanufacturing cost per unit while fulfilling orders for remanufactured products. The model determines the number, type and quality of end-of-life products to take back in a given time period and how to disassemble, remanufacture, or dispose of them. Inderfurth and Langella (2008) introduced a more generalized optimization model that allows consideration of multi-level product structures and partial disassembly. Kang and Hong (2012) integrated the problem of disassembly sequencing into DTO decision making. Their multi-period optimization model allowed the sequence and level of product disassembly to dynamically change depending on part requirements.

These studies provide an excellent background for a demand-driven approach to remanufacturing. However, their approaches focus more on scheduling disassembly than planning for the entire remanufacturing process, although remanufacturing includes various activities to treat end-of-life products and disassembled parts, such as reconditioning, recycling (i.e., material recovery), disposal, part resale, and reassembly. Also, the previous studies overlooked how recovery targets imposed by legislation (e.g., take-back and recovery target rates) can affect the remanufacturing process. Importantly, the environmental implications of remanufacturing were not considered.

2.2 Remanufacturing Optimization for Product Family

The studies in this field aim at identifying an optimal remanufacturing plan for multiple types of products that have some commonalities. The objective is to maximize the profit from remanufacturing, and the main concerns include how to disassemble and reprocess end-of-life products and which treatment option (i.e., reconditioning, recycling, disposal, or resale) to choose for disassembled parts.

Franke *et al*. (2006) modeled a generic remanufacturing process for mobile phones and proposed an optimization model to find the optimal remanufacturing plan with the maximum profit margin. Factory capacities for remanufacturing operations (e.g., sorting, disassembly, cleaning, testing, reassembly) were considered as key constraints in the model. Xanthopoulous and Lakovou (2009) proposed a MILP model that address the optimization of multi-product and multi-period remanufacturing processes. Legislative constraints that impose minimum requirements for product take-back and recovery were included in the model so as to reduce the overall produced waste. Kwak and Kim (2011) presented a MILP model for assessing the profitability of product family from a remanufacturing perspective. The model identified an optimal strategy for product take back and remanufacturing, thereby estimating the maximum profits for the product family during the end-of-life stage. The profit value was used as a quantitative measure to evaluate product family designs.

The models in this field are differentiated from those in the DTO studies in that they can optimize the entire remanufacturing process, including not only product disassembly but also part reconditioning and product reassembly. However, these models cannot examine how demand targets would affect the process. Also, most of the models only aim to maximize economic profit, giving less attention to the environmental impact caused by remanufacturing.

2.3 Life Cycle Assessment (LCA) on Remanufactured Products

Another relevant stream of research applies life cycle assessment (LCA) to remanufactured products. LCA is a well-known and widely-used technique for quantifying the total environmental impact associated with a product. It takes a "cradle to grave" approach and examines all stages over the lifespan of a product (i.e., manufacturing, use, maintenance, and end-of-life). Following the ISO 14040 standard, an LCA systematically assesses various types and levels of environmental impact, including life-cycle inventory (e.g., carbon dioxide, sulfur dioxide, and cadmium), life-cycle impact (e.g., global warming potential, acidification, eco-toxicity, and resource depletion), and an aggregated impact score which is determined by a weighted sum of multiple types of life-cycle impacts. For detailed reviews of LCA, see Rebitzer *et al*. (2004).

With an aim to evaluate and justify the environmental benefit of remanufacturing, a number of LCA studies have been reported on various products, including consumer electronics, appliances, automobiles, and mechanical parts (e.g., engines and transmissions). Smith and Keoleian (2004) presented LCA on an automotive gasoline engine and showed that remanufacturing engines has significant advantages over manufacturing new ones from various environmental-impact perspectives including raw material and energy consumption, solid waste generation, and greenhouse gas emissions. Warsen *et al*. (2011) conducted a comparative LCA study on a pair of newly-manufactured and remanufactured manual transmissions and showed that the energy consumption is reduced by 33% for the remanufactured product. Liu *et al*. (2014) analyzed the energy consumption and environmental emissions of a brand-new diesel engine compared with its remanufactured counterpart. They showed that a remanufactured engine can reduce approximately 70% of energy consumption. Goldey *et al*. (2010) compared the results from LCA studies on telecommunication equipment and demonstrated that remanufacturing can achieve an approximately 30-40% reduction in the global warming potential (GWP), compared to producing new equipment. Boustani *et al*. (2010) and Gutowski *et al*. (2011) demonstrated cases where remanufacturing may cause higher energy consumption compared to purchasing a new product. They showed that the technological obsolescence (i.e., less energy efficiency) of a remanufactured unit can offset energy savings by remanufacturing, especially if the product generates most of its life-cycle impact at the use phase.

Most previous studies have conducted a one-to-one comparison between a remanufactured product and its equivalent brand-new version. One limitation exists, however, in that the environmental impacts have been assessed and compared under the assumption of a fixed remanufacturing process. The environmental impact, however, interrelates with the remanufacturing process (e.g., how many parts are reused, newly purchased, recycled, and disposed) and is easily changed by take-back and recovery decisions. Thus, LCA should be integrated with remanufacturing decision-making so that the consequential environmental impact can be assessed correctly.

3. MODEL FORMULATION

3.1 Nomenclature

• *Decision variable*

I = Index set for product, $i \in I$

J = Index set for part, $j \in J$

X_i^t = Number of units of end-of-life product i that should be taken back

X_i^d = Number of units of end-of-life product i that should be disassembled

X_i^m = Number of units of end-of-life product i that should be recycled (material recovery)

X_i^l = Number of units of end-of-life product i that should be disposed of

X_j^c = Number of units of disassembled part j that should be reconditioned

X_j^a = Number of units of disassembled part j that should be reused for remanufacturing

$X_{j,w}^m$ = Number of units of disassembled, working part j that should be recycled

$X_{j,n}^m$ = Number of units of disassembled, non-working part j that should be recycled

$X_{j,w}^l$ = Number of units of disassembled, working part j that should be disposed of

$X_{j,n}^l$ = Number of units of disassembled, non-working part j that should be disposed of

Y_j = Number of units of brand-new part j that should be purchased for remanufacturing

Z_i = Number of units of remanufactured product i to produce

Z_j = Number of units of reconditioned part j to resell in the second-hand market

• *Parameter*

A_i = Number of units of end-of-life product i that is available for take back

α = Legislative target on the minimum take-back rate

β = Legislative target on the minimum recovery rate

γ_i = Demand target (order quantity) for remanufactured product i

γ_i = Demand for reconditioned part j

w_i, w_j = Weights of product i and part j in kilogram (kg), respectively

λ_{ij} = Disassembly yield rates; number of units of reusable part j obtainable from product i

μ_{ij} = Number of units of part j that is included in product i

c_i^t, c_i^d = Cost of taking back and disassembling a unit of product i, respectively

c_i^l, c_j^l = Cost of disposing of a unit of product i and part j, respectively

c_j^c = Cost of reconditioning a unit of part j

c_j^y = Cost of purchasing a unit of brand-new part j

c_i^s = Cost of reassembling and remarketing a unit of remanufactured product i

c_i^p = Penalty cost per unit of product i for not meeting the order quantity

r_i^s, r_j^s = Revenue from selling a unit of remanufactured product i and part j, respectively

r_i^m, r_j^m = Revenue from selling a unit of product i and part j to recycler, respectively

e_i^t, e_i^d = Environmental impact of taking back and disassembling a unit of product i, respectively

e_i^l, e_j^l = Environmental impact of disposing of a unit of product i and part j, respectively

e_i^m, e_j^m = Environmental impact of recycling a unit of product i and part j, respectively

e_j^c = Environmental impact of reconditioning a unit of part j

e_j^y = Environmental impact of purchasing a unit of brand-new part j

e_i^s = Environmental impact of reassembling, packaging, and remarketing a unit of product i

3.2 Remanufacturing Process

This paper proposes a model for planning demand- and legislation-driven remanufacturing of a product family. Figure 1 describes the remanufacturing process considered in this paper. As shown in the figure, remanufacturing typically consists of four main sequential operations: product take back, disassembly, part reconditioning, and reassembly.

Product take back is the process of collecting used, end-of-life products. Since the quantities of reusable parts are determined at this stage, the main concern here is to acquire the right types and quantities of end-of-life products (i.e., $\mathbf{X}_i^t$). The collected products pass through a sorting process, determining the next step to follow for

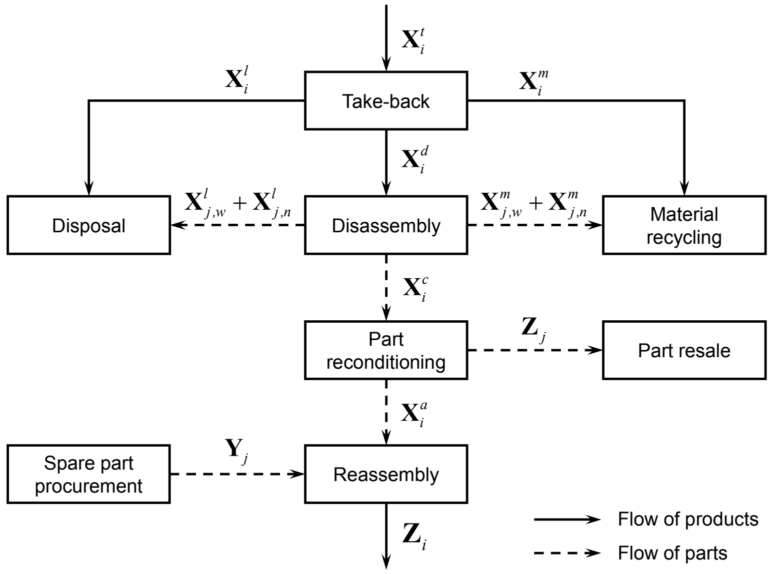

Figure 1. Remanufacturing process.

each of the collected units. Three options are considered for each product, i.e., disassembly, material recycling, and disposal, and the number of products that should take each option (i.e., $\mathbf{X}_i^d$, $\mathbf{X}_i^m$, and $\mathbf{X}_i^l$, respectively) is determined.

In disassembly, a product is broken down into a set of parts. While the product loses its identity, the disassembled parts continue their own life as independent units. An important point is that not all disassembled parts are reusable. Depending on its functioning and cosmetic conditions, a determination is made about whether a part is working (reusable) or non-working. In the next step, a working part can proceed along three paths, i.e., reconditioning (e.g., cleaning, lubricating, testing), material recycling, and disposal. Considering the demand level for the part, the number of parts that should follow each option is determined (i.e., $\mathbf{X}_j^c$, $\mathbf{X}_{j,w}^m$, and $\mathbf{X}_{j,w}^l$, respectively). A non-working part has only two options, i.e., disposal or material recycling, and the number of products that should take each option (i.e., $\mathbf{X}_{j,n}^m$, and $\mathbf{X}_{j,n}^l$, respectively) is determined.

Reconditioning is the process of recovering a used part into a like-new condition. Recovered parts can be either reused for remanufacturing (i.e., $\mathbf{X}_i^a$) or resold to the second-hand part market (i.e., $\mathbf{Z}_j$). When in-house reuse is chosen, the part proceeds to the reassembly stage where $\mathbf{Z}_i$ units of remanufactured products are produced and distributed to the market. Market demands for remanufactured products (or, the order quantities) create production targets for individual products, and the target must be fulfilled as closely as possible. Production below the target is regarded as negative and causes a penalty cost. When $\mathbf{X}_i^a$ units of parts are insufficient in quantity to meet targets, newly-manufactured parts are externally procured (i.e., $\mathbf{Y}_j$).

The remanufacturing process is mainly driven by the market demands for remanufactured products and recovered parts (i.e., γ_i and γ_j), but are also greatly affected by environmental legislation, such as the Waste Electrical and Electronics Equipment (WEEE) directive. Environmental legislation requires that manufacturers be responsible for the environmental burdens created by their products. To cope with the regulatory pressures, manufacturers must conduct responsible take back for their products; they must collect a certain weight of end-of-life products so that the total weight collected exceeds a mandatory minimum-weight target. Manufacturers are also required to meet a specified minimum recovery rate. More than a certain weight of end-of-life products must be recovered either by material recycling or reuse.

3.3 Problem Statement

The proposed model is summarized by the following optimization problem:

(1) Given

- Product family design in which its part composition and shared parts are already identified
- Demand (i.e., order quantities for remanufactured products) and legislative targets (i.e., mandatory take-back and recovery rates)
- Maximum amount of end-of-life products available for take back
- Disassembly yield rates of product variants
- Costs and revenue of executing remanufacturing operations
- Penalty cost for unmet demand
- Demand for reconditioned parts in the second-hand part market

(2) Find
- Optimal remanufacturing plan: amount and type of end-of-life products that should be taken back; amount and type of products and parts that should follow each disposal and recovery; amount and type of spare parts to acquire for remanufacturing; production quantities for remanufactured products.

(3) Subject to
- Flow volume balance: For each remanufacturing operation (take back, disassembly, part conditioning, and reassembly), its flow balance between input and output should be maintained with respect to an item (product i and part j).
- Environmental legislation: Mandatory take-back and recovery targets must be satisfied.
- Remanufacturing quota: The total production of remanufactured products cannot exceed the total collection amount of end-of-life products.
- Take-back availability: There are limits on the amount of available end-of-life products that can be collected.
- No excessive fulfilment: The supply of remanufactured products and recovered parts cannot exceed the demands for them.

(4) Maximizing
- Total net profit from managing the remanufacturing of a family of products
- Total environmental-impact saving from managing the product family remanufacturing: environmental impact that can be asserted to be avoided by remanufacturing, as compared to the case when equivalent products (of the same design and quantity) are newly manufactured.

(5) Assuming
- Single-period planning
- Deterministic parameter values: Disassembly yield rates, market demand, operation costs and revenues are known and deterministic.
- Two-level product structure: Each product variant has a two-level assembly structure consisting of a product and parts.
- Same product design between generations: There is no change in the product design between the end-of-life and remanufactured products. This assumption, however, may not always be valid, especially for products having a relatively short market life cycle, e.g., IT equipment. If design changes are required for remanufactured products, this assumption can be easily relaxed by adding such remanufactured products to the output set while assuming their take-back availability as zero.
- Unlimited part procurement: It is assumed that as many as needed spare parts can be procured without any upper limits, and the procurement can be conducted with no lead time.
- Unlimited facility capacity: The remanufacturing facility has no limits on the number of items or the number of operations that can be processed.
- Third-party recycling: Instead of carrying out recycling operations on its own account, the company sells products and parts to its recycling partners who perform actual recycling operations.

3.4 Mathematical Model for Product Family Remanufacturing

The mathematical formulation for product family remanufacturing can be stated as follows.

$$\text{maximize } f_{econ} = \sum_{n=1}^{2} R_n - \sum_{n=1}^{5} C_n \tag{1}$$

where
$$R_1 = \sum_{i\in I} r_i^s \cdot Z_i + \sum_{j\in J} r_j^s \cdot Z_j$$
$$R_2 = \sum_{i\in I} r_i^m \cdot X_i^m + \sum_{j\in J} r_j^m \cdot (X_{j,w}^m + X_{j,n}^m)$$
$$C_1 = \sum_{i\in I} c_i^t \cdot X_i^t + \sum_{i\in I} c_i^d \cdot X_i^d$$
$$C_2 = \sum_{j\in J} c_j^c \cdot X_j^c + \sum_{j\in J} c_j^y \cdot Y_j + \sum_{i\in I} c_i^s \cdot Z_i$$
$$C_3 = \sum_{i\in I} c_i^l \cdot X_i^l + \sum_{j\in J} c_j^l \cdot (X_{j,w}^l + X_{j,n}^l)$$
$$C_4 = \sum_{i\in I} c_i^p \cdot (\gamma_i - Z_i)$$

$$\text{maximize } f_{env} = E_0 - \sum_{n=1}^{4} E_n \tag{2}$$

where
$$E_0 = \sum_{i\in I} e_i^l \cdot X_i^t + \sum_{i\in I} (\sum_{j\in J} \mu_{ij} \cdot e_j^y + e_i^s) \cdot Z_i + \sum_{j\in J} e_j^y \cdot Z_j$$
$$E_1 = \sum_{i\in I} e_i^t \cdot X_i^t + \sum_{i\in I} e_i^d \cdot X_i^d$$
$$E_2 = \sum_{j\in J} e_j^c \cdot X_j^c + \sum_{j\in J} e_j^y \cdot Y_j + \sum_{i\in I} e_i^s \cdot Z_i$$
$$E_3 = \sum_{i\in I} e_i^l \cdot X_i^l + \sum_{j\in J} e_j^l \cdot (X_{j,w}^l + X_{j,n}^l)$$
$$E_4 = \sum_{i\in I} e_i^m \cdot X_i^m + \sum_{j\in J} e_j^m \cdot (X_{j,w}^m + X_{j,n}^m)$$

Subject to (3)

$$h_1 : X_i^t = X_i^d + X_i^l + X_i^m \qquad \forall i \in I$$
$$h_2 : \sum_{i\in I} \lambda_{ij} \cdot X_i^d = X_j^c + X_{j,w}^l + X_{j,w}^m \qquad \forall j \in J$$
$$h_3 : \sum_{i\in I} (1-\lambda_{ij}) \cdot X_i^d = X_{j,n}^l + X_{j,n}^m \qquad \forall j \in J$$
$$h_4 : \sum_{i\in I} X_j^c = X_j^a + Z_j \qquad \forall j \in J$$
$$h_5 : \sum_{i\in I} \mu_{ij} \cdot Z_i = X_j^a + Y_j \qquad \forall j \in J$$
$$g_1 : \alpha \cdot \sum_{i\in I} w_i \cdot A_i - \sum_{i\in I} w_i \cdot X_i^t \le 0$$
$$g_2 : \sum_{i\in I} w_i \cdot X_i^l + \sum_{j\in J} w_j \cdot (X_{j,w}^l + X_{j,n}^l) - (1-\beta) \cdot \sum_{i\in I} w_i \cdot X_i^t \le 0$$
$$g_3 : \sum_{i\in I} Z_i \le \sum_{i\in I} X_i^t$$
$$g_4 : X_i^t \le A_i \qquad \forall i \in I$$
$$g_5 : Z_i \le \gamma_i; \;\; Z_j \le \gamma_j \qquad \forall i \in I, \forall j \in J$$
$$X_i^t, X_i^d, X_i^l, X_i^m, Z_i \ge 0 \text{ and integer} \qquad \forall i \in I$$

$X_j^c, X_j^a, Z_j \geq 0$ and integer; $X_{j,w}^l, X_{j,n}^l, X_{j,w}^m, X_{j,n}^m \geq 0$ $\forall j \in J$

The objective function in Eq. (1) is to maximize the total net profit from remanufacturing a product family. This is estimated by the gap between the total revenue from remanufacturing and total operation cost. The revenue originates from two sources: sales of remanufactured products and recovered parts (R_1) and the sales of end-of-life products and disassembled parts to third-party recyclers (R_2). The operation cost includes the costs of take back and disassembly (C_1), part reconditioning, spare part procurement, and reassembly (C_2), disposal (C_3), and penalty for unmet demand targets (C_4).

Eq. (2) presents the second objective function of maximizing total environmental-impact savings. This measures the environmental benefit of remanufacturing by subtracting the impact of remanufacturing (i.e., sum of E_1 though E_4) from the impact of equivalent manufacturing (E_0). Here, the equivalent manufacturing implies a case where brand-new products and parts that are the same as the remanufactured products and recovered parts are newly manufactured. Since no take back is conducted, all end-of-life products are assumed to be discarded. Accordingly, the impact of equivalent manufacturing consists of three components: the impact of disposing $\mathbf{X}_i^t$ units of end-of-life products (i.e., $\sum_{i \in I} e_i^l \cdot X_i^t$), the impact of manufacturing $\mathbf{Z}_i$ products (i.e., $\sum_{i \in I} (\sum_{i \in I} \mu_{ii} \cdot e_i^y + e_i^s) \cdot Z_i$), and the impact of manufacturing $\mathbf{Z}_i$ parts (i.e., $\sum_{i \in I} e_i^y \cdot Z_i$). The impact of remanufacturing, on the other hand, includes four impact sources: take back and disassembly (E_1), part reconditioning, spare part procurement, and reassembly (E_2), disposal (E_3), and recycling (E_4). As defined in Sec. 3.1, impact parameters (e.g., e_i^t, e_i^d) indicate per-unit environmental impacts, i.e., how much environmental impact is caused by processing a unit of part j or product i. They can be life-cycle inventory (e.g., carbon dioxide, sulfur dioxide, and cadmium), life-cycle impact (e.g., global warming potential, acidification, eco-toxicity, and resource depletion), or an aggregated impact score. LCA is conducted to estimate the values.

Eq. (3) shows the constraints of the optimization model. Constraints h_1 through h_5 represent the flow balance equations for the products and parts. Constraints g_1 and g_2 ensure that the mandatory take-back and recovery targets are satisfied, respectively, where α and β denote the legislative targets on the minimum take-back and recovery rates, respectively. Constraint g_1 let the company take back enough end-of-life products so that the total collection exceeds α of the total available end-of-life products in terms of weight. Constraint g_2 lets the total amount of reuse and recycling exceed β of the total take back in terms of weight. In other words, the maximum allowable disposal amount is constrained to be (1-β) of the total weight collected. Finally, constraints g_3 through g_5 represent the constraints on remanufacturing quota, take-back availability, and no excessive fulfilment, respectively, followed by variable conditions.

Given the bi-objective problem, one can expect that there exists a trade-off between the two objectives. To attain better performance in one objective, sacrifice in the other objective is unavoidable, and a possibly infinite number of Pareto optimal solutions can be derived depending on how much sacrifice is made. The *ε-constraint approach* (Andersson, 2000; Mavrotas, 2009; Kwak and Kim, 2015) is one of the methods that can handle such multi objective problems. Pareto optimal solutions are obtained by optimizing one objective function (i.e., f_{econ} in this paper) using the other objective function (i.e., f_{env}) as constraints. More details will be discussed in Section 4.2.

4. ILLUSTRATIVE EXAMPLE: ALTERNATOR FAMILY

4.1 Family Design Information

This section presents an illustrative case study using the example of an automotive alternator family to demonstrate how to apply the proposed model and how it supports decision making in remanufacturing. Suppose that the alternator family consists of three product variants, Alternators 1, 2, and 3. Table 1 and Table 2 give detailed information about the alternator family, assumed based on Schau *et al*. (2012). As shown in Table 1, Alternator 1 is a light-weight generator selling at a medium-level price. Alternator 2 is a conventional generator with the cheapest price, but the heaviest weight; Alternator 3 is a ultra-lightweight generator with the highest price. In the current market, Alternator 1 is most preferred by customers, and Alternator 2 comes the next. Accordingly, the remanufacturing demand targets are given as 450, 300, and 150 units for Alternators 1, 2, and 3, respectively.

Table 1. Alternator product variant information

Product variant i	Available end-of-life unit (A_i)	Weight [kg] (w_i)	Selling price [$] ($r_i^s$)	Penalty cost [$] ($c_i^p$)	Demand target (γ_i)
Alternator 1	675	4.378	273	27.3	450
Alternator 2	450	6.069	238	23.8	300
Alternator 3	225	3.952	301	30.1	150

Currently, it is known that 675 units of Alternator 1, 450 units of Alternator 2, and 225 units of Alternator 3 are available for take back, which corresponds to a total of 6,575kg in terms of weight. The mandatory minimum take-back and recovery rates are assumed to be α = 0.85 and β = 0.8. Thus, the company must take back at least 5,589kg of alternators and recover (either reuse or recycle) at least 4,471kg (In other words, at most 1,118 kg of alternators can be discarded).

As described in Table 2, each alternator consists of 11 parts, and seven parts (i.e., stators, rotor coil, rotor, drive shaft, spacer, slip ring N and slip ring S) are shared by all three variants. Some parts are shared by two variants; for example, belt fitting 1 and bearing 1 are shared by Alternators 1 and 2, while fan 1 and housing 1 are shared by Alternators 1 and 3. This implies that a part disassembled from one alternator can be used in remanufacturing another type of alternator.

The goal of this study is to identify an optimal remanufacturing strategy for a product family, whereby the manufacturer can achieve demand and legislative targets more profitably and in an environmentally-friendly manner. To this end, the developed model was applied, and the optimization results are shown in the next section. The parameter settings are given in Tables 3 and 4. They are assumed based on a literature and web search (e.g., Bhuie *et al*., 2004; Sodhi and Reimer, 2001; Schau *et al*., 2012), and an LCA study was also conducted to estimate environmental impact. The IPCC 2007 method was used in the LCA, and Global Warming Potential (GWP) was used as the measure for the environmental impact (Goedkoop and Spriensma, 2000). The GWP of a system quantifies the greenhouse gas emissions to air generated by the system. The unit of GWP is kilograms of carbon dioxide equivalents (hereinafter kg CO_2 equivalent). (How to perform the LCA is beyond the scope of this study, and as such details are not shown here).

4.2 Optimization Results

The optimization model was applied two times with different objective functions. Table 5 and Table 6 show the optimal solution under the first objective function of maximizing the total net profit. Table 7 and Table 8 show the optimal solution under the second objective function of maximizing the total environmental-impact saving. The objective function values are given separately in Table 9 and Table 10. Table 9 and Table 10 help understand how the net profit and impact

Table 2. Family design information: part inclusion in product variants

Part j	Material	Weight [kg] (w_i)	Alternator 1 (μ_{1j})	Alternator 2 (μ_{2j})	Alternator 3 (μ_{3j})
Stator	Steel	0.773	1	1	1
Rotor coil	Copper	0.55	1	1	1
Rotor	Iron cast	1.094	1	1	1
Drive Shaft	Steel	0.262	1	1	1
Belt fitting 1	Steel	0.519	1	1	
Belt fitting 2	Aluminum	0.18			1
Fan 1	Plastic/PP	0.016	1		1
Fan 2	Steel	0.138		1	
Spacer	Aluminum	0.003	1	1	1
Bearings 1	Rolled steel	0.099	1	1	
Bearings 2	Plastic/PP	0.011			1
Slip ring N	Copper	0.033	1	1	1
Slip ring S	Copper	0.071	1	1	1
Housing 1	Aluminum	0.958	1		1
Housing 2	Iron cast	2.527		1	

Table 3. Parameter setting for product variants: per-unit cost (in US dollar) and environmental impact (in kg CO_2 equivalent) of remanufacturing operations

Product variant i	Take back		Disposal		Recycling		Disassembly		Reassembly	
	c_i^t	e_i^t	c_i^l	e_i^l	c_i^m	e_i^m	c_i^d	e_i^d	c_i^s	e_i^s
Alternator 1	39	0.25	0.41	1.03	-3.15	0.08	5	0.86	15	2.26
Alternator 2	34	0.35	0.57	2.33	-1.90	0.12	5	0.86	15	2.36
Alternator 3	43	0.23	0.37	1.02	-3.33	0.08	5	0.86	15	2.23

Table 4. Parameter setting for parts: per-unit cost and revenue (in US dollar) and environmental impact (in kg CO_2 equivalent) of remanufacturing operations

Part j	Reusability	Disposal		Recycling		Reconditioning		Part resale		Spare purchase		Demand for reconditioned part
	λ_{ij}	c_j^l	e_j^l	r_j^m	e_j^m	c_j^c	e_j^c	r_j^s	e_j^s	c_j^y	e_j^y	γ_j
Stator	0.8	0.073	0.022	0.111	0.01	2.78	0.54	10.44	0.04	13.91	2.71	200
Rotor coil	0.78	0.052	0.233	1.164	0.01	3.17	0.42	11.88	0.03	15.84	2.09	100
Rotor	0.81	0.103	0.568	0.060	0.02	1.58	0.75	5.91	0.06	7.88	3.73	200
Drive Shaft	0.9	0.025	0.007	0.038	0.01	0.94	0.18	3.54	0.02	4.72	0.92	200
Belt fitting 1	0.9	0.049	0.015	0.074	0.01	1.87	0.36	7.01	0.03	9.34	1.82	200
Belt fitting 2	0.25	0.017	0.008	0.274	0.00	1.17	0.43	4.37	0.01	5.83	2.14	100
Fan 1	0	0.002	0.010	0.003	0.00	0.05	0.01	0.17	0.00	0.23	0.05	100
Fan 2	0.9	0.013	0.004	0.020	0.00	0.50	0.10	1.86	0.01	2.48	0.48	200
Spacer	0.5	0.000	0.000	0.005	0.00	0.02	0.01	0.07	0.00	0.10	0.04	0
Bearings 1	0.5	0.009	0.003	0.014	0.00	0.36	0.04	1.34	0.01	1.78	0.20	0
Bearings 2	0	0.001	0.007	0.002	0.00	0.03	0.01	0.12	0.00	0.16	0.04	0
Slip ring N	0	0.003	0.014	0.070	0.00	0.19	0.03	0.71	0.00	0.95	0.13	0
Slip ring S	0	0.007	0.030	0.150	0.00	0.41	0.05	1.53	0.00	2.04	0.27	0
Housing 1	0.6	0.090	0.042	1.457	0.02	6.21	2.28	23.28	0.06	31.04	11.40	100
Housing 2	0.85	0.238	1.313	0.139	0.05	3.64	1.72	13.65	0.15	18.19	8.62	200

Table 5. Optimization result (max. total net profit f_{econ}): product variants

Product variant i	Take back (X_i^t)	Disposal (X_i^l)	Recycling (X_i^m)	Disassembly (X_i^d)	Reassembly (Z_i)
Alternator 1	670	0	0	670	450
Alternator 2	439	0	0	439	300
Alternator 3	0	0	0	0	150

Table 6. Optimization result (max. total net profit f_{econ}): parts

Part j	Disposal		Recycling		Reuse	Spare purchase	Part resale
	$X_{j,w}^l$	$X_{j,n}^l$	$X_{j,w}^m$	$X_{j,n}^m$	X_j^a	Y_j	Z_j
Stator	0	0	0.2	221.8	887	13	0
Rotor coil	0	0	0.02	243.98	865	35	0
Rotor	0	0	0.29	210.71	898	2	0
Drive Shaft	0	0	0.1	110.9	900	0	98
Belt fitting 1	0	0	48.1	110.9	750	0	200
Belt fitting 2	0	0	0	0	0	150	0
Fan 1	0	0	0	670	0	600	0
Fan 2	0	0	0.1	43.9	300	0	95
Spacer	0	0	0.5	554.5	554	346	0
Bearings 1	0	0	0.5	554.5	554	196	0
Bearings 2	0	0	0	0	0	150	0
Slip ring N	0	0	0	1109	0	900	0
Slip ring S	0	0	0	1109	0	900	0
Housing 1	0	0	0	268	402	198	0
Housing 2	0	0	0.15	65.85	300	0	73

saving will vary depending on which objective function is chosen.

When the model aims to maximize the total profit, the optimal take-back plan is to collect 670 and 439

Table 7. Optimization result (max. total environmental-impact saving f_{env}): product variants

Product variant i	Take back (X_i^t)	Disposal (X_i^l)	Recycling (X_i^m)	Disassembly (X_i^d)	Reassembly (Z_i)
Alternator 1	675	0	0	675	450
Alternator 2	450	0	0	450	300
Alternator 3	225	0	0	225	150

Table 8. Optimization result (max. total environmental-impact saving f_{env}): parts

Part j	Disposal		Recycling		Reuse	Spare purchase	Part resale
	$X_{j,w}^l$	$X_{j,n}^l$	$X_{j,w}^m$	$X_{j,n}^m$	X_j^a	Y_j	Z_j
Stator	0	0	0	270	900	0	180
Rotor coil	0	0	53	297	900	0	100
Rotor	0	0	0.5	256.5	900	0	193
Drive Shaft	0	0	115	135	900	0	200
Belt fitting 1	0	0	62.5	112.5	750	0	200
Belt fitting 2	0	0	0.25	168.75	56	94	0
Fan 1	0	0	0	900	0	600	0
Fan 2	0	0	0	45	300	0	105
Spacer	0	0	0	675	675	225	0
Bearings 1	0	0	0.5	562.5	562	188	0
Bearings 2	0	0	0	225	0	150	0
Slip ring N	0	0	0	1350	0	900	0
Slip ring S	0	0	0	1350	0	900	0
Housing 1	0	0	0	360	540	60	0
Housing 2	0	0	0.5	67.5	300	0	82

units of Alternators 1 and 2, respectively (Table 5). Collecting Alternator 3 is not recommended considering its relatively high collection fee ($43 per unit compared to $39 and $34 of Alternators 1 and 2, respectively; see Table 3) and less demand for the remanufactured product (150 units compared to 450 and 300 units of Alternators 1 and 2, respectively). The model shows that the company can fully satisfy the demand targets (not only the targets for Alternators 1 and 2, but also the target for Alternator 3) with only two types of alternators; part interchangeability enables this. As shown in Table 6, by disassembling the collected alternators, the company can harvest a sufficient amount of reusable parts to cover most of the demand targets: for instance, more than 850 units of stator, rotor coil, rotor, and drive shaft can be harvested when the total demand for the parts is 900 units each. Although some parts that are used by Alternator 3 only (e.g., belt fitting 2 and bearings 2) require external spare purchase, this is cheaper than conducting take back, considering the unit part cost in Table 4.

When the objective function was changed to maximizing the total environmental-impact saving, however, different results are obtained. Instead of saving the cost of take back, the model rather chooses to collect more (actually all, in this case) end-of-life products and reuse and recycle more. Compared to Table 6, Table 8 shows that the amounts of recycling, reuse, and part resales are increased, whereas the amount of spare purchase is decreased. It is true that this leads to significant cost and impact increases in take-back, disassembly and reconditioning, but they can be offset by a reduction in spare purchase. In addition, the revenue increase from recycling and part resale also help to recover the financial loss. Table 9 and Table 10 help to figure out the difference between the two optimizations more clearly.

The results in Table 9 and Table 10 show the economic and environmental potentials of the alternator family from a remanufacturing perspective, i.e., a maximum profit of $158,605 and a maximum environmental-impact saving of 15,687kg CO_2 equivalent, respectively. If a company cares only about the economic performance, they can attempt to achieve the maximum net profit by following the optimal remanufacturing plan in Table 5 and Table 6. If a company is only concerned with environmental performance, they can maximize their environmental-impact saving by adopting the second plan in Table 7 and Table 8. A more realistic scenario is that a company seeks to maximize both economic and environmental performance. However, Table 9 and Table 10 imply that simultaneously maximizing both profit and environmental-impact saving is impossible. There exists a trade-off between the two objectives, and the company need to slightly sacrifice one objective to attain better performance in the other objective. Depending on how much the company is willing to sacrifice on a particular objective, a possibly infinite number of Pareto optimal remanufacturing plans can be derived.

In this study, the Pareto optimal solutions were obtained using an *ε-constraint approach* (Andersson, 2000; Mavrotas, 2009; Kwak and Kim, 2015). In the ε-constraint approach, the bi-objective problem in Eq. (4) is reformulated as Eq. (5), where one objective function (i.e., f_{econ} in this paper) is optimized using the other objective function (i.e., f_{env}) as constraints.

$$\max_x \; [f_{econ}(x), f_{env}(x)] \tag{4}$$
subject to
$$g_l(x) \le 0 \quad l = 1, 2, \cdots, L$$
$$h_m(x) = 0 \quad m = 1, 2, \cdots, M$$

$$\max_x \; f_{econ}(x) \tag{5}$$
subject to
$$g_l(x) \le 0 \quad l = 1, 2, \cdots, L$$
$$h_m(x) = 0 \quad m = 1, 2, \cdots, M$$
$$f_{env}(x) \ge \varepsilon$$
where
$$\varepsilon = f_{env}(x_{econ}^*) + (f_{env}(x_{env}^*) - f_{env}(x_{econ}^*)) \cdot \eta \quad (0 \le \eta \le 1)$$

In Eq. (5), the objective function f_{env} is bounded from below by ε. The lower bound ε is set by a two-step approach. First, by solving the model only with one objective at a time (i.e., first, maximizing the total net profit, and next, maximizing the environmental-impact saving), calculate the range of f_{env}, i.e., the lower bound $f_{env}(x_{econ}*)$ and the upper bound $f_{env}(x_{env}*)$. In this study, the range was defined in Table 9 and Table 10 as 12,997.65 and 15,687.11 kg of CO_2 equivalent, respecttively. Next, apply a η value between 0 and 1. By pro-

Table 9. Optimization result: f_{econ} (total net profit) under two optimization settings

	Max. f_{econ}	Max. f_{env}
Cost in total	84710.12	93105.15
Take back	41056.00	51300.00
Disassembly	5545.00	6750.00
Reconditioning	13596.94	15930.02
Reassembly	13500.00	13500.00
Spare purchase	11012.18	5625.13
Disposal	0.00	0.00
Penalty	0.00	0.00
Revenue in total	243315.40	248397.50
Recycling	994.35	1367.68
Part resale	2921.05	7629.83
Product resale	239400.00	239400.00
Total profit [$]	158605.29	155292.36

Table 10. Optimization result: f_{env} (total environmental saving) under two optimization settings

	Max. f_{econ}	Max. f_{env}
Reference impact (E_0)	25244.92	27098.55
Impact in total	12247.28	11411.44
Take back	325.78	382.68
Disassembly	955.96	1163.70
Reconditioning	3667.31	4349.25
Reassembly	2056.92	2056.92
Spare purchase	3140.92	1325.23
Disposal	0.00	0.00
Recycling	24.45	31.18
Part resale	19.03	45.58
Product resale	2056.92	2056.92
Total impact saving [kg CO_2 equivalent]	12997.65	15687.11

gressively increasing the η value, Pareto optimal solutions can be sampled from the solution with the maximum profit (η = 0) to the solution with the maximum impact-saving (η = 1). The black line with circles ('Alternator family (w/ sharing)') in Figure 2 presents the resulting Pareto optimal solutions. It shows that the proposed model can provide a company an infinite number of remanufacturing plans representing various economic and environmental performance combinations. A company can choose a plan depending on their business goals and objectives.

4.3 Discussion

In addition to identifying an optimal production plan for product-family remanufacturing, the proposed model can also be used for other design and business purposes. This section discusses two potential applications: (1) Design for Remanufacturing (DfR) of product family, and (2) remanufacturing portfolio planning.

• *Design for Remanufacturing of Product Family*

As shown in the previous study, part sharing greatly affects the profitability and environmental sustainability of remanufacturing. Therefore, commonality decisions in product family design should be taken very carefully, and to this end, it is essential to have a way to measure the effect of part sharing.

The proposed model can assist in Design for Remanufacturing (DfR) of a product family (i.e., improving product family design from a remanufacturing perspective) by measuring the economic and environmental effects of part sharing. Suppose that there exist multiple design alternatives for a product family with different levels of part sharing. By applying the model to the design alternatives one by one, one can quantify the effect of part-sharing decisions on the total net profit and environmental-impact saving at the remanufacturing stage. This helps figure out which design alternative is better and why from the remanufacturing perspective.

To illustrate, the model was applied to two different family designs: the original alternator family design with part sharing (Table 2) and a reference family design with no sharing (i.e., all parts are product specific; parts from an alternator cannot be used in remanufacturing other types of alternators). The results are shown in Figure 2, where each line reveals the economic and environmental potentials of a family design. By comparing the two lines, one can easily see that the original family design outperforms the reference design without any part sharing, in terms of both economics and environmental savings. Furthermore, the figure helps clearly measure how much net profit and environmental-impact saving can be improved by part sharing.

• *Remanufacturing Portfolio Planning*

In addition to DfR, the model can assist in planning a remanufacturing strategy by identifying a more profitable and environmentally sustainable way to recover end-of-life products. Remanufacturing portfolio planning is one potential application in this regard. When the same amounts and types of end-of-life products are given, the model can be used to determine the best remanufacturing portfolio, i.e., what remanufactured products to offer.

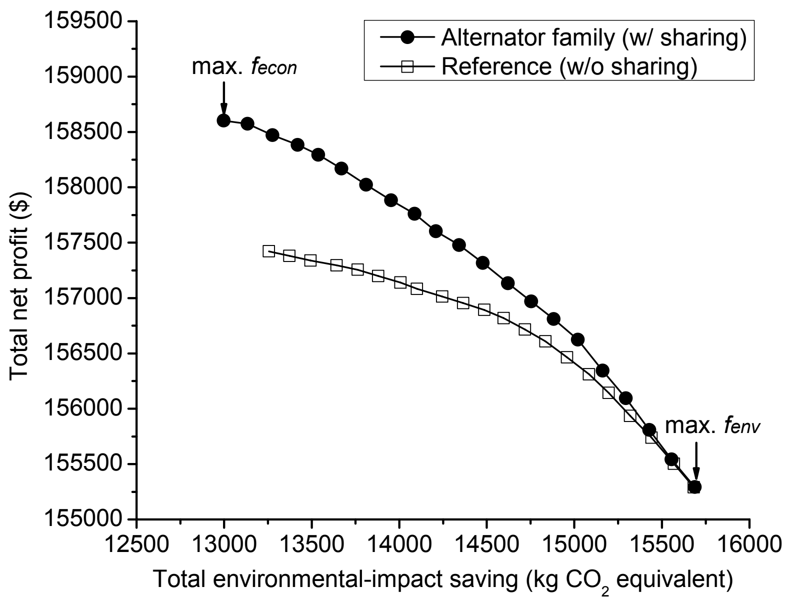

Figure 2. Pareto optimal solutions: family remanufacturing with and without part sharing.

In the previous case study, it was assumed that all types of alternators are remanufactured and distributed to the market. Remanufacturing all types of alternators may attract more customers by offering more choices to the market. Some customers prefer a light-weight alternator and are willing to pay a higher price for lighter products; while other customers prefer a cheaper product despite a heavy weight. By offering more variations in products to the market, more orders are expected. However, some downsides exist. For example, having various product types means less commonality amongst product variants and more complex remanufacturing operations, which may increase the total operational costs. Considering the trade-off, a company may want to explore other possibilities. For example, what if only Alternators 1 and 2 are offered to the market? What if only Alternator 1 is offered?

To show how the proposed model can address such portfolio planning, this paper applied the model to the alternator family case, assuming that there exist seven possible portfolio alternatives: 'Fam 123' (i.e., remanufacturing Alternators 1, 2 and 3), 'Fam 12' (i.e., remanufacturing Alternators 1 and 2), 'Fam 13', 'Fam 23', 'Prod 1' (i.e., remanufacturing Alternator 1 only), 'Prod 2', and 'Prod 3'. To reflect demand changes by portfolio design, additional assumptions were made as shown in Tables 11 and 12.

As described in Table 11, there are three types of customers: Types 1, 2, and 3. Each customer prefers Alternators 1, 2, and 3, respectively, which provides the highest utility. Currently, it is known that the size of each customer group is 450, 300, and 150 (in unit) for Types 1, 2, and 3, respectively. If all types of alternators are offered, customers will choose their best option. If their best option is not offered, most of them will choose the next best option while some will leave (i.e., loss in

Table 11. Market information: preference towards alternator variants

Customer	Population	Utility			Current choice
		Alternator 1	Alternator 2	Alternator 3	
Type 1	450	0.208	0.136	0.194	Alternator 1
Type 2	300	0.149	0.172	0.096	Alternator 2
Type 3	150	0.267	0.101	0.293	Alternator 3

Table 12. Demand targets under different remanufacturing scenarios

	Fam123	Fam12	Fam13	Fam23	Prod1	Prod2	Prod3
Alternator 1	450	586	710	0	846	0	0
Alternator 2	300	300	0	300	0	645	0
Alternator 3	150	0	150	570	0	0	737
Total demand	900	886	860	870	846	645	737

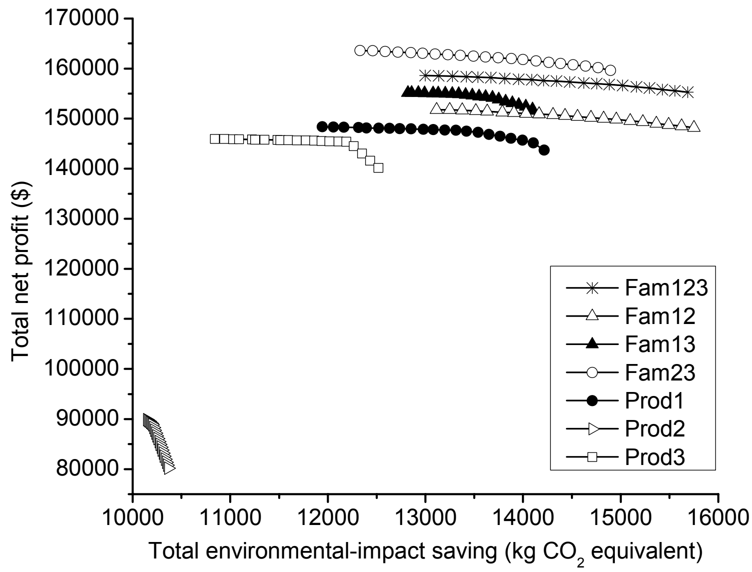

Figure 3. Pareto optimal solutions of different remanufacturing portfolio.

the market share). Here, the demand loss is assumed to be in proportion to utility decrease. For instance, if Fam 12 is chosen as the portfolio, about 91.1% (= 0.267/0.293) of Type-3 customer will move to Alternator 1, their next best option. Type-1 and Type-2 customers will choose Alternator 1 and Alternator 2, respectively, as previously. Following the same logic, Table 12 calculates the demand targets under different portfolio scenarios. Note that all other assumptions and parameter settings (including the available end-of-life products) are the same as Tables 1 through 4.

Figure 3 compares the total net profit and environmental-impact saving of seven different remanufacturing portfolios. From the profit perspective, Fam 23 shows the best performance, Fam 123 is the next, and Fam 13 third. From an impact-saving perspective, Fam 12 and Fam 123 show the greatest potential, and Fam23 is the next. The results imply that making portfolio decisions is not a simple task, in that a fixed rule (such as 'offering all products is the best' and 'offering only one homogeneous product is the best') is not applicable. As such, a scientific method to help and justify the decision is needed, and the proposed model can be a solution to serve this need.

5. CONCLUSION

Remanufacturing has emerged as a new business opportunity in the manufacturing industry as a way to achieve both economic profitability and environmental sustainability. However, remanufacturing is a complex problem that involves multiple types of products sharing common parts. Both individual product designs as well as the interactions between designs greatly influence the remanufacturing process and both economic and environmental performance. Take-back and recovery rates assigned by environmental legislation and market demand add more difficulty to the problem. As such, a systematic approach is needed to find a more profitable, environmentally-sustainable way to meet demand and legislative targets.

With an aim to support the demand- and legislation-driven remanufacturing of a product family, this paper introduced a bi-objective mixed-integer linear programming model for remanufacturing planning. Given a product family design, the model identifies optimal remanufacturing plans for the product family, whereby the remanufacturer achieves demand and recovery targets with a maximum net profit or a maximum environmental-impact saving. An example with an alternator-family remanufacturing illustrated how the model can identify an optimal plan for product-family remanufacturing, and how it can be used for DfR of a product family and pursuit of remanufacturing portfolio planning.

In the future, the developed model can be extended or improved along several points. Although the current model focuses on the remanufacturing stage, it can be extended to an integrated approach that simultaneously considers both initial manufacturing and end-of-life remanufacturing stages. By understanding the effect of part sharing on the entire life cycle, more advanced product family design can be attained. Incorporating uncertainty is also an important future work. The proposed model requires many uncertain, stochastic parameters, which are assumed to be deterministic in this paper. Future work should include the development of a stochastic model that can reflect effectively the uncertainty in real-world decisions. Finally, the current model assumes that the design of a product family is given and fixed. In the future, the model should be improved to incorporate design optimization.

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