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ORIGINAL ARTICLE

Fastening method selection with simultaneous consideration of product assembly and disassembly from a remanufacturing perspective

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Abstract
In recent years, remanufacturing has received increased attention as a sustainable and profitable product recovery strategy. To facilitate the remanufacturing of used product returns, factors which affect remanufacturability should be considered during the product design stage. The selection of fastening method during the product design stage is one of the critical decisions which affects the remanufacturability as well as the total cost of disassembly and re-assembly of used products. Hence, both product assembly and disassembly issues should be considered in the product design stage for the selection of fastening methods. Simultaneous consideration of product assembly and disassembly in the product design stage for the fastening method selection has not been properly addressed in previous studies. In this paper, a methodology for selecting appropriate fastening method from a remanufacturing perspective is proposed in which both product assembly and disassembly are addressed. In the proposed methodology, an optimization model is formulated with the objective of minimizing the total cost of product assembly and disassembly. The genetic algorithm is employed to solve the model. A case study on the selection of fastening method for a laptop computer is conducted to illustrate the proposed methodology and to evaluate its effectiveness. The effect of the degree of product disassembly and the demand size for remanufactured products on the total cost of product assembly and disassembly was also investigated. The results showed the proposed methodology provide significant cost savings in the total product assembly and disassembly cost.

Keywords Design for disassembly · Design for assembly · Fastener selection · End-of-life products · Genetic algorithm

1 Introduction

The shortening life-span coupled with the unsustainable usage and disposal of consumer products has resulted in accumulation of e-waste in many countries. To mitigate the impact of direct disposal of end-of-life (EOL) and end-of-use (EOU) products, many countries have passed regulations and directives which mandate manufacturers to take back and recover products at the end of their useful lives. For instance, the waste electrical and electronic equipment (WEEE) and the end-of-life vehicles (ELV) directives passed by the EU set targets for the recovery of WEEE and ELV waste, respectively EU directive [1, 2]. In response to the legislative pressures and to satisfy the increasing consumers demand for environmentally responsible products, product recovery strategies such as remanufacturing, reconditioning, reuse, and recycling have gained increasing attention in recent years. Among the alternative product recovery strategies, remanufacturing has been widely recognized as a sustainable and profitable option due to its economic and environmental advantages [3]. Remanufacturing returns used products to the original specification with a warranty equivalent to the brand new product [4], through a process which involves the reuse, refurbishment, and replacement of components [5, 6]. Remanufacturing conserves the material and energy embodied in EOL and EOU products which translates into significant saving in the cost of production and reduces the impact on the environment. According to Mitra [7], the cost of remanufacturing a hi-tech consumer products is estimated

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between 40 and 60% of a brand new product. On the other hand, the price of a remanufactured product is estimated between 30 and 40% of the brand new version [8]. Several multinational companies such as Caterpillar, Xerox, Dell, Apple, HP, and Sony have offered remanufactured (often named "refurbished") products to the market. Some common remanufactured products include consumer electronics, furniture, printing equipment, and automotive and aircraft components.

The design of a product has been reported to be one of the major challenges in remanufacturing [9, 10]. Design methodologies developed in previous studies mainly focus on the ease of manufacture, ease of product assembly, environmental impact assessment, and cost reduction [11]. However, design for remanufacturing is quite often overlooked in the product design stage that leads to high remanufacturing cost of used product returns. Therefore, if a company intends to remanufacture used product returns, various issues of product remanufacturing such as ease of disassembly, ease of inspection, and ease of cleaning should also be considered in the product design stage. The selection of fastening method is one of the critical decisions made during the product design stage which affect not only the product assembly/re-assembly but also the disassembly of used products upon which key remanufacturing processes such as cleaning, inspection, and testing depend. In this paper, "assembly" refers to the process of joining components into subassemblies or final assembly using appropriate fastening methods during the manufacture of new products. On the other hand, "re-assembly" refers to the process of joining components which have been harvested from used product returns in a remanufacturing process. The proposed methodology is therefore applied to select appropriate fastening methods which lead to the minimum overall assembly and re-assembly times as well as assembly and disassembly cost. A fastening method which facilitate the assembly/re-assembly process may cause difficulty during the disassembly of used product returns for remanufacturing and vice versa. For example, some fastening methods such as snap-fit joints and adhesives are quick and require little effort in assembly but are difficult to disassemble. Besides, the total cost of disassembly of used product returns and re-assembly substantially depends on the total time required for disassembly and re-assembly which is highly affected by the types of fastening methods involved. Therefore, fastening method selection during the product design stage must consider both product assembly and disassembly issues simultaneously. However, no previous studies on fastening method selection has been found thus far which addresses both issues simultaneously from a remanufacturing perspective.

In this paper, a methodology for simultaneous consideration of product assembly and disassembly for the fastening method selection during the design stage is proposed. In the proposed methodology, the fastening method selection problem is formulated as an optimization model with the objective of minimizing the total product assembly and disassembly cost of products. This paper is structured as follows. Section 2 presents related research studies; Section 3 discusses the proposed methodology for fastening method selection; and in Section 4, a case study on the selection of fastening method for a laptop computer is presented to illustrate the proposed methodology. Finally, conclusion and future work are given in Section 5.

2 Related work

In recent years, there has been a growing research interest in "Design for remanufacturing" (DfRem)—a design activity that involves the consideration of a variety of design factors which enhance the remanufacturability of a product [12]. Early studies include Bras and Hammond [13], Sundin [14], and Zwolinski and Brissaud [15], which focused on identifying design features for facilitating the remanufacturing of products and assessment of the remanufacturability of a product design. Bras and Hammond [13] developed a method for assessing the remanufacturability of a product design based on factors such as disassemblability, cleaning difficulty, damage correction, and quality assurance. Sundin [14] and Zwolinski and Brissaud [15] conducted case studies on several remanufactured products to develop methods for assessing remanufacturability of a product design. Sundin [14] proposed a design tool called the "RemPro" matrix which serves as a design guidance to identify product properties such as ease of access, ease of handling, wear resistance, etc. which facilitate the remanufacturing process. Similarly, Zwolinski and Brissaud [15] conducted a study on a wide range of current remanufacturable products and identified 11 "remanufacturable" product profiles. Their experiment resulted in the development of a software tool known as "Repro2," used for assessing the remanufacturability of a product design by comparing it with the identified "remanufacturable product profiles." Recently, Du et al. [16] and Fang et al. [17] developed metrics for assessing the remanufacturability of a product design by considering a variety of factors such as (i) disassembly complexity, (ii) cleaning difficulty, (iii) types of fastening methods, and (iv) fastener accessibility.

Quite a number of design for assembly (DFA) and design for disassembly (DFD) methods were developed in previous studies to address product assembly and disassembly issues during design stage. Much of the studies on the DFA methods involve the evaluation of assemblability of parts and the interpretation of the evaluation scores to suggest design improvements. Early studies in this regard include the Boothroyd and Dewhurst DFA methodology [18], the Lucas method [19], and the Hitachi's Assembly Evaluation Method [20]. On the other hand, the DFD methods developed in previous studies mainly involve evaluation of a product's design using disassembly difficulty factors such as the types of fastening methods, accessibility of fasteners and components, positioning requirements, tool requirement, force requirement, and part handling difficulty [21–23]. Rampersad [24] proposed a methodology to compute DFA index by considering multi-factor which includes (1) weight, (2) number of unique components, (3) stiffness, (4) length, (5) presence of the base component, (6)vulnerability hardness, (7) shape, (8) size, (9) composing movement, (10) composition direction, (11) symmetry, (12) alignment, and (13) jointing method. The DFA index allows design engineers to compare alternative design concepts during design stage.

Some previous studies have developed methods for evaluating the disassemblability of a product during design stage. Das et al. [21] developed a multi-factor index to estimate the disassembly effort using factors such as time, force, tool and fixture requirement, and degree of accessibility of fasteners. Desai and Mital [23] developed a disassemblability evaluation score based on factors such as the degree of accessibility of fasteners and components, force, tool, and positioning requirements, and material handling factors. Sabaghi et al. [25] developed a methodology for evaluating the disassemblablity of components considering five parameters: accessibility, relative position of components, tools requirement, types of fastening methods, and quantity of fastening methods used. Soh et al. [26] proposed a disassembly index based on the disassembly complexity and accessibility of parts to determine optimal disassembly route. In their methodology, factors such as part handling difficulty, fastener removal difficulty, and directional constraints were considered. Several authors have also proposed methods based on work measurement analysis for estimating the disassembly time which was then used for evaluating the disassemblability of products [22, 27, 28].

There has been a limited number of studies on fastening method selection during the product design stage which consider product assembly and disassembly issues. Shu and Flowers [29] considered the probabilities of fasteners failure during disassembly and re-assembly processes for fastening method selection. Sodhi et al. [30] conducted experimental investigation on commonly used fastening methods to develop an unfastening effort (U-effort) model which was used to compute the unfastening time based on set of causal attributes such as size, shape, and operational characteristics. However, their method can only be applied for a limited type of fastening methods. Besides, other factors which influence the unfastening time such as the time needed for identifying joints, changing tools, positioning requirements, etc. were not considered. Güngör [31] adopted an analytic network process approach for the selection of connection types from the DFD perspective. In their methodology, assembly concerns, in-use period concerns, and disassembly concerns were considered. However, the ANP procedure requires running multiple scenarios which takes longer time to setup, hence can delay the product design process. Ghazilla et al. [32] proposed the PROMETHEE-based multi-criteria decision model for fastening method selection for disassembly. Qualitative and quantitative parameters which influence disassembly were taken into consideration. Kobayashi et al. [33] proposed a genetic algorithm approach for optimization of the time required for the removal of high-value components. Minimization of fastener removal time which is computed as summation of basic unfastening time and tool preparation time was considered as an objective function. Recently, Sabbaghi and Behdad [34] proposed a non-linear integer programming model to minimize the mean time to repair of products by considering the types of fastening methods used, the repairability needs, and the disassembly sequence as constraints.

From the review of related works, although some previous studies have proposed various methodologies for fastening methods selection, none of them considered both product assembly and disassembly issues in the product design stage from a remanufacturing perspective. To fill the research gap, we propose a methodology in this paper for fastening method selection which considers product assembly and disassembly issues simultaneously in the product design stage when both new and remanufactured products are planned to be offered in the markets. Details of the proposed methodology are presented in the next section.

3 Proposed methodology for fastening method selection

To minimize the total cost of assembly of new and remanufactured products and the disassembly of used product returns, the selection of fastening method during the design stage should consider both product assembly and disassembly issues. To this end, the proposed fastening method selection methodology is formulated as an optimization model whose objective function is to minimize the total product assembly and disassembly cost. The outline of the proposed methodology is given in Fig. 1. The fastening method selection problem is formulated as an optimization model which involves the selection of fastening method for individual parts such that the total product assembly and disassembly cost of products is minimized. To develop the model, estimates of the assembly and disassembly times of parts are required which are computed based on the estimates of fastening/unfastening times and several other factors which affect product assembly and disassembly. For the fastening/unfastening times, the database of fastening methods and their estimated fastening and unfastening times is required to be established. To solve the optimization model, the genetic algorithm (GA) approach is adopted in the study as it is widely used to solve combinatorial optimization problems. Details of the formulation of the

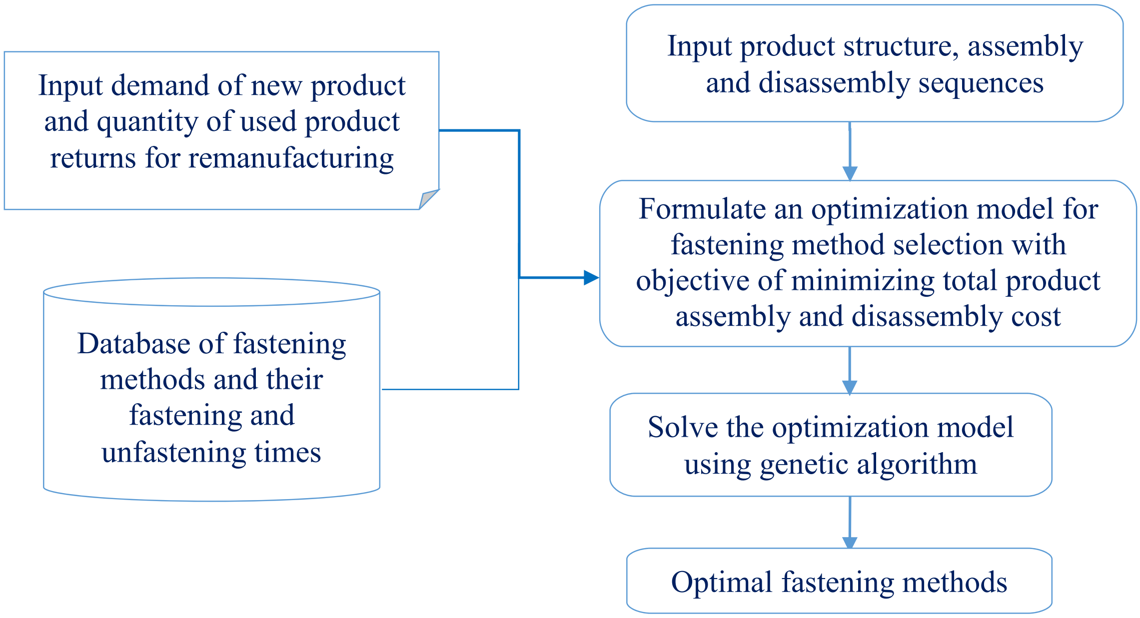

Fig. 1 Proposed methodology for fastening methods selection

optimization model and its solving are described in the following sub-sections.

3.1 Formulation of optimization model

In this study, the assembly difficulty factors, the disassembly difficulty factors, and the total assembly and disassembly costs are considered in the formulation of an optimization model. The following set of assumptions are considered for the formulation of the optimization model: (i) the optimal sequences of product assembly and disassembly are assumed to be known; (ii) the quality of product returns to be disassembled are assumed to be identical and hence individual products require the same degree of disassembly difficulty; (iii) product durability is not influenced by the types of fastening methods selected; (iv) the alternative fastening methods to be considered in the optimization model are assumed to fulfill the fastening requirements of products.

The following notations are used to formulate the optimization model:

Indices:

i Index for parts in a product, $i = 1, 2, 3, \cdots I$
j Index for fastening methods used in a part, $j = 1, 2, 3, \cdots J$

Parameters:

t_{ij}^{a} Assembly time of the ith part given the jth fastener is selected
t_{ij}^{d} Disassembly time of the ith part given the jth fastener is selected
t_{ij}^{pre} Tool preparation time when the jth fastener is selected for the ith part
t_{ij}^{acc} Time required for accessing the jth fastener selected for ith part
t_{ij}^{pos} Time required for positioning tool to unfasten the jth fastener from the ith part
t_{ij}^{f} Time required for fastening the jth fastener selected for the ith part
t_{ij}^{uf} Time required for unfastening the jth fastener selected for ith part
t_{i}^{h} Time required for handling the ith part
Q_{n} Quantity of new products demanded which are required to be assembled
Q_{r} Quantity of used products returned which are required to be disassembled
L Hourly rate of assembly and disassembly workers
W_{a} Number of assembly workers hired
W_{d} Number of disassembly workers hired
C_{as}^{n} Estimated cost of assembling new products
C_{dis}^{r} Estimated cost of disassembling used product returns
C_{as}^{r} Estimated cost of re-assembling remanufactured products
C_{T} Total cost of assembly, disassembly, and re-assembly
q_{ij}^{f} Quantity of jth fastener required to fasten the ith part
V_{max}^{f} The maximum number of types of fastening methods to be used on a single part
F_{ij}^{D} Fastening/unfastening direction, $F_{ij}^{D} \in \{-x, +x, -y, +y, -z, +z\}$
α_{i} Penalty due to change in fastening/unfastening direction between successive parts
β_{i} Penalty due to change in fastening method between successive parts

Decision variables:

s_i^j Binary variable which represents whether the j^{th} fastener is selected for the i^{th} part

$$= \begin{cases} 1, & \text{if } j^{th} \text{fastening method is selected for } i^{th} \text{ part} \\ 0, & \text{otherwise} \end{cases}$$

q_{ij}^f Quantity of the jth fastener selected for the ith part

The objective function of the optimization model is to minimize the total cost of assembly of new products, the disassembly of used product, and the re-assembly of remanufactured products which can be described by using Eqs. (1–6).

$$\text{Min}: C_T = C_{as}^n + C_{dis}^r + C_{as}^r \quad (1)$$

$$C_{as}^n = \frac{1}{3600} Q_n W_a L \left(\sum_i \sum_j \left(t_{ij}^a s_i^j q_{ij}^f \right) + \sum_i (\alpha_i + \beta_i) \right) \quad (2)$$

$$C_{dis}^r = \frac{1}{3600} Q_r W_d L \sum_i \sum_j \left(t_{ij}^d s_i^j q_{ij}^f \right) + \sum_i (\alpha_i + \beta_i) \Big) \quad (3)$$

$$C_{as}^r = \frac{1}{3600} Q_r W_a L \left(\sum_i \sum_j \left(t_{ij}^a s_i^j q_{ij}^f \right) + \sum_i (a_i + \beta_i) \right) \quad (4)$$

$$t_{ij}^a = q_{ij}^f t_{ij}^f + t_i^h \quad (5)$$

$$t_{ij}^d = q_{ij}^f * \left(t_{ij}^{acc} + t_{ij}^{pos} + t_{ij}^{uf} \right) + t_{ij}^{pre} + t_i^h \quad (6)$$

The following constraints are required in the formulation of the optimization model:

$$1 \le \sum_j s_i^j \le V_{max}^f, \forall i \in I \quad (7)$$

$$\sum_j s_i^j \le q_{ij}^f, \forall i \in I \quad (8)$$

$$\alpha_i = \begin{cases} 0, & \text{if fastening/unfastening direction of ithpart is same as its predecessor} \\ 1 \text{ sec}, & \text{if } 90° \text{direction change is required, e.g., from } +x \text{ to } +y \\ 2 \text{ sec}, & \text{if } 180° \text{direction change is required, e.g., from} -x \text{ to } +x \end{cases} \quad (9)$$

$$\beta_i = \begin{cases} 2.54 \text{ sec}, & \text{if fastening method of ithpart is different from its predecessor} \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

$$s_i^j \in \{0, 1\}, \quad \forall \ i, j \quad (11)$$

$$q_{ij}^f, \cdot \ge 0 \ \ \forall i, j \quad (12)$$

The constraints given in Eq. (7) and Eq. (8) are related to the quantity and variety of fastening methods used on a given part. Equation (7) ensures that at least one fastening method is selected and the number of types of fastening methods do not exceed the maximum variety fastening methods allowed on a single part. Equation (8) ensures the variety of fasteners cannot exceed the total quantity of fasteners selected for a given part. Equation (9) denotes the penalty time for fastening/unfastening direction change. Equation (10) denotes the penalty time for fastening method change. Equation (11) defines fastening method selection variable as binary. Equation (12) defines non-negativity for the quantity of fastening methods selected.

3.2 Estimation of assembly and disassembly time

The proposed methodology requires the estimation of the assembly and disassembly times of parts for each feasible alternative fastening method. In this study, five types of fastening methods are considered: (i) discrete fasteners (separate fasteners) such as screw and rivets used to join parts together; (ii) integral fasteners (integrated with parts) such as snap fits, locks, etc.; (iii) adhesive bonding such as glues; (iv) energy bonding such as welding and soldering which uses energy to create fastening between parts; and (v) other fasteners. A database of fastening/unfastening times of alternative fastening methods is required to be developed for the proposed methodology.

For estimation of the assembly time, techniques developed by Boothroyd et al. [18] were adopted in this study. According to this approach, the assembly time for each component is computed by summing up the handling time and insertion time provided by using a chart of synthetic data [18]. For instance, a component requires six pieces of Phillips PM2.5 × 4.5 screws to be assembled and the component is easily handled by assembly operators. The estimated time for handling the component and for tightening a single screw fastener based on the Boothroyd's DFA synthetic table partially shown in Fig. 2 is 2.5 s (corresponding to code 50) and 5 s (corresponding to code-92) respectively. Hence, the total assembly time can be computed as 2.5 + 6 × 5 = 32.5 s.

For estimation of the disassembly time, several factors which influence the disassembly time are considered, such as preparation time, unfastening time, part removal time, change in disassembly direction, and change in disassembly method. The Maynard Operation Sequence Technique (MOST) proposed by Kroll and Carver [35] is adopted in this study to estimate the time for each influencing factors. According to this technique, the motion related to each disassembly task is determined and modeled using general move, controlled move, and tool use sequence models [36]. For instance, to compute unfastening time, motion related to unfastening operation is modeled using the |Lx| parameter and removal of loose fastener(s) is modeled using the |AxBxGxAxPx| sequence of parameters. The unfastening time for Phillips PM2.0 × 3.0 fastening screw can be modeled as

MANUAL HANDLING-ESTIMATED TIMES (s)

Key: One hand

Parts can be grasped and manipulated by one hand without the aid of grasping tools		Parts are easy to grasp and manipulate					Parts present handling difficulties (1)				
		Thickness >2 mm			Thickness ≤2 mm		Thickness >2 mm			Thickness ≤2 mm	
		Size >15 mm	6 mm ≤ size >15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm	Size >15 mm	6 mm ≤ size ≤15 mm	Size <6 mm	Size >6 mm	Size ≤6 mm
		0	1	2	3	4	5	6	7	8	9
(α+β) < 360°	0	1.13	1.43	1.88	1.69	2.18	1.84	2.17	2.65	2.45	2.98
360° ≤ (α+β) < 540°	1	1.5	1.8	2.25	2.06	2.55	2.25	2.57	3.06	3	3.38
540° ≤ (α+β) < 720°	2	1.8	2.1	2.55	2.36	2.85	2.57	2.9	3.38	3.18	3.7
(α+β) = 720°	3	1.95	2.25	2.7	2.51	3	2.73	3.06	3.55	3.34	4

Key: Separate operation

		Mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-mechanical fastening processes (part(s) already in place but not secured immediately after insertion)				Non-fastening processes	
		None or localized plastic deformation			Bulk plastic deformation (large proportion of part is plastically deformed during fastening)	Metallurgical processes			Chemical processes (e.g. adhesive bonding, etc.)	Manipulation of parts or sub-assembly (e.g. orienting, fittings or adjustment of part(s), etc.)	Other processes (e.g. liquid insertion, etc.)
		Bending or similar process	Riveting or similar processes	Screw tightening or other processes		No additional material required (e.g. resistance, friction welding, etc.)	Additional material required: Soldering processes	Additional material required: Weld/braze processes			
		0	1	2	3	4	5	6	7	8	8
Assembly processes where all solid parts are in place	9	4	7	5	12	7	8	12	12	9	12

Fig. 2 Synthetic data for estimates of manual handling and insertion times (extracted from [18])

|L10|+ |A1B0G1A1P1| which corresponds to 140 time-measurement-units (100 + 10 + 0 + 10 + 10 + 10 = 140 TMUs or 140 × 0.036 = 5.04 s). Values of the indices are determined based on the MOST data card [18]. Table 1 presents example of disassembly time estimation considering a part which involves four units of Phillips PM2.0 × 3.0 screws. After time estimates corresponding to the factors which affect the disassembly time are determined, the disassembly time of a part is computed based on Eq. (6) as t_{ij}^{d} =4(1.08 + 1.4 + 5.04) + 2.52 + 2.88 = 35.5 s.

3.3 Solving the optimization model

The search space of the fastening method selection problem could be very large as the problems often involve large number of alternative fastening methods and the consideration of various assembly and disassembly related factors. Thus, deterministic solving techniques may not be effective to solve such a problem. Various studies have shown that metaheuristic solving techniques such as GA, simulated annealing, and ant colony optimization could solve such a problem well [37]. In

Table 1 Example of disassembly time estimation

		Times due to influencing factors (sec)					
Part index, i	Fastener index, j	Quantity of fasteners q_j^f	Accessibility t_{ij}^{acc}	Positioning t_{ij}^{pos}	Tool preparation t_{ij}^{pre}	Unfastening t_{ij}^{uf}	Part removal t_i^h
1	1	4	1.08	1.4	2.52	5.04	2.88

this study, GA is adopted to solve the optimization model as it has been widely used to solve combinatorial optimization problems. According to the proposed GA approach, the sequence of genes in a chromosome represent the part index, the selected fastening method, the fastening/unfastening direction, the assembly time, and the disassembly times respectively as shown in Fig. 3.

The length of a chromosome is defined by the number of parts considered. While part indices are taken from product assembly/disassembly sequence information, fastening methods are randomly selected from feasible alternative fastening methods. The corresponding assembly and disassembly time are obtained from the fasteners database. For instance, the chromosome structure shown in Fig. 4 represents the 1st index part fastened by 2nd index fastening method in the + z direction which requires an assembly time of 4.5 s and disassembly time of 5.5 s.

The next procedure in GA involves (i) the evaluation of chromosomes (potential solutions) based on the fitness function, i.e., total assembly and disassembly cost; (ii) selection, (iii) crossover and (iv) mutation operations to creation of new population. In this research, roulette wheel selection procedure is employed to select chromosomes for subsequent operation. For the crossover operation, the one-point crossover technique is adopted where the point of crossover is selected randomly based on the crossover rate. This operation interchanges the sequence of genes which represent the selected fastening method, the assembly time, and the disassembly time between two parents to create new child chromosomes which retain some of the parents' characteristics. For the mutation, the genes which represent the fastening methods (and estimated assembly and disassembly times) are randomly swapped with a very low probability. Mutation operation ensures genetic diversity is maintained from one generation of a population of chromosomes to the next.

4 Case study

The proposed methodology can be applied to a wide range of product types such as consumer electronics, office equipment, and computer products. To illustrate the applicability of the proposed methodology and to evaluate its effectiveness, a case study on fastening method selection for a laptop computer is presented in this section. The case study considers a company which faces an increasing social concern on environmental friendliness and stringent environmental protection laws and hence plans to remanufacture laptop computers. Figure 5 shows the assembly structure and component information of the product.

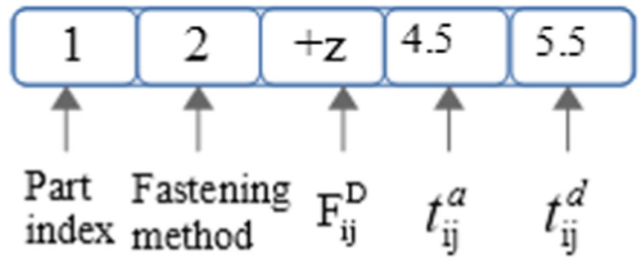

Fig. 4 Chromosome encoding

A total of 14 major components, all of which are assembled on the bottom casing, are considered in the case study. In the design of the laptop, disassemblablity issues were not properly considered. Table 2 shows the types and quantity of fastening methods used, and the estimated assembly and disassembly times of the original design. The assembly and disassembly times were estimated according to the methods described in Section 3.2.

It was assumed that four assembly/disassembly workers are required to undertake the product assembly/disassembly operations with a labor wage rate of US$15 per hour. To facilitate assembly during manufacturing of new laptops and disassembly of used laptop returns, appropriate fastening methods must be considered during the design of the new laptop computer. Six types of alternative fastening methods were considered in the design of new laptop: retaining tabs, cantilever snap fit (snapfit-1), cylindrical snap fits (snapfit-2), Philips PM2.5 × 3.0 screws, captive screws, and adhesives.

The proposed methodology is applied to select appropriate fastening methods for the new laptop which will minimize the total product assembly and disassembly cost. A set of possible solutions (chromosomes) are generated randomly. The sequence of genes in a chromosome represent the part index, index of the fastening method selected, and the assembly/disassembly direction respectively as shown in Fig. 6.

To determine the appropriate settings of parameters for the GA, different values of crossover rate, mutation rate, and number of population were investigated. First, the population size was varied from 40 to 180 in steps of 20 keeping the crossover and mutation rates at 0.5 and 0.01 respectively. The results of the experiment as shown in Fig. 7 indicate that a population size of 160 provides better convergence. Next, the crossover rate was varied between 0.5 and 1.0 in steps of 0.1 keeping the population size at 160 and the mutation rate at 0.01. Similar experiment was conducted to determine the setting of the mutation rate. Based on the experimental results as shown in Fig. 7, the crossover rate, mutation rate, and

Fig. 3 Chromosome encoding

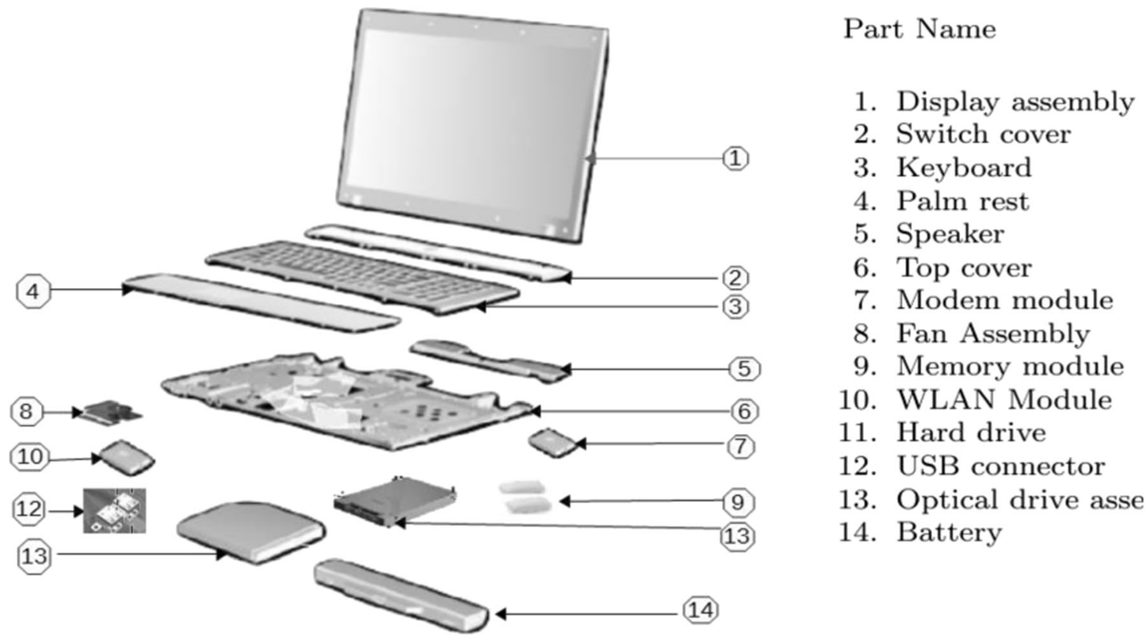

Fig. 5 Parts information of the case product

Table 2 Fastening methods used in the original design

Part index, i	Part name	Fastening methods	F_{ij}^{D}	q_{ij}^{f}	t_{ij}^{a}	t_{ij}^{d}	$t_{ij}^{a}+t_{ij}^{d}$
1	Display assembly	PM2.5 × 4.5	$-x$	6	32.5	45.7	78.2
2	Switch cover	PM2.5 × 3.0	$+z$	7	37.5	52.9	90.4
3	Keyboard	PM2.5 × 4.5	$+z$	2	12.5	16.9	29.4
4	Palm rest	PM2.0 × 3.0	$+z$	3	17.5	24.1	41.6
5	Speaker	PM2.0 × 30	$+z$	4	22.5	31.3	53.8
6	Top cover	T8M2.5 × 6.0	$+z$	22	167.5	222.5	390
7	Modem module	PM2.5 × 3.0	$+z$	2	12.5	16.9	29.4
8	Fan assembly	PM2.5 × 8.0	$+z$	7	37.5	72.5	110
9	Memory module	Retaining tab	$-y$	2	4	5.04	9.04
10	WLAN module	PM2.5 × 3.0	$+z$	2	12.5	16.9	29.4
11	Hard drive	PM2.0 × 4.0	$+z$	3	17.5	24.1	41.6
12	USB connector	PM2.5 × 3.0	$+z$	2	12.5	19.7	32.2
13	Optical drive	PM2.5 × 4.5	$-y$	1	7.5	9.7	17.2
14	Battery	Releasable latches	$+z$	4	4	5.04	9.04
				Total	398	563.3	961.3

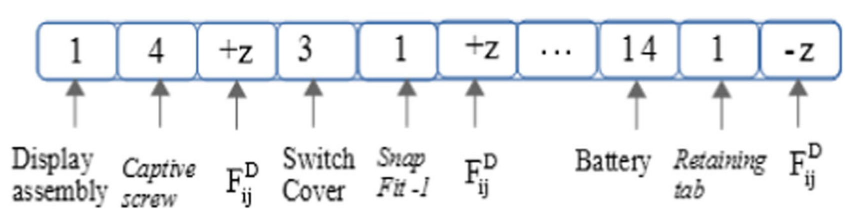

Fig. 6 Chromosome encoding

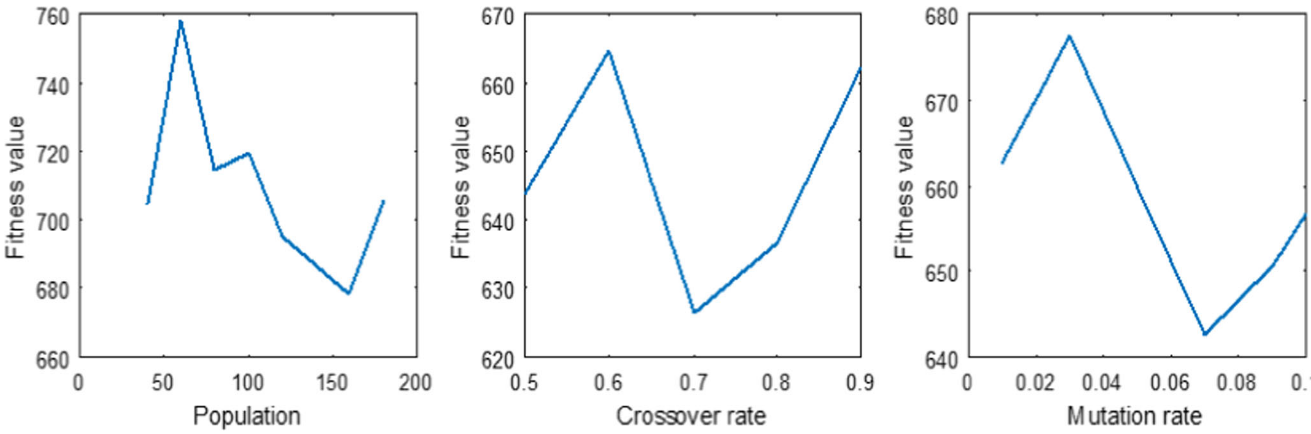

Fig. 7 Convergence rate for different GA parameters

population size were set as 0.7, 0.07, and 160 respectively. The GA was then set to run for 100 generations to solve the optimization model. Figure 8 shows the convergence pattern of the GA solution obtained after 62 generations. Table 3 shows the fastening methods selected by GA algorithm and the corresponding assembly and disassembly times for each part. It can be seen from the results that the fastening methods selected based on the proposed methodology resulted in a reduction of 361 s (from 961 to 600), which is approximately 6 min, in the total assembly and disassembly time of a product.

4.1 Effectiveness of the proposed approach in terms of cost savings

To investigate the effectiveness of the proposed methodology on reducing cost, two cost savings are calculated. First, the optimization model was modified by removing the consideration of product disassembly. GA was employed again to solve the model and a new set of fastening methods was obtained which is named as the solution obtained based on DFA in this paper. Table 4 shows the product assembly and disassembly times computed based on the original fastening methods, fastening methods selected based on the DFA methodology and the proposed methodology. The disassembly times and assembly times were computed according to the methods discussed in Section 3.2.

Then, three scenarios of the demands of new and remanufactured products as shown in the upper part of Table 5 are considered with respect to cost savings. For each scenario, the total product assembly and disassembly costs, CT, of the new and remanufactured products were calculated based on the original design, DFA, and proposed methodology as shown in lower part of Table 5. Hence, two cost savings can be calculated. The first cost saving, CS_1, is calculated by subtracting the total assembly and disassembly cost calculated based on DFA from that based on proposed methodology. The

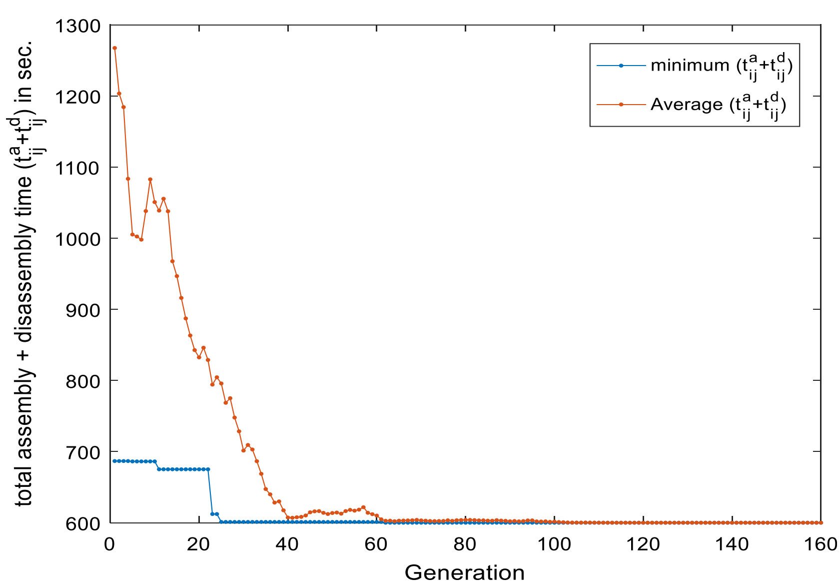

Fig. 8 Convergence rate of the minimum total assembly and disassembly time

Table 3 Fastening methods selected based on the proposed methodology

Part index, i	Part name	Fastening method, j	q_{ij}^{f}	t_{ij}^{a} (sec)	t_{ij}^{d} (sec)	$t_{ij}^{a}+t_{ij}^{d}$ (sec)
1	Display assembly	PM2.5 × 4.5	8	32.5	45.7	78.2
2	Switch cover	Snap fit-1	2	20	38.5	58.5
3	Keyboard	PM2.5 × 4.5	4	12.5	16.9	29.4
4	Palm rest	PM2.5 × 4.5	4	17.5	24.1	41.6
5	Speaker	PM2.5 × 4.5	4	22.5	31.3	53.8
6	Top cover	Snap fit-1	8	40	74.5	114.5
7	Modem module	PM2.5 × 4.5	2	12.5	16.9	29.4
8	Fan assembly	Snap fit-1	4	20	38.5	58.5
9	Memory module	Snap fit-1	2	4	4	8
10	WLAN module	PM2.5 × 4.5	2	12.5	16.9	29.4
11	Hard drive	Snap fit-1	2	20	20.5	40.5
12	USB connector	PM2.5 × 4.5	1	12.5	19.7	32.2
13	Optical drive	PM2.5 × 4.5	2	7.5	9.7	17.2
14	Battery	Retaining tab	4	4	5.04	9.04
	Total			238	362.24	600.24

Table 4 Comparison of the assembly and disassembly times

Part index, i	Selected fastening method (j)			Original		DFA		Proposed methodology	
	Original	DFA	Proposed methodology	t_{ij}^{a}	t_{ij}^{d}	t_{ij}^{a}	t_{ij}^{d}	t_{ij}^{a}	t_{ij}^{d}
1	PM2.5 × 4.5	PM2.5 × 4.5	PM2.5 × 4.5	32.5	45.7	32.5	45.7	32.5	45.7
2	PM2.5 × 3.0	Snap fit-1	Snap fit-1	37.5	52.9	20	38.5	20	38.5
3	PM2.5 × 4.5	PM2.5 × 4.5	PM2.5 × 4.5	12.5	16.9	12.5	16.9	12.5	16.9
4	PM2.0 × 3.0	Adhesive	PM2.5 × 4.5	17.5	24.1	14.5	100	17.5	24.1
5	PM2.0 × 30	Adhesive	PM2.5 × 4.5	22.5	31.3	14.5	100	22.5	31.3
6	T8M2.5 × 6.0	Adhesive	Snap fit-1	167.5	222.5	29	300	40	74.5
7	PM2.5 × 3.0	PM2.5 × 4.5	PM2.5 × 4.5	12.5	16.9	12.5	16.9	12.5	16.9
8	PM2.5 × 8.0	Snap fit-1	Snap fit-1	37.5	72.5	20	38.5	20	38.5
9	Retaining tab	Snap fit-1	Snap fit-1	4	5.04	4	4	4	4
10	PM2.5 × 3.0	PM2.5 × 4.5	PM2.5 × 4.5	12.5	16.9	12.5	16.9	12.5	16.9
11	PM2.0 × 4.0	PM2.5 × 4.5	Snap fit-1	17.5	24.1	17.5	24.1	20	20.5
12	PM2.5 × 3.0	PM2.5 × 4.5	PM2.5 × 4.5	12.5	19.7	12.5	16.9	12.5	19.7
13	PM2.5 × 4.5	PM2.5 × 4.5	PM2.5 × 4.5	7.5	9.7	7.5	9.7	7.5	9.7
14	Releasable latches	Retaining tab	Retaining tab	4	5.04	4	5.04	4	5.04
			Total	398	563.3	213.5	733.1	238	362.2

Table 5 Total cost of assembly and disassembly under different scenarios

		Scenario 1	Scenario 2	Scenario 3
Demand	New products, Q_n	40,000	40,000	40,000
	Remanufactured products, Q_r	8000	12,000	15,000
Total cost C_T (US$)	Original design	393,504	457,589.3	505,653.3
	DFA	268,552	331,661.3	378,993.3
	Proposed methodology	238,699	278,715	308,727

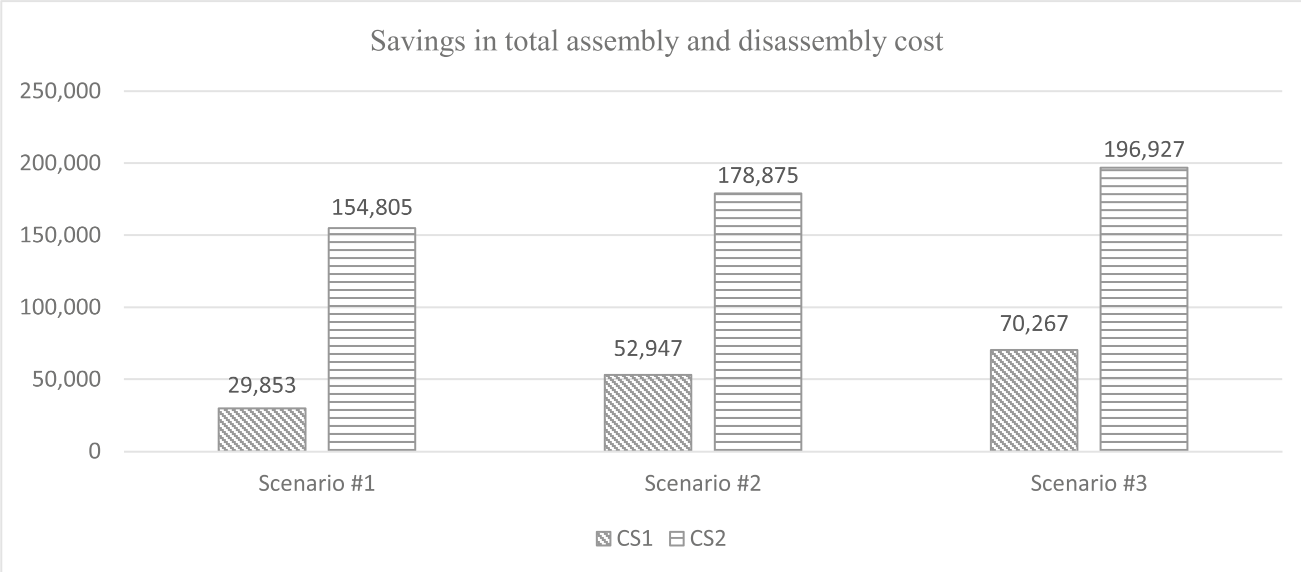

Fig. 9 Savings in total assembly and disassembly cost under different scenarios

second cost saving, CS_2, can be calculated by subtracting the total assembly and disassembly cost calculated based on original design from that based on proposed methodology.

Figure 9 shows the CS_1 and CS_2 of individual scenarios from which it can be found that the proposed methodology provides higher cost savings under all the three scenarios.

4.2 Effect of degrees of product disassembly

Different degrees of product disassembly are often required in remanufacturing because of variations in the quality of individual product returns. To investigate the effect of degrees of product disassembly on the cost savings, the degrees of product disassembly ranging from "0.1" to "1" were studied. The "0.1" degree indicate a slight disassembly while the "1" degree indicate a complete disassembly. Figure 10a, b shows the cost savings obtained by subtracting the total assembly and disassembly cost calculated based on the proposed methodology from the total assembly and disassembly cost calculated based on original design and the DFA approach respectively. The results show that the proposed methodology provides higher cost savings when higher degree of product disassembly is involved. Nevertheless, the result shown in Fig. 10b also indicates that the DFA approach provides a better cost saving

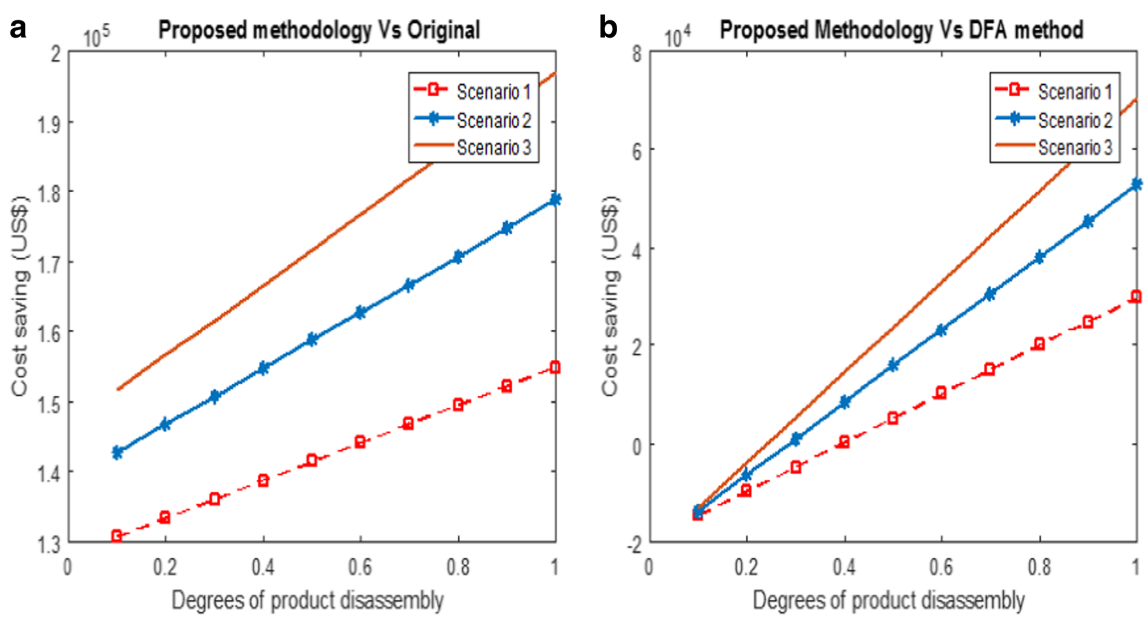

Fig. 10 Cost savings when compared with **a** original fastening methods and **b** fastening methods selected based on DFA method

for the scenario where fewer number of used products are returned which require a small degree of disassembly.

5 Conclusion

The types of fastening methods selected in the product design stage affect not only the assembly efficiency of new products but also the disassembly efficiency of used product returns for remanufacturing. Thus, the selection of fastening methods should consider both product assembly and disassembly issues simultaneously in the product design stage. However, no previous studies on fastening method selection was found thus far which addressed both issues simultaneously for fastening method selection from a remanufacturing perspective.

In this research, a methodology for fastening method selection which considers both product assembly and disassembly simultaneously in the product design stage is proposed. In the proposed methodology, the fastening method selection problem is modeled as an optimization model with the objective function of minimizing the total product assembly and disassembly cost. The genetic algorithm is proposed to solve the optimization model. The solution of the optimization model serves as a design guide to select appropriate fastening methods which minimize the total cost of assembly and disassembly in remanufacturing. To illustrate the applicability of the proposed methodology, a case study on a company which offers both new and remanufactured version of a laptop computer was conducted. The proposed fastening method selection methodology was applied to select appropriate fastening method for the laptop computer such that the total cost of assembly of new laptops and disassembly of used laptop returns were minimized. To evaluate the effectiveness of the proposed methodology, different scenarios of the demand of remanufactured products and the degrees of product disassembly were studied. The results of the studies have shown that the proposed methodology can yield better cost savings in product assembly and disassembly in all scenarios compared with the original fastening methods and the fastening methods determined based on DFA.

The proposed methodology can be extended to include consideration of conditions of returned products. In this study, the conditions of returned products are assumed to be identical, which means that each used product return requires the same effort in disassembly. However, the condition of individual product returns could vary which would require different disassembly efforts. Further work would involve the modeling of conditions of used product returns and the consideration of the impact of condition variability in the proposed methodology.

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