Simultaneous consideration of assemblability and disassemblability for fastening method selection

M.W. Geda and Dr. C.K. Kwong
Department of Industrial and Systems Engineering
The Hong Kong Polytechnic University
Hong Kong, China
mohammed.w.geda@connect.polyu.hk, c.k.kwong@polyu.edu.hk

Abstract

Remanufacturing has achieved increased attention in recent years for reprocessing end-of-use (EUO) and end-of-life (EOL) products. Technical feasibility as well as profitability of a remanufacturing process is affected by the assemblability and disassemblablity of products. Selection of fastening methods during the design stage affects not only product assemblability but also the disassemblability of used products for remanufacturing. Fastening methods selected for easier assembly during initial manufacturing may cause difficulties during disassembly for remanufacturing or vice versa. This would in turn have an impact on the cost of assembly and disassembly. Hence, decisions made during early product development regarding fastening method should address assemblability, disassemblability and cost concerns. In previous studies, simultaneous consideration of assemblabilty, disassemblablity and cost factors for fastening method selection was not addressed properly. In this paper, a methodology for fastening method selection is proposed by which all the three factors are simultaneously considered in the selection of fastening methods. In the proposed methodology, the selection problem is formulated as an optimization model with the objective of minimizing the overall assembly and disassembly costs. Genetic algorithm (GA) are employed to solve the model. A case study on the selection of fastening methods for laptop computers is conducted to illustrate the proposed methodology and to evaluate its effectiveness.

Keywords
Design for Disassembly, Design for Assembly, Fastener Selection, End-of-life products, Genetic Algorithm

1. Introduction

Over the last few years, various countries have passed directives and legislation which hold manufacturers responsible for taking back and reprocessing end-of-use (EOU) and end-of-life (EOL) products in an environmentally friendly manner. Remanufacturing has gained increasing attention in recent years as a sustainable and profitable product recovery option (Lund & Hauser, 2010; Matsumoto et al., 2016). Remanufacturing is an industrial process whereby a used products is brought back to operating condition through reuse, refurbishment and replacement of its components (Ismail et al., 2014; Östlin et al., 2009). Giutini and Gaudette (2003) estimated that the cost of producing a remanufactured product is 40–65% lower compared to that of a new product. Despite the attractiveness of the remanufacturing business, quite a few companies such as Apple, Fuji Xerox, HP, and Sony are currently offering remanufactured products in the market. It was reported that most of the technical barriers to product remanufacturability are due to design issues (Charter & Gray, 2008; Yang et al., 2016). Remanufacturability of EOU and EOL products is largely affected by their disassemblability.

Types of fastening methods used during the design stage affects product's disassemblablity. Decision making with regard to the selection of fastening method is a critical and challenging task for designers when remanufacturing is planned to be undertaken. This is due to the fact that fastening methods which facilitate assembly during initial manufacturing may cause difficulties during disassembly when used products are disassembled for component recovery. Similarly, fastening methods which can facilitate disassembly of used products may not be appropriate from an assembly point of view. For example, fastening methods such as snap-fit joints, and adhesives are quick and require little effort to assembly, but cause difficulty in disassembly. Therefore, to facilitate remanufacturing of used products, design for disassembly (DfD) should be considered together with design for assembly (DFA) when selecting fastening methods. Quite few studies have attempted to develop DFA and DFD based methodologies for fastening method selection. However, simultaneous consideration of assemblability, disassemblability and cost issues during the design stage was not properly addressed in previous studies. In this paper, a methodology for fastening method selection is proposed where DFA, DFD and cost concerns are simultaneously considered. In the proposed methodology, the fastening method selection problem is formulated as an optimization model with the objective of minimizing the overall assembly and disassembly costs. Genetic algorithms (GA) are employed to solve the model.

The rest of the paper is organized as follows. Section 2 presents a review of related studies. The proposed methodology for fastening method selection is described in Section 3. In Section 4, a case study of selection of fastening method for a laptop design is presented to illustrate the proposed methodology. Finally, conclusion and future work are presented in Section 5.

2. Literature review

Assemblability and disassemblability of a product are critical factors which affect cost effectiveness of manufacturing new products as well as remanufacturing of used products. To minimize overall assembly and disassembly costs, assemblability and disassemblability issues must be considered during the design stage. To this end, several design for assembly (DFA) and design for disassembly (DFD) based methods have been developed over the past few decades to facilitate products assemblability and disassemblability.

Conventional DFD based methods mainly involve evaluation of a product's design using disassembly difficulty factors. Ehud Kroll (1996); Ehud Kroll and Carver (1999); E. Kroll and Hanft (1998) developed a disassembly difficulty evaluation chart based on work measurement analysis of standard disassembly tasks. Desai and Mital (2005) developed a disassemblablity evaluation score based on factors such as the degree of accessibility of fasteners and components, force, tool, and positioning requirements, and material handling factors. Das et al. (2000) developed a multi-factor index to estimate disassembly effort required using factors such as time, force, tool and fixture requirement, degree of accessibility and hazard. Sabaghi et al. (2016) developed a methodology to evaluate the disassemblablity of components. They considered five parameters: accessibility, relative position of components, tools requirement, type and quantity of fastening methods used. Soh et al. (2016) proposed a methodology to compute a disassembly index of disassembly routes based on the disassembly complexity and part accessibility. In their methodology, factors such as part handling difficulty, fastener removal difficulty and directional constraints were considered. Hitachi (Tokyo, Japan) developed a method known as the Disassemblability Evaluation Method (DEM) for quantitative evaluation of the ease with which a product can be disassembled (Go et al., 2011).

Disassembly evaluation based on disassembly time provides objective measures on the disassemblability of a product. In addition, it can also help designers conduct feasibility studies of the disassembly operation. In this regard, few previous studies have proposed disassembly time as a measure of disassemblablity of a product design. Ehud Kroll and Carver (1999) developed a disassembly time estimation method based on the MOST work-measurement system. Yi et al. (2003) developed a method to estimate the disassembly time using the work factor method. According to their method, total disassembly time calculated by adding time estimates for preparation, movement, disassembly and post-processing operations. Desai and Mital (2003, 2005) developed a method of estimating the disassembly time which was computed by assigning time based numeric difficulty scores to factors such as force, material handling, tool requirement, accessibility of components and fasteners, and tool positioning.

Assemblability evaluation during the design stage has not been adequately addressed in previous studies. Most of the studies conducted on assemblability evaluation involved assigning scores to factors which could affect the assembly process as well as interpretation of the scores to suggest design improvements. Early work in this regard includes the Boothroyd–Dewhurst (B&D) method, the Lucas method, the Hitachi Assembly Evaluation Method. B&D is a design procedure which involves two-steps: evaluation of parts for elimination and estimating an assembly time by determining the size, orientation/symmetry, handling, and insertion difficulties (Boothroyd et al., 2010). The Lucas DFA method measures the relative assembly difficulty based on three indices: functional, feeding (or handling) and fitting (Mašín, 2014). Hitachi's Assembly Evaluation Method (AEM) measures the assemblability score of parts on a 100 point scale (Leaney, 1996). To compute the AEM score, a part which can be assembled by simple downward motion without resistance is assigned 100 points and any deviation from this ideal scenario gets penalized. Gao et al. (2014) proposed quantitative assessment of component assemblability according to an estimate of its assembly time. Overall product assemblabilty is then determined on the basis of the assemblability of each component.

The efficiency of assembly operations during initial manufacturing and disassembly operations during EOL reprocessing depend on the type of fastening methods used. Therefore, for companies which offers both new and remanufactured products, it is essential to consider both assembly and disassembly concerns when selecting fastening methods. Previous studies developed methodologies for fastening method selection. Shu and Flowers (1999) considered the probabilities of failure of fasteners due to disassembly and reassembly as a criteria for selecting fastening methods. Sodhi et al. (2004) conducted experiments on commonly used fastening methods to develop an unfastening effort (U-effort) model which allows designers to evaluate fasteners based on casual attributes such as size, shape and operational characteristics. However, this method can only be applied for limited number of fastener categories. Further, it did not account for factors such as the time needed for identifying joints, changing tools, positioning etc. Güngör (2006) adopted analytic network process (ANP) approach for selection of connection types from the DFD perspective. The ANP procedure requires running multiple scenarios which could delay the product design process. Ghazilla et al. (2014) proposed a multi-criteria decision model based on PROMETHEE for selecting fastening methods for disassembly. In their method, qualitative and quantitative parameters which influence disassembly were taken into consideration. Kobayashi et al. (2015) proposed a method for optimizing fastening methods using a genetic algorithm. Their method allows selection of fastening methods for efficient disassembly for reuse and recycling with minimum fastener removal time. Recently, Sabbaghi and Behdad (2017) proposed a non-linear integer programming model to minimize the mean time to repair products by considering connection criteria, reparability needs, and the disassembly sequence as constraints.

In the previous studies on fastening method selection, assemblability and disassemblability issues were considered separately. This result in a suboptimal solution by only improving efficiency of either the assembly process during initial manufacturing or the disassembly process during EOL processing. Besides, the impact of fastening method selection on the overall cost of assembly and disassembly operations were not addressed in previous studies.

3. Proposed methodology for fastening method selection

In this research, a new methodology is proposed which simultaneously considers assemblabilty, disassemblablity and cost factors for fastening method selection. Figure 1 outlines the proposed methodology. The fastening method selection problem involves comparison of large number of fasteners, so heuristic search algorithms can be used to obtain reasonably good results in short computation time. In the proposed methodology, genetic algorithm (GA) is adopted to solve the optimization model to determine optimal fastening methods which minimizes the overall assembly and disassembly cost.

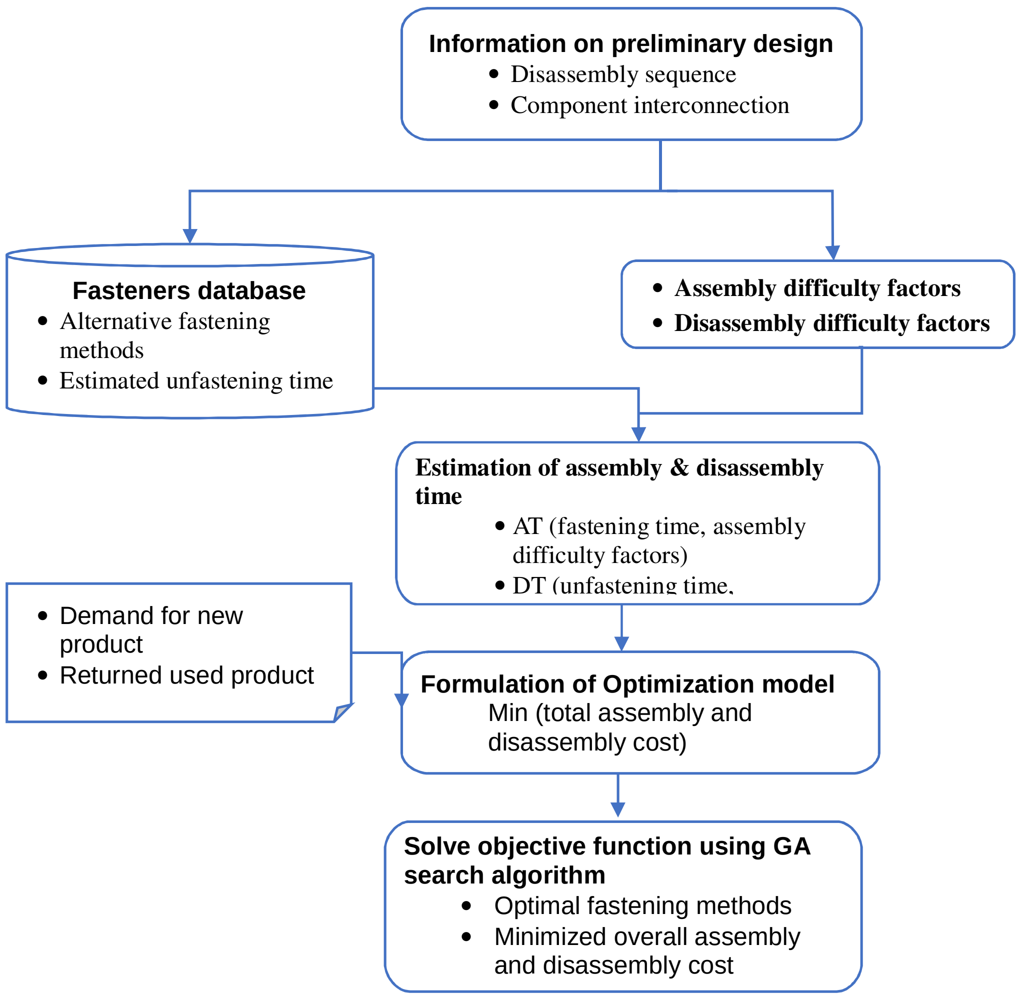

Figure 1. Proposed methodology for fastening method selection

3.1 Formulation of the optimization model and solution

The following notations are used for GA formulation:

N	total number of parts/components in a product
F	number of types of alternative fastening methods
i	part index according to a disassembly sequence
j	index of fastening methods
at_{ij}	estimate of assembly time of i^{th} part when j^{th} fastening method is used
dt_{ij}	estimate of disassembly time of i^{th} part when j^{th} fastening method is used
AT	estimated product assembly time
DT	estimated product disassembly time
TC	total assembly and disassembly cost

To implement GA, candidate solutions to the problem are encoded in chromosomes to generate the initial population. Encoding of a chromosome involves representation of sequence of four elements: the 1st section represents the part index, 2nd section represents the selected fastening method, the 3rd and 4th represent the assembly and the disassembly time respectively as shown in figure 2.

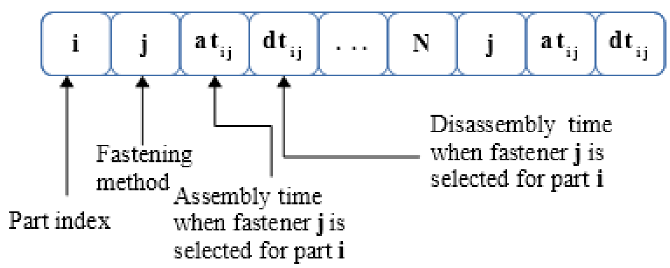

Figure 2. Chromosome encoding

Input data for part index is obtained from assembly and disassembly sequence information. We assume the same sequence for assembly and disassembly. Fastening methods are randomly selected. Related assembly and disassembly time are read from a fastener data-base. For instance, the chromosome structure shown in figure 3 represents the 1^{st} part in the assembly/disassembly sequence, joined by a type-2 fastening method, which is characterized by assembly time of 4.5 sec and disassembly time of 5.5 sec.

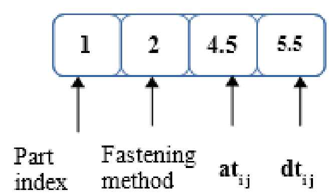

Figure 3. Example of chromosome encodings

After the initial population is created from a random set of chromosomes, i.e feasible solutions, each chromosome is evaluated based on a fitness function. Total assembly and disassembly cost is considered as a fitness function, and cost include the labor and tool cost required to perform assembly and disassembly operations. To compute the product assembly and disassembly cost, estimates of product assembly time and disassembly time is required. Procedure to estimate the assembly and disassembly times is discussed in section 3.2. Computation procedure for the fitness function is described in the following equations:

$$\text{Disassembly time of a product, } DT = \sum_{i=1}^{N} dt_i \quad (1)$$

$$Assembly\ time\ of\ a\ product, AT = \sum_{i=1}^{N} at_i \quad (2)$$

$$Total\ assembly\ and\ disassembly\ cost, TC = Labor\ cost + Tool\ cost$$
$$= (QnxAT + QrxDT)x(R1 + R2) \quad (3)$$

where

- Q_n and Qr represent the quantity of new products to be assembled and the quantity of used products to be disassembled respectively,
- R1 and R2 denote the average per hour rate of assembly/disassembly worker and the average per hour rate of tooling used for assembly/disassembly operations respectively

The next step in GA implementation is to apply selection, crossover and mutation operations. The selection operation evaluates candidate chromosomes (potential solutions) based on fitness function, i.e. the total assembly and disassembly cost. In this research, roulette wheel selection technique is employed. For crossover operation, the one-point crossover technique is adopted where the point of crossover is selected randomly for selected chromosome pairs. Candidate chromosomes for crossover are selected based on the crossover rate. This operation interchanges a sequence of genes between the two parents to create new offspring chromosomes. The sequence of genes interchanged are those which represent the fastening method, assembly time and disassembly time. Mutation operation ensures genetic diversity is maintained in the population. The swap mutation operator is employed in this study in which contents of two randomly chosen sequence of genes representing the 'fastening methods', 'assembly time' and 'disassembly time' are swapped.

3.2 Assembly and disassembly time estimate

In this study, disassembly time is estimated based on the time estimates for preparation, unfastening operation and part removal. Table 1 outlines descriptions of the factors which influence the disassembly time under each time category.

Table 1. Factors which influence disassembly time

S.no	Time category	Influencing factor	Description of the factor
1	Preparation time	Joint accessibility	Time spent accessing joints
		Positioning	Degree of accuracy required to position tool against fastening element
		Preparation of tool	Time spent to reach and access tool
2	Unfastening time	Type and quantity of fasteners	Time spent for unfastening and removing of loose fasteners
3	Part removal time	Handling due to part size, thickness and symmetry	Time spent for handling and manipulating loose part for removal

The Maynard Operation Sequence Technique (MOST) proposed by Ehud Kroll and Carver (1999) is adopted to estimate each time category. According to this technique, motion related to each disassembly task is determined and modelled using general move, controlled move and tool use sequence models (Zandin, 2002).To compute the unfastening time, motion related to unfastening operation is modeled using the |Lx| parameter and removal of loose fastener(s) is modelled using the |AxBxGxAxPx| sequence of parameters. Index values for the parameters are determined based on the MOST data card provided by Zandin (2002). To illustrate the technique, the disassembly time calculation for dismantling a part fastened using a Phillips PM2.0×3.0 screw is illustrated in table 2. Unfastening time for this task is modelled as |L10|+ |A1B0G1A1P1| according to the MOST sequence. This sequence corresponds to 140 time-measurement-units (100+10+0+10+10+10=140 TMUs) which is equivalent to 140*0.036 sec=5.04 seconds.

Table 2. Example of disassembly time calculation

Fastener type	Fastener quantity (Qf)	Joint accessibility (t_{ij}^{acc})	Positioning (t_{ij}^{pos})	Preparation of tool (t_{ij}^{pre})	Unfastening time (t_{ij}^{uf})	Part removal time (t_{ij}^{rem})
PM2.0X3.0 screw	4	1.08	1.4	2.52	5.04	2.88
Part disassembly time, $\boldsymbol{dt}_{ij}=q_{ij}^{f} * (t_{ij}^{acc}+t_{ij}^{pos}+t_{ij}^{uf})+t_{ij}^{pre}+t_{ij}^{rem}$ $\boldsymbol{dt_{ij}}$ = 4x(1.08+1.4+5.04)+2.52+2.88=**35.5sec**						

.

To estimate the assembly time, the DFA method proposed by B&D is adopted in this study (Boothroyd et al., 2010, pp. 83-84). B&D conducted a large number of empirical observations of manual assembly tasks involving various operators and equipment and proposed a method for estimating assembly time of a product. Based on part's assembly information, the method uses catalog of generic part features to estimate handling and insertion difficulties. Each handling and insertion difficulty has a code which is used to retrieve the associated insertion and handling time. The obtained handling and insertion times are then added together to determine the overall assembly time of a part. The procedure is repeated for all parts to determine overall assembly time of a product.

4. Case Study

To validate the proposed methodology, a case study was conducted on fastening method selection for a laptop computer. The case considered is a company which offers both new and remanufactured product. It is assumed that each product returned to be remanufactured will be disassembled to individual parts. List of parts, fastening methods used in original design, assembly time, and disassembly time are given in table-3. The assembly time and disassembly time pertaining to alternative fastening methods is computed using assembly and disassembly time computation procedure described in section 3.1.

Table 3. Fastening method used in original design

Part Index	Part List	Fastening method	No. of fastening element	at_{ij} (sec)	dt_{ij} (sec)	at_{ij} +dt_{ij} (sec)
1	Battery	Releasable latches	2	4	5.04	9.04
2	Switch cover	PM2.5×3.0 screws	7	37.5	52.9	90.4
3	Keyboard	Phillips PM2.5×4.5	2	12.5	16.9	29.4
4	Palm rest	Phillips PM2.0×3.0	3	17.5	24.1	41.6
5	Speaker	Phillips PM2.0×3.1	4	22.5	31.3	53.8
6	Optical drive assembly	Phillips PM2.5×4.5	1	7.5	9.7	17.2
7	Memory module	Retaining tab	2	4	5.04	9.04
8	Hard drive	Phillips PM2.0×4.0	3	17.5	26.9	44.4
9	WLAN Module	Phillips PM2.5×3.0	2	12.5	16.9	29.4
10	Display Assembly	Phillips PM2.5×4.5	6	32.5	45.7	78.2
11	Top cover	Torx T8M2.5×6.0	22	112.5	160.9	273.4
12	USB Connector	Phillips PM2.5×3.0	2	12.5	19.7	32.2
13	Modem Module	Phillips PM2.5×3.0	2	12.5	16.9	29.4
14	Fan Assembly	Phillips PM2.5×8.0	7	37.5	72.5	110
					Total	**847.48**

The proposed methodology is implemented to select an appropriate fastening method for the product such that the overall assembly and disassembly time is minimized. Five types of fastening methods, commonly used in laptop computers, were analyzed in this study. Table-4 shows the estimated assembly and disassembly times for each part with respect to alternative fastening methods.

Table 4. Estimated assembly and disassembly time (sec) of alternative fastening methods

Part Index	Snap fit-1 / Retaining tab		Snap fit-2		Phillips PM2.5×4.5		Phillips captive screw		glue	
	at_{ij}	dt_{ij}	at_{ij}	dt_{ij}	at_{ij}	dt_{ij}	at_{ij}	dt_{ij}	at_{ij}	dt_{ij}
1	4	5.04	30	32.5	22.5	31.3	30	42.5	14.5	100
2	20	38.5	30	62.5	37.5	52.9	52.5	72.5	30	200
3	20	20.5	30	32.5	12.5	16.9	15	22.5	14.5	200
4	20	20.5	30	32.5	17.5	24.1	22.5	32.5	14.5	100
5	20	20.5	30	32.5	22.5	31.3	30	42.5	14.5	100
6	20	20.5	30	32.5	7.5	9.7	7.5	12.5	14.5	100
7	4	4	30	32.5	12.5	16.9	15	22.5	14.5	100
8	20	20.5	30	32.5	17.5	24.1	22.5	32.5	14.5	100
9	20	20.5	30	32.5	12.5	16.9	15	22.5	14.5	100
10	40	74.5	60	62.5	32.5	45.7	45	62.5	29	300
11	40	74.5	60	122.5	112.5	160.9	165	222.5	29	300
12	20	20.5	30	32.5	12.5	16.9	15	22.5	14.5	100
13	20	20.5	30	32.5	12.5	16.9	15	22.5	14.5	100
14	20	38.5	30	62.5	37.5	52.9	52.5	72.5	29	200

A genetic algorithm is implemented for selecting the optimal fastening methods for each part. To simplify chromosome encoding, only the part index and fastening method were considered as shown in figure 4. In the optimization model, assembly and disassembly times corresponding to alternative fastening methods are obtained from the fastener database. After chromosome encoding, an initial population is generated. In this study, we set the population size at 120 chromosomes.

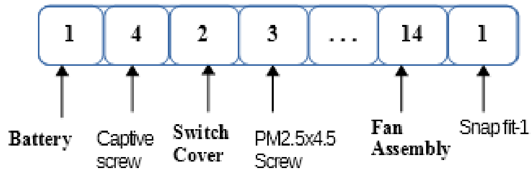

Figure 4. Chromosome encoding

An optimization problem was formulated to determine the optimal fastening methods with the objective of minimizing the total assembly and disassembly time. The problem was solved using a GA which was implemented using MATLAB software. A crossover rate of 0.6, mutation rate of 0.05 and maximum number of generation of 200 is used for the GA parameters. The result of the GA after 147 iterations is shown in table 5. The results indicate that, fastening method selected by the proposed methodology resulted in a total assembly and disassembly time saving of **217.5 sec** per product when compared with the original design.

Table 5. Selected fastening methods

Part Index	Fastening method	No. of fastening element	at (sec)	dt (sec)	at+dt (sec)
1	Releasable latches	2	4	5.04	9.04
2	Snap fit-1	2	20	38.5	58.5
3	Phillips PM2.5×4.5	4	12.5	16.9	29.4
4	Snap fit-1	4	20	20.5	40.5
5	Snap fit-1	4	22.5	31.3	53.8
6	Phillips PM2.5×4.5	1	7.5	9.7	17.2
7	Phillips PM2.5×4.5	2	12.5	16.9	29.4
8	Snap fit-1	4	20	20.5	40.5
9	Phillips PM2.5×4.5	2	17.5	24.1	41.6
10	Phillips PM2.5×4.5	8	32.5	45.7	78.2
11	Snap fit-1	8	40	74.5	114.5
12	Phillips PM2.5×4.5	2	12.5	16.9	29.4
13	Phillips PM2.5×4.5	2	12.5	16.9	29.4
14	Snap fit-1	4	20	38.5	58.5
		Total	**254**	**375.94**	**629.94**

To analyze the impact of the selected fastening methods on the overall assembly and disassembly cost of the company, three scenarios were considered regarding the quantity of new products assembled, and the quantity of used products returned to be disassembled. Total assembly and disassembly cost was computed for both the original design and the redesigned version considering the total assembly and disassembly time of the two cases. It was assumed that four workers are hired with a pay rate of R1=15US$/hr each and the tool usage cost was assumed to be R2= 3$/hr. From the result of the comparison shown in table 6, we can see that, the design revision made in accordance with the new fastening methods has led to significant cost reduction.

Table 6. Comparison of total cost of assembly and disassembly

	Scenario 1	**Scenario 2**	**Scenario 3**
Demand for new product (Qn)	3,000	4,000	5,000
Demand for remanufactured product (Qr)	120	800	2,000
Total cost (US$) Original design	5,447.7	8,877.9	13,619.8
Total cost (US$) Redesign	4,035.6	6,583.8	10,109.4
Cost saving (US$)	**1,412**	**2,294.2**	**3,510.4**

5. Conclusions

A company which plans to offer both new and remanufactured products must consider assemblability and disassemblability issues during design stage. Assemblability and disassemblablity of a product is affected by the types of fastening methods used. Some fastening methods which facilitate the assembly process may not be appropriate from the disassembly perspective and vice versa which makes selection of appropriate fastening method a critical and challenging task.

In this study, a methodology for fastener selection which simultaneously considers assemblability, disassemblability and cost factors is proposed. In the proposed methodology, an optimization model is formulated with the objective of minimizing the sum of the product assembly and disassembly costs. A genetic algorithm was used to model the problem which was then solved in Matlab. To illustrate the proposed methodology, a case study on fastening method selection for a laptop computers was conducted. The result of the experiment showed the model's effectiveness in selecting optimal fastening methods for ease of assembly and disassembly such that the overall assembly and disassembly cost can be reduced. The proposed methodology offers a guide to designers in selecting optimal fastening methods by simultaneously considering ease of assembly, disassembly and related cost.

The proposed methodology can be improved further. In this study, variability of condition of the EOL product which can affect the disassembly time, was not taken into account. Furthermore, the degree of damage caused to fasteners during product's life time was also not considered. These two factors could be considered in future to further enhance the model's capability.

Acknowledgements

The work described in this paper was supported by a PhD studentship (Project account code: RUNJ) from The Hong Kong Polytechnic University.

References

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). *Product Design for Manufacture and Assembly, Third Edition*: Taylor & Francis.

Charter, M., & Gray, C. (2008). Remanufacturing and product design. *International Journal of Product Development, 6*(3-4), 375-392.

Das, S. K., Yedlarajiah, P., & Narendra, R. (2000). An approach for estimating the end-of-life product disassembly effort and cost. *International Journal of Production Research, 38*(3), 657-673.

Desai, A., & Mital, A. (2003). Evaluation of disassemblability to enable design for disassembly in mass production. *International Journal of Industrial Ergonomics, 32*(4), 265-281.

Desai, A., & Mital, A. (2005). Incorporating work factors in design for disassembly in product design. *Journal of Manufacturing Technology Management, 16*(7), 712-732.

Gao, W., Shao, X., & Liu, H. (2014). Virtual assembly planning and assembly-oriented quantitative evaluation of product assemblability. *The International Journal of Advanced Manufacturing Technology, 71*(1), 483-496.

Ghazilla, R. A. R., Taha, Z., Yusoff, S., Rashid, S. H. A., & Sakundarini, N. (2014). Development of decision support system for fastener selection in product recovery oriented design. *The International Journal of Advanced Manufacturing Technology, 70*(5), 1403-1413.

Giutini, R., & Gaudette, K. (2003). Remanufacturing: The next great opportunity for boosting US productivity. *Business Horizons, 46*(6), 41-48.

Go, T. F., Wahab, D. A., Rahman, M. N. A., Ramli, R., & Azhari, C. H. (2011). Disassemblability of end-of-life vehicle: a critical review of evaluation methods. *Journal of Cleaner Production, 19*(13), 1536-1546.

Güngör, A. (2006). Evaluation of connection types in design for disassembly (DFD) using analytic network process. *Computers and Industrial Engineering, 50*(1-2), 35-54.

Ismail, N. H., Mandil, G., & Zwolinski, P. (2014). A remanufacturing process library for environmental impact simulations. *Journal of Remanufacturing, 4*(1), 2.

Kobayashi, M., Horiuchi, H., & Higashi, M. (2015). Optimal Design of Component Layout and Fastening Methods for the Facilitation of Reuse and Recycle. *Computer-Aided Design and Applications, 12*(5), 537-545.

Kroll, E. (1996). Application of Work-Measurement Analysis to Product Disassembly for Recycling. *Concurrent Engineering, 4*(2), 149-158.

Kroll, E., & Carver, B. S. (1999). Disassembly analysis through time estimation and other metrics. *Robotics and Computer-Integrated Manufacturing, 15*(3), 191-200.

Kroll, E., & Hanft, T. A. (1998). Quantitative evaluation of product disassembly for recycling. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering, 10*(1), 1-14.

Leaney, P. G. (1996). Case Experience with Hitachi, Lucas and Boothroyd-Dewhurst DFA Methods. In G. Q. Huang (Ed.), *Design for X: Concurrent engineering imperatives* (pp. 41-71). Dordrecht: Springer Netherlands.

Lund, R. T., & Hauser, W. M. (2010). *Remanufacturing - An American perspective.* Paper presented at the IET Conference Publications.

Mašín, I. (2014). A Comparison of DFA Methods for Manual Assembly. In L. Ševĉik, P. Lepšík, M. Petrů, I. Mašín, & R. Martonka (Eds.), *Modern Methods of Construction Design: Proceedings of ICMD 2013* (pp. 265-271). Cham: Springer International Publishing.

Matsumoto, M., Yang, S., Martinsen, K., & Kainuma, Y. (2016). Trends and research challenges in remanufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology, 3*(1), 129-142.

Östlin, J., Sundin, E., & Björkman, M. (2009). Product life-cycle implications for remanufacturing strategies. *Journal of Cleaner Production, 17*(11), 999-1009.

Sabaghi, M., Mascle, C., & Baptiste, P. (2016). Evaluation of products at design phase for an efficient disassembly at end-of-life. *Journal of Cleaner Production*.

Sabbaghi, M., & Behdad, S. (2017). *Optimal Positioning of Product Components to Facilitate Ease-of-Repair*.

Shu, L. H., & Flowers, W. C. (1999). Application of a design-for-remanufacture framework to the selection of product life-cycle fastening and joining methods. *Robotics and Computer-Integrated Manufacturing, 15*(3), 179-190.

Sodhi, R., Sonnenberg, M., & Das, S. (2004). Evaluating the unfastening effort in design for disassembly and serviceability. *Journal of Engineering Design, 15*(1), 69-90.

Soh, S. L., Ong, S. K., & Nee, A. Y. C. (2016). Design for assembly and disassembly for remanufacturing. *Assembly Automation, 36*(1), 12-24.

Yang, S. S., Ong, S. K., & Nee, A. Y. C. (2016). *A Decision Support Tool for Product Design for Remanufacturing.* Paper presented at the Procedia CIRP.

Yi, H. C., Park, Y. C., & Lee, K. S. (2003). *A study on the method of disassembly time evaluation of a product using work factor method.* Paper presented at the Proceedings of the IEEE International Conference on Systems, Man and Cybernetics.

Zandin, K. B. (2002). *MOST Work Measurement Systems, Third Edition*: Taylor & Francis.

Biographies

M.W. Geda is currently working towards a Ph.D. degree in the Department of Industrial and Systems Engineering of The Hong Kong Polytechnic University, Hong Kong. He received BSc. degree in Industrial Engineering from Mekelle University, Mekelle, Ethiopia, in 2007 and MSc degree in Industrial Engineering and Management from Politecnico di Torino in 2011. His research interests include design for remanufacturing and product EOL recovery strategy.

Dr. C.K. Kwong is currently an Associate Professor in the Department of Industrial and Systems Engineering of The Hong Kong Polytechnic University, Hong Kong. He received M.Sc. degree in Advanced Manufacturing System from the University of Nottingham, UK, and the Ph.D. degree in Manufacturing Engineering from the University of Warwick, Warwick, UK. His research interests include new product development, product line design, design for manufacture, and integrated design