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A new model for estimating End-of-Life disassembly effort during early stages of product design

S. Harivardhini[1] · Amaresh Chakrabarti[1]

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Abstract In this paper, a new model for estimating disassembly effort during early stages of product design is proposed. The model has been developed by integrating two well-known models in the field of product disassembly: Das et al. Disassembly Effort Index (DEI) model and Kroll and Hanft Disassembly Evaluation model. The first one is a multi-factor cost and effort model, which is widely used for determining disassembly effort in terms of a DEI score. This score is a representative of the total operating cost incurred in disassembling a product. The second model is commonly used for evaluating ease of disassembly, by assigning task difficulty scores to disassembly tasks. Data necessary for determining these scores are obtained from work-measurement analyses of standard disassembly tasks. The proposed model has been demonstrated by an estimation of disassembly effort for a CRT monitor disassembly process using the model and validated by benchmarking the results obtained using the proposed model against results from an existing model for a case study conducted on fifteen computer electronic products.

Keywords Disassembly effort · Product design · Disassembly time · Tool and hand manipulations

✉ S. Harivardhini
vardhini@cpdm.iisc.ernet.in

1 IDeaS Lab, Centre for Product Design and Manufacturing, Indian Institute of Science, Bangalore 560012, India

Introduction

Product disassembly is generally defined as "the processes of systematic removal of desirable constituent parts from an assembly while ensuring that there is no impairment of the parts due to the process" (Brennan et al. 1994). "Product disassembly is a vital strategy of industrial recycling and remanufacturing which retrieves the desired parts and/or subassemblies by separating a product into its constituents" (Vinodh et al. 2011). From the recycling perspective, it is defined as a process to ensure "efficient separation of hazardous materials, or the accumulation of worthy ingredients for further recovery" (Feldman et al. 1999). Many research studies have emphasized the importance of ease of disassembly for a product, especially from the End-of-Life (EoL) perspective. Ease of disassembly is considered as a significant requirement in order to efficiently carry out recovery processes such as remanufacturing, reuse, recycling, and repair. "End-of-life product disassembly is an important process that makes the parts of a product available for different material and part recycling processes at the end of its useful life" (Viswanathan and Allada 2001). For the success of any EoL product disassembly process, the amount of effort spent in disassembling a product is a crucial factor. In many instances, the extent to which the disassembly effort has to be spent in a disassembly process ends up in deciding whether a product will be disassembled or not, for the benefit of environment and/or profit. This is because an effort-intensive disassembly process is worthwhile only if it has significant gain. "While the total cost of disassembly includes several components such as logistics & material handling, the key cost factor is the effort associated with the actual disassembly action" (Sodhi et al. 2004). "EoL disassembly is driven by the objective to maximize the value (both from an environmental and an economic standpoint) extracted from the fully assembled product at the end of its useful life, while minimizing the cost of the disassembly" (Viswanathan and Allada 2001).

Therefore, in the current study, a model for estimating EoL disassembly effort during the early stages of product design is proposed. Using this model, the amount of disassembly effort which would need to be spent at the EoL phase of a product could be estimated during the early stages of design.

Design takes a relatively short period in a product's life cycle. Utilization of this prime time to create a successful product has been widely discussed in literature such as Keys (1990), Fabrycky and Blanchard (1991), Dowlatshahi (1996), Appelqvist et al. (2004) as mentioned by Chiu and Kremer (2011). It is during this stage that best savings can be achieved, and the earlier the improvements are made, the greater is the cost reduction (Carter and Baker 1992). As shown by Berliner and Brimson (1988), decisions taken during early stages of design typically have a greater impact on the cost committed in product development, while changing decisions in these stages are usually more cost-effective than during later stages; therefore, being able to estimate the impact of disassembly at the EoL during the early stages of design has the advantage of making substantial improvement in the product without having to incur much additional cost.

There are many models and methods which stress the importance of addressing the issues of disassembly effort and associated difficulty by evaluating various disassembly parameters of a product at the early design stage itself. These are discussed in our earlier work (Harivardhini and Chakrabarti 2014) as well. For instance, Hitachi Disassemblability Evaluation Method (DEM) was developed in 1993 for quantitative evaluation of the difficulty level associated with disassemblably of a new product. This DEM score acts as an index for both ease of disassembly and to indicate areas which require design improvement (Go et al. 2011). Subramani and Dewhurst (1994) introduced time standard charts to make disassembly evaluation. Harjula et al. (1996) compared the financial lines for disassembly of several products. In all cases, the benefits of redesign suggested by a Design for Assembly (DfA) analysis have been clearly shown. It appears that typical DfA redesigns will be equally beneficial in simplifying disassembly at the end of product life. However, in addition to the usual DfA suggestions, design changes should also be considered that will simplify the easy removal of critical items. Suga et al. (1996) proposed an approach for evaluation of disassemblability by introducing two parameters (energy for disassembly and entropy for disassembly) that quantitatively describe disassemblability. Gungor and Gupta (1997) developed a methodology for measuring efficiency of a disassembly sequence by determining disassembly time, disassembly directions, number of components, and joint types. Mok et al. (1997) defined disassembly based upon disassembly mechanisms and processes. Also design guidelines for improving disassembly have been proposed and evaluated quantitatively.

Sodhi and Knight (1998) mentioned that the product analysis tools (that support modeling of bulk material separation and incorporating these results into previously developed product analysis procedures) help designers to evaluate the ease of disassembly and recycling of alternative product concepts during early stages of design. Kroll and Hanft (1998) ease of disassembly evaluation method is predominantly used to estimate disassembly time associated with a disassembly process based on five factors: access, force, positioning, base time, and special. Veerakamolmal and Gupta (1999) developed a technique to analyze efficiency of designing electronic products using an index called Design for Disassembly Index (DfDI). "The development of DfDI involves the analysis of the tradeoff between the costs and benefits of EOL disassembly to find the combination of components that provides the optimum cost-benefit ratio for end-of-life retrieval." Wang and Allada (2000) developed a quantitative methodology for serviceability evaluation by calculating disassembly, reassembly, and handling indices through a fuzzy neural network model. In Das et al. (2000), a multi-factor model was developed to compute a disassembly effort index (DEI) score based on seven factors: time, tools, fixture, access, instruct, hazard, and force. Information related to product structure that should be available to use this method at the design stage are as follows: a detailed disassembly process plan describing specific details on time, tools, fixture, access, hazard, instruct, and force associated with the disassembly process of a product. Viswanathan and Allada (2001) developed a formal model, called the configuration-value (CV) model to evaluate the effect of configuration on disassembly. The model is used to identify critical bottlenecks in a configuration, to help designer identify the design changes that need to be made to improve 'disassemblability.'

Chen (2001) developed a method with which an evaluation score for ease of both disassembly and recycling can be generated by axiomatic design. Yi et al. (2003) proposed a method for disassembly time evaluation considering type, size, weight, and connection parts of a product. Desai and Mital (2003) developed a methodology with which time-based numeric indices can be assigned to each design factor. A higher score indicates anomalies in product design from the disassembly perspective. According to Desai and Mital (2003), disassemblability could be increased by addressing these anomalies. This method is commonly used to enhance disassemblability of a product by identifying design weaknesses from a disassembly perspective, based on several criteria. The design details that should be known for using this method at the design stage are as follows: disassembly force (Straight line motion without exertion of pressure, Straight line and twisting motion without pressure, etc.), material handling (component size and component symmetry), requirement of tools (exertion of force and exertion of torque), accessibility of joints (dimensions and locations), and positioning of tools (level of accuracy required to position the tools). Campbell and Hasan (2003) developed a methodology for estimating disassembly profitability for recycling by representing recovered net worth against disassembly time. Sodhi et al. (2004) developed an unfastening effort analysis (U-effort) model, which helps designers to evaluate and select their fastener options. For each fastener type, the model identifies several causal attributes and uses these to derive the U-effort index for a given case. Gungor (2006) used Analytic Network Process (ANP) to evaluate alternative connection types from a DfD perspective. Giudice and Kassem (2009) proposed a DfD methodology for characterizing disassembly depths of product components with respect to their need for removal and recovery at EoL.

Apart from addressing the disassembly effort issue at the early design stage, several research studies have come up with software tools based on the concept of disassembly planning. They are as follows: AMETIDE, ATROID, DemAP, DfD Compact, DFE, DP#, ED, Green Advisor, LaySiD, LINKER, REM, and Virtual Disassembly Manager. The features of these tools are discussed in detail in Santochi et al. (2002).

However, a careful examination of the above-mentioned literature revealed the following: only one method could be used to quantify EoL disassembly effort at the early stages of product design in the form an index. The specific requirement of the current study is the estimation of EoL disassembly effort quantified in the form of an Index or numeric score that could be directly taken as an equivalent for the EoL disassembly effort. The only method that fits into the above-mentioned requirement is Multi-factor DEI model (Das et al. 2000). However, there are several difficulties in using the method in early stages of design, as described below. The first difficulty is that a substantial amount of data related to the product structure are required and therefore must be available a priori for estimating disassembly effort using the method. Such data are typically not available during early stages of design. The second issue is that it does not have provisions for estimating disassembly effort for multiple feasible disassembly sequences of a product during its design stage. These issues are the motivations for the research reported in this paper. The model proposed in this paper is intended to support the estimation of EoL disassembly effort using fewer data, using those that are typically available in early stages of product design, and using less time, for both existing products and new designs for multiple feasible disassembly sequences.

The paper is structured as follows: Section 1 contains introduction. Section 2 discusses in detail the two existing methods available for evaluating disassembly effort and disassembly time. Development of the proposed model and how the model can be used for estimating EoL disassembly effort are discussed in Sect. 3. Validation of the model and conclusions are given in Sects. 4 and 5.

Two existing models used in this study

This section discusses in detail about two well-known models in the field of product disassembly that are commonly used for evaluating disassembly processes for the effort and time involved. Using a disassembly process of a CRT monitor as an example, the approach followed in the two methods for the disassembly evaluation is explained. The section also outlines the reasons underlying the selection of these two methods for the development of a new model, proposed in this paper, for supporting estimation of EoL disassembly effort at early phases of product design.

Das et al. DEI model

Das et al. DEI model is a multi-factor model to compute a Disassembly Effort Index (DEI) score based on seven factors: time, tools, fixture, access, instruct, hazard, and force. This model is widely used to determine the disassembly effort in terms of a DEI score. The DEI score is considered to be a representative of the operating costs of disassembly operations. According to their model, each disassembly step is either an (i) unfastening process such as removal of screws or a (ii) disassembly process such as cutting or drilling. At each disassembly step, one or more parts with certain commonalities are removed. Each disassembly step is evaluated for all seven factors based on a DEI scoring card developed by them. According to them, the removal process and its associated logistics are the primary determinants of disassembly effort, and disassembly time is a direct measure of the labor cost. Their model is step focused and not part focused. Importantly, according to this model, in addition to time, six other factors (tools, fixture, access, instruct, hazard, and force) contribute to disassembly effort. In order to use the model to compute disassembly effort, a detailed disassembly plan should be available. Further, detailed information on all seven factors, i.e., time, tools, fixture, access, instruct, hazard and force, is necessary.

An example: evaluation of disassembly effort in CRT monitor disassembly using Das et al. DEI model

Table 1 shows the evaluation of disassembly effort in a CRT monitor disassembly process using Das et al. DEI model. Complete disassembly process of a CRT monitor is captured in the form of a video taken by E-waste guide (E-waste: dismantling a CRT monitor). This video was used to identify the underlying Disassembly Process Plan (DPP) used in the process captured in the video, which was then used in this evaluation. According to Das et al. (2000), "Disassembly is a multi-step process and it can be represented by a Disassembly Process Plan (DPP)." A DPP is described by a sequence of processing steps that are needed for removing or separating fasteners, parts, and subassemblies from the product in order to accomplish complete disassembly of the product (Das et al. 2000). The approach followed in carrying out the evaluation is as follows: Each step of a DPP was evaluated based on seven factors (time, tools, fixture, access, instruct, hazard, and force), a cost/effort indexing scale, and a DEI score is given based on the evaluation. The cost–effort index scale is defined in the range of 0–100. This range is assigned on a weighted basis to each of the seven factors. Each factor has its own independent utility scale with assigned range as anchors. Evaluation of each step was carried out by choosing appropriate anchors from the scoring card (Harivardhini and Chakrabarti 2014).

Except for the factors instruct, hazard, and force, all other four factors (time, tools, fixture, and access) could be assessed with the information extracted from the disassembly video. However, for the three factors instruct, hazard, and force, the values would not be directly available from such a video. Thus, these values should be calculated from other information available in the given situation. These values were determined in our earlier work, as follows: (i) appropriate anchors for the factor *instruct* were: a) training, b) group discussion and c) time range for the worker to assess the next step is >30 s, for the disassemblers from formal unit, informal unit and trained individual, respectively, (ii) appropriate anchors for the factor *hazard* were identified based on the necessity of wearing gloves, arm wrap/face mask etc. and (iii) appropriate anchors for the factor *force* were derived from the kind of tools used in the dismantling process, e.g.: force is

Table 1 Calculation of DEI score using Das et al. DEI model for CRT monitor disassembly (Harivardhini and Chakrabarti 2015)

Dismantling steps	Time	Tools	Fixture	Access	Instruct	Hazard	Force	DEI
Cut the main connection wires	10 s 2	Pliers 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (leverage) 12	36
Removal of side cover by chiseling out	16 s 3	Chisel 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (leverage) 12	37
Removal of whole plastic casing by unscrewing 6 screws	64 s 12	Screw driver 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (torsional) 4	38
Equalize pressure in the CRT glass body Punch carefully a whole into CRT glass	18 s 1	Hammer and screw driver 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (orthogonal) 8	31
Cut the connection wires inside the monitor by pliers	17 s 3	Pliers 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (leverage) 12	37
Unscrew 2 screws to remove the PCB fixed at the base of the monitor	35 s 7	Screw driver 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (torsional) 4	33
Removal of front plastic casing by unscrewing 4 screws	55 s 11	Screw driver and pliers 4	Two hands 6	Nil	Training 10	Gloves, face mask 2	Unfastening (torsional) 4	37
Removal of magnetic deflector yoke assembly at the top of the CRT	11 s 2	Hand 2	One hand 3	Nil	Training 10	Gloves, face mask 2	Unfastening (torsional) 4	23

Formal unit location: Cape town, South Africa

Source: 'E-Waste: Dismantling a CRT monitor', video by e-waste guide

Total disassembly time: 3 min 57 s

Total DEI score: 272

torsional for screw driver, leverage for pliers and chisel, and orthogonal or low impact for hammering (Harivardhini and Chakrabarti 2014).

Kroll and Hanft ease of disassembly evaluation model

Kroll and Hanft model is intended to be used for evaluating the ease of disassembly of a product by estimating disassembly time. This method is typically used for estimating the time taken to dismantle small products by a seated person using hand-held tools. The authors consider four main evaluation criteria: accessibility, positioning, force, and base time to evaluate ease of disassembly of products. According to Kroll and Hanft, physical configurations of product are related to key aspects of task performance such as accessibility and positioning. Assigning disassembly difficulty ratings to each of these task performance aspects will help us determine the total disassembly difficulty score of the product. Disassembly difficulty ratings are given for all four criteria for each product based on scores derived from the work-measurement analysis of standard disassembly tasks. From the total difficulty score, overall disassembly time can be computed. Similar to Das et al. DEI model, their model is also task focused and not part focused.

Using this model, two single-number metrics can be calculated, and they are (i) design effectiveness for disassembly and (ii) overall disassembly time. In order to use this model to evaluate ease of disassembly of a product, information on number of parts, minimum number of parts, task type, number of task repetitions, required tools, accessibility, positioning, force, base time, and special is required. In order to use this method for estimating disassembly time, the above data should be processed to determine the following: actual difficulty score, ideal difficulty score, and the number of tool and hand manipulations.

An example: evaluation of overall disassembly time and tool and hand manipulations in CRT monitor disassembly using Kroll and Hanft model

In the current study, Kroll and Hanft ease of disassembly evaluation model was used to determine two important factors about the disassembly process: (i) overall disassembly time and (ii) total number of tool and hand manipulations carried out in the process. The approach followed is explained with an example of CRT monitor disassembly process. The chart shown in Table 2 was formulated for a CRT monitor disassembly process based on the Kroll and Hanft disassembly evaluation model. This chart is called the disassembly evaluation chart by Kroll and Hanft. It is used to determine the actual difficulty score, the ideal difficulty score, and the number of tool and hand manipulations; from these, the overall disassembly time is calculated. The information on the CRT monitor disassembly process that has been used to create the above-mentioned disassembly evaluation chart was extracted from an exploded view drawing of a CRT monitor. The detailed procedure on how to formulate the disassembly evaluation chart is discussed elaborately in Kroll and Hanft (1998).

According to them, "A tool manipulation occurs each time a tool is picked up or put down, and is implied each time different tool codes appear on successive rows of the chart. A hand manipulation is defined as the movement of the hand to or from a part." The number of tool and hand manipulations can be calculated from column 6 shown in Table 2. There are 8 different tool codes: WC, CH, PS, HM, WC, PS, WC, and PS; and 6 different blank rows in column "Tool" in Table 3. They correspond to tasks carried out by tools and hands, respectively. In order to show the distinction between them, the ones in the rows are marked in italics and bold, respectively, as shown in Table 3. Thus, based on the definition by Kroll and Hanft, the total number of tool manipulations was found to be 16. Similarly, the total number of hand manipulations was found to be 12. Thus, the total number of tool and hand manipulations carried out in this CRT monitor disassembly process was identified as 28. In order to show the distinction between them, the ones in the rows are marked in italics and bold, respectively, as shown in Table 3.

Overall disassembly time taken in a disassembly process can be estimated, using Kroll and Hanft ease of disassembly evaluation model, as in the following.

The disassembly evaluation chart shown in Table 2 and the following equation should be used together to estimate the overall disassembly time taken in a disassembly process:

$$\begin{aligned}\text{Disassembly time (s)} &= \left(\sum \text{column } 13 - 5 \times \sum \text{column } 5\right) \times 1.04 \\ &\quad + (\text{Number of tool and hand manipulations}) \\ &\quad \times 0.9 (\text{Kroll and Hanft 1998}).\end{aligned} \tag{1}$$

Using the above equation for estimating the overall disassembly time taken in a CRT monitor disassembly process gave the following results:

$$\text{Disassembly time (s)} = (320 - 5 \times 29) \times 1.04 + 28 \times 0.9 = 207.2\ \text{s (3 min 27 s)}.$$

Thus, it can be seen that the overall disassembly time that was taken directly from the disassembly video (refer Table 1) differs from the overall disassembly time that was calculated using Kroll and Hanft ease of disassembly evaluation model only by 30 s.

Table 2 Disassembly evaluation chart for CRT monitor disassembly

1 Part no.	2 Qnty	3 Min no. parts	4 Task type	5 No. of task repetitions	6 Tool	7 Access	8 Positioning	9 Force	10 Base time	11 Special	12 Sub total	13 Total
A Main wires	1	–	Cu	1	WC	1	2	1	2	1	7	7
B Side cover	1	–	We (pry)	1	CH	1	1	2	2	3 (additional motions)	9	9
C Whole plastic casing	1	–	Un	6	PS	1	2	3	8	1	15	90
			Re	1		1	1	1	1	1	5	5
D PCB	1	–	Pu (pull)	1		1	1	2	1	1	6	6
			Ha	1	HM	1	2	1	3	1	8	8
			Pu (push)	1	WC	1	1	1	1	1	5	5
			Cu	4	PS	1	2	1	2	1	7	28
			Un	2	WC	1	2	3	8	1	15	30
			Cu	4		1	2	1	2	1	7	28
E Magnetic deflector assembly	1	–	Tu	1		1	1	1	1	1	5	5
			Re	1		1	1	1	1	1	5	5
F CRT	1	–	Un	4	PS	1	2	10	8	1	22	88
			Re	1		1	1	2	1	1	6	6
G Front plastic casing	1	–	–	–	–	–	–	–	–	–	–	–
												320

Table 3 Calculation of tool and hand manipulations carried out in CRT monitor disassembly

Part no.	Qnty	Task type	No. of task repetitions	Tool
A Main wires	1	Cu	1	WC *1*
B Side cover	1	We (pry)	1	CH *1*
C Whole plastic casing	1	Un	6	PS *1*
		Re	1	**1**
D PCB	1	Pu (pull)	1	**1**
		Ha	1	HM *1*
		Pu (push)	1	**1**
		Cu	4	WC *1*
		Un	2	PS *1*
		Cu	4	WC *1*
E Magnetic deflector assembly	1	Tu	1	**1**
		Re	1	**1**
F CRT	1	Un	4	PS *1*
		Re	1	**1**
G Front plastic casing	1	–	–	–

Total number of tool and hand manupulations: 28

Tool manupulations and hand manupulations are marked in italics and bold, respectively

The reasons for choice of the above two models for development of the new model are the following: (i) both the methods are task/step based and not part based; (ii) both generally evaluate disassembly difficulty of product disassembly and specifically focus on evaluation of EoL disassembly difficulty or EoL disassembly effort of product disassembly; (iii) both are meant for product disassembly, especially disassembly of electronic appliances; and (iv) both are intended for manual disassembly of products.

A new model for evaluating EoL disassembly effort

Development of a new model

Das et al. DEI model works well for evaluating effort involved in a disassembly process carried out on an existing product. Data required for using this model are as follows: For an existing product, (i) a complete disassembly process (captured in the form of a video is sufficient) and information on factors like instruct, hazard, and force that will be used in the calculation of DEI or (ii) a detailed disassembly process plan describing specific details on time, tools, fixture, access, hazard, instruct, and forces associated with the disassembly process of a product is required. For a product design, a detailed disassembly process plan describing specific details on time, tools, fixture, access, hazard, instruct, and forces associated with the disassembly process of a product is required. Among the seven factors mentioned above, their model gives more weightage to time (25 % out of 100) while estimating the overall disassembly effort (Das et al. 2000). But unfortunately at the design stage of a product, the time taken to disassemble each part will not be available in most instances. In order to overcome this issue, this model gives provision for assuming disassembly time at each disassembly step. This might lead to an incorrect DEI score. Also this model can be used to evaluate the disassembly effort associated with only one disassembly sequence of a product for which a disassembly process plan is available. This disassembly sequence may or may not be the best disassembly sequence for the product (Das et al. 2000). The model does not have provision for evaluation of disassembly effort associated with multiple feasible disassembly sequences of a product. These issues necessitate the development of a new model for estimating EoL disassembly effort of a product disassembly process. The new model proposed in this paper is intended to support estimation of EoL disassembly effort with fewer data that are typically available in early stages of product design, and in less time for both existing products, and new designs for multiple feasible disassembly sequences.

The new DEI model developed is intended to be used to determine the disassembly effort associated with many feasible, alternative disassembly sequences carried out on an existing product. Not only for an existing product, it can also be used during the embodiment phase of the product design stage to estimate the amount of disassembly effort which would be spent in the disassembly process at the later stages of a product life cycle, especially at the EoL phase of the product's life cycle. Also, it can be applied to the design of any product to estimate the disassembly effort associated with alternative feasible disassembly sequences of the (design of the) product. Data required to carry out the evaluation of disassembly effort using the new DEI model are as follows: For an existing product, (i) a complete disassembly process captured in the form of a video or (ii) information on parts dismantled, task type, task repetition, tool, tool clearance, and kind of object resistance for the disassembly tasks involved is required. For a product design, the data needed are (i) an exploded view or an assembly drawing of a product and a disassembly process plan or (ii) information on parts dismantled, task type, task repetition, tool, tool clearance and kind of object resistance for the disassembly tasks involved. These data are typically available during the embodiment phase of the product design. Thus, the new DEI model requires less data and time to estimate the EoL disassembly effort of an existing product's disassembly process. It requires data only on two aspects of a product disassembly process. The first is the overall disassembly time of the disassembly process; the second is the total number of tool and hand manipulations. The overall disassembly time can be directly taken from a disassembly video, and the total number of tool and hand manipulations can be calculated using Kroll and Hanft model.

Kroll and Hanft ease of disassembly evaluation model will not give an estimation of the disassembly effort spent in a disassembly process; however, it is a highly powerful method to evaluate many parameters associated with a disassembly process. This method is used in our study to determine the following two factors: (i) total number of tool and hand manipulations carried out in a disassembly process and (ii) overall disassembly time taken for a disassembly process. These are the two important factors in the new DEI model that are necessary for the estimation of disassembly effort for both existing products and new product designs. Thus, our study attempts to translate the Kroll and Hanft model which is disassembly time based into a disassembly effort based model. The primary reasons for developing the new model are the following: there are no existing methods which can determine disassembly effort associated with alternative, feasible disassembly sequences for both existing products and product designs with few pieces of data (a dismantling video for an existing product and an exploded view drawing for a product design) and little time for carrying out the evaluation.

Quantification of disassembly effort using the proposed DEI model

Multiplication of overall disassembly time taken for a disassembly process with the total number of tool and hand manipulations carried out in a disassembly process will give an estimate of the total amount of disassembly effort spent in that particular product disassembly process:

$$\text{Total disassembly effort} = \text{Overall disassembly time} \times \text{Total number of tool and hand manipulations.} \tag{2}$$

An example application of the proposed model for an existing product: evaluation of disassembly effort in CRT monitor disassembly using new DEI model

As mentioned earlier, the data required to carry out the evaluation of disassembly effort for an existing product using the proposed DEI model is either a disassembly video showcasing the complete disassembly process carried out on the product or information on the product disassembly process plan as mentioned above. The same video on the complete disassembly process of a CRT monitor which was used in the assessment of DEI score using Das et al. DEI model had been used to estimate the disassembly effort using the proposed DEI model. As mentioned in the above section, the two primary data that are needed to estimate disassembly effort using the proposed DEI model are the following: (i) overall disassembly time taken for a disassembly process and (ii) total number of tool and hand manipulations carried out in a disassembly process. Overall disassembly time can be taken directly from the video of CRT monitor disassembly. The overall disassembly time was found to be 3 min 57 secs or 3.95 min. The total number of tool and hand manipulations carried out in the CRT monitor disassembly process was determined from the video using Kroll and Hanft model, which was found to be 28. Thus, using the quantification formula of the proposed DEI model, disassembly effort can now be estimated and was found to be 110.6.

An example for a product design: evaluation of disassembly effort in CRT monitor disassembly using new DEI model

Evaluation of disassembly effort for a design of a product using the proposed DEI model requires an exploded view or an assembly drawing of the product. The following is the procedure to be followed in the new model:

Step 1 Develop an exploded view or assembly drawing of a product.
Step 2 Assign names to all parts (A, B, C, etc.).
Step 3 Set the target (i.e., select the parts that need to be disassembled).
Step 4 Draw an AND/OR graph while taking into account the disassembly constraints, and identify all feasible disassembly sequences for the product.
Step 5 Develop a Kroll's disassembly evaluation chart for each sequence as shown in Table 4.
Step 6 Calculate the total number of tool and hand manipulations for each sequence.
Step 7 Calculate overall disassembly time for each sequence using the disassembly evaluation chart and the equation mentioned in previous section (Eq. 1).
Step 8 Determine the Disassembly Effort Index (New DEI) for each sequence using the quantification formula developed in proposed DEI model.

In this example, all parts are chosen to be disassembled. Thus, the disassembly effort spent in the complete disassembly process of the CRT monitor needs to be estimated.

Typically, four disassembly modeling strategies are used to represent all feasible and complete disassembly sequences with correct precedence relations. They are Connection graph, Directed graph, AND/OR graph, and Disassembly Petri net (Vinodh et al. 2011). In our work, AND/OR graph has been used to represent the sequences. The AND/OR graph for the CRT monitor disassembly is shown in Fig. 1. The blocks that are blue in Fig. 1 are disassembled and taken apart from the product, and those that are in yellow are parts which remain intact in the product. The disassembly constraints that should be respected while creating the graph are as follows: (i) same direction should be followed while disassembling (no change in disassembly direction is allowed); (ii) only one part should be disassembled at a time, and parallel disassembly is not allowed (only sequential disassembly is allowed); and (iii) semi-destructive disassembly techniques are allowed to disturb the connections only (since the recovery option is recycling). Respecting the constraints mentioned above, each part was disassembled, and whenever a disassembly task occurred that caused a change in the product structure due to some parts being taken apart from the product, it was marked as t1, t2, t3, etc. This way a complete AND/OR graph was created for the CRT monitor disassembly process, and the feasible disassembly sequences were derived from the graph as shown in Fig. 2. Six different disassembly sequences are feasible for this product based on the constraints. Among the six sequences derived from the graph, the first sequence is the disassembly sequence that is shown in the video of CRT monitor disassembly (E-waste: dismantling a CRT monitor).

Once sequences are derived, a Kroll and Hanft disassembly evaluation chart should be created for each sequence as shown in Table 4. Disassembly evaluation charts for sequence 1 and sequence 2 are shown in Table 4. In this way, disassembly evaluation charts were created for all six sequences. With the help of these charts, the total number of tool and hand manipulations and the overall disassembly time can be calculated for all the six sequences, as shown in Table 5. Using the quantification formula developed in the proposed DEI model for estimating the

Table 4 Kroll's disassembly evaluation charts for sequence 1 and sequence 2

1 Part no.	2 Qnty	3 Min no. parts	4 Task type	5 No. of task repetitions	6 Tool	7 Access	8 Positioning	9 Force	10 Base time	11 Special	12 Sub total	13 Total
Sequence 1												
A Main wires	1	–	Cu	1	WC	1	2	1	2	1	7	7
B Side cover	1	–	We (pry)	1	CH	1	1	2	2	3 (additional motions)	9	9
C Whole plastic casing	1	–	Un	6	PS	1	2	3	8	1	15	90
			Re	1		1	1	1	1	1	5	5
D PCB	1	–	Pu (pull)	1		1	1	2	1	1	6	6
			Ha	1	HM	1	2	1	3	1	8	8
			Pu (push)	1	WC	1	1	1	1	1	5	5
			Cu	4	PS	1	2	1	2	1	7	28
			Un	2	WC	1	2	3	8	1	15	30
			Cu	4		1	2	1	2	1	7	28
E Magnetic deflector assembly	1	–	Tu	1		1	1	1	1	1	5	5
			Re	1		1	1	1	1	1	5	5
F CRT	1	–	Un	4	PS	1	2	10	8	1	22	88
			Re	1		1	1	2	1	1	6	6
G Front plastic casing	1	–	–	–	–	–	–	–	–	–	–	–
												320
Sequence 2												
A	1		Cu	1	WC	1	2	1	2	1	7	7
B	1		We (pry)	1	CH	1	1	2	2	3 (additional motions)	9	9
C	1		Un	6	PS	1	2	3	8	1	15	90
			Re	1		1	1	1	1	1	5	5
E	1		Pu (pull)	1		1	1	2	1	1	6	6
			Ha	1	HM	1	2	1	3	1	8	8
			Pu (push)	1	WC	1	1	1	1	1	5	5
			Cu	4		1	2	1	2	1	7	28
			Tu	1		2	1	1	1	1	6	6
			Ho+	1		3	1	1	1	2	8	8 } 13
			Re	1		1	1	1	1	1	5	5
D	1		Un	2	PS	1	2	3	8	1	15	30
			Cu	4	WC	1	2	1	2	1	7	28
F	1		Un	4	PS	1	2	10	8	1	22	88
			Re	1		1	1	2	1	1	6	6
G	1	–	–	–	–	–	–	–	–	–	–	–
												329

EoL Disassembly Effort, new DEI can now be calculated as shown in Table 5.

From the results obtained, it can be seen that sequences 1 and 4 have less DEI score compared to other sequences (See Table 5). Thus, in order to carry out the CRT monitor disassembly process with minimum effort, either sequence 1 or sequence 4 should be chosen. In this way, the proposed DEI model can be used to determine the EoL disassembly

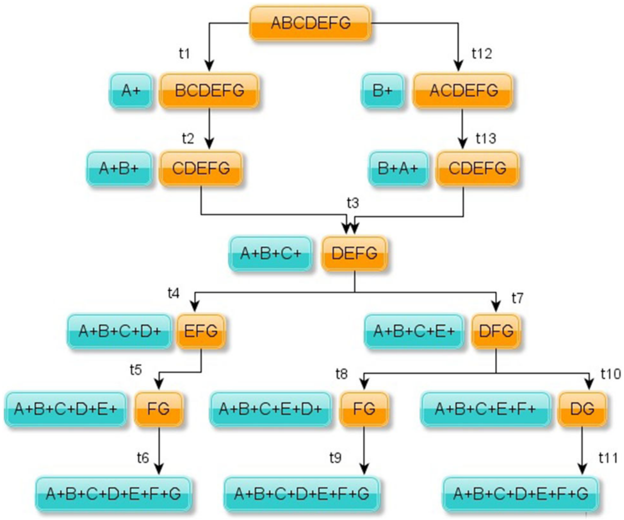

Fig. 1 AND/OR graph for CRT monitor disassembly

effort, not only for an existing product but also for a product which is at its early design stage and for all the feasible sequential disassembly sequences possible for the product.

Validation of the proposed DEI model

The proposed DEI model has been validated with a case study conducted on fifteen computer electronic products. The EoL disassembly effort spent in the disassembly processes carried out on all fifteen computer electronic products was evaluated by both Das et al. DEI model and the proposed DEI model. Fifteen videos on disassembly processes of the products were collected for this study. Each video was assessed for disassembly effort using both Das et al. DEI model and the proposed DEI model. As discussed earlier, all seven factors, namely time, tools, fixture, access, instruct, hazard, and force, were assessed for each product's disassembly process. DEI scores were calculated for all fifteen products using Das et al. DEI model (See Table 6). CRT monitor is one of the fifteen products disassembled for which the DEI score is shown in Table 1.

Sequence 1: t1 + t2 + t3 + t4 + t5 + t6

Sequence 2: t1 + t2 + t3 + t7 + t8 + t9

Sequence 3: t1 + t2 + t3 + t7 + t10 + t11

Sequence 4: t12 + t13 + t3 + t4 + t5 + t6

Sequence 5: t12 + t13 + t3 + t7 + t8 + t9

Sequence 6: t12 + t13 + t3 + t7 + t10 + t11

Fig. 2 Disassembly sequences derived from AND/OR graph

Similarly, the same fifteen videos were used for the estimation of new DEI using the proposed DEI model. As mentioned earlier, the two primary factors that are needed for the estimation of disassembly effort using the new DEI model are (i) the overall disassembly time taken for a disassembly process and (ii) the total number of tool and hand manipulations carried out in a disassembly process. Overall disassembly time for each product can be directly taken from the respective video. The total number of tool and hand manipulations was calculated for all fifteen products using Kroll and Hanft model. One such example is explained with a CRT monitor disassembly in Table 3. Thus, using the quantification formula of the proposed DEI model, new DEI for CRT monitor disassembly was found to be 110.6 as mentioned in the earlier section. This way, new DEIs were estimated for all fifteen products that were disassembled.

In order to identify whether the new DEI model developed gives similar results to that using Das et al. DEI model, correlation between the results from the two models was studied. Since the data type is of ordinal or ranked data type, Spearman's Rank correlation coefficient method was used to study the correlation between the results. Spearman's Rank correlation coefficient is used to identify and test the strength of a relationship between two sets of data. The dataset should include a minimum of 15 cases to be valid (Spearman's Rank correlation coefficient—Excel guide, Royal Geographical Society). The correlation results are shown in Table 6.

In Table 6, it can be seen that Spearman's Rank correlation coefficient (r) is 0.9714 or 0.97. Since the value is closer to $+1$, there exists a strong positive correlation between the two datasets (results of Das et al. model and new DEI model). In other words, if DEI score calculated using Das et al. model increases, new DEI score estimated using the proposed DEI model will also increase. To see if this coefficient value (r) is significant, a Spearman's Rank significance table or graph must be used as shown in Fig. 3.

Degrees of freedom must be calculated in order to find the significance. Degrees of freedom $= n - 2$, where 'n' is the number of samples. Thus, in this case, degrees of freedom $= 13$. Using degrees of freedom and Spearman's Rank correlation coefficient (r), significance level of the data can be assessed with the help of Fig. 3.

In Fig. 3, a black line that cuts across the red lines is drawn to show the significance level of the datasets. It can be seen that the black line falls in the area above the line of 0.1 %, meaning that there is a greater than 99 % chance that the relationship is significant and not random. In other words, the likelihood of the correlation occurring by chance is 0.1 %. Thus, with the higher significance level, it can be concluded that there is a strong relationship between the results of proposed DEI model and the results of Das

Table 5 Tool and hand manipulations and overall disassembly time for CRT monitor disassembly for all six sequences

Disassembly sequences	Total number of tool and hand manipulations	Overall disassembly time (min)	New DEI (min)
1	28	3.45	96.6
2	30	3.55	106.5
3	36	3.85	138.6
4	28	3.45	96.6
5	30	3.55	106.5
6	34	3.64	123.7

Table 6 Correlation between results of new DEI model and Das et al. DEI model

Products disassembled	Das DEI	Das DEI rank	New DEI	New DEI rank	*d*	d^2
Keyboard (INF)	34	15	0.82	15	0	0
Keyboard (F)	47	14.5	3.4	14	0.5	0.25
Cables (F)	47	14.5	4	12.5	2	4
PCB1 (INF)	55	13	4	12.5	0.5	0.25
PCB2 (INF)	57	12	6	11	1	1
Cables (INF-Guiyu)	62	11	8	8.5	2.5	6.25
Mobile PWB (F)	64	10	7.08	10	0	0
CRT (INF)	67	9	10	7	2	4
Cables (INF-Ghana)	74	8	8	8.5	0.5	0.25
Mobile phone (F)	113	6	11	6	0	0
PCB (F)	123	5	19.28	5	0	0
CPU (INF)	128	4	24	4	0	0
Hard disk (F)	228	3	104.04	3	0	0
CRT (F)	272	2	110.6	2	0	0
CPU (F)	297	1	252	1	0	0
						16

$n = 15$

$n^3 = 3375$

$n^3 - \mathrm{n} = 3360$

$r = 1 - 6 \sum d^2/n^3 - n$

Spearman's correlation coefficient = 0.9714

et al. DEI model. In other words, the DEI score estimated using the proposed DEI model is very similar to that of the DEI score calculated using the Das et al. DEI model.

The potential reasons behind the strong positive correlation between the results of Das et al. DEI model and the proposed new DEI model are the following: In both the models, disassembly time is given more weightage as a significant factor contributing to an overall disassembly effort associated with any disassembly process. Although the model of Das et al. claims that in addition to time, several other factors contribute to an indirect activity cost or effort associated with a disassembly process (Das et al. 2000), disassembly time is given the highest weightage (25 percent) among all seven factors used in this model for assessment of disassembly effort. Similarly in the proposed DEI model, overall disassembly time is considered as one of the two primary factors contributing to the disassembly effort. Among the seven factors evaluated in Das et al. DEI model, score for access has been always zero for all the disassembly steps in each of the product disassembly process considered in this study. This is because all the disassembly processes considered in this study are complete, sequential disassembly processes. Sequential disassembly is defined as a process in which only one part is disassembled at a given time. It was observed in the study that every disassembler considered that part which is readily accessible to be disassembled next, and thus, there was no accessibility issue at all in any of the disassembly

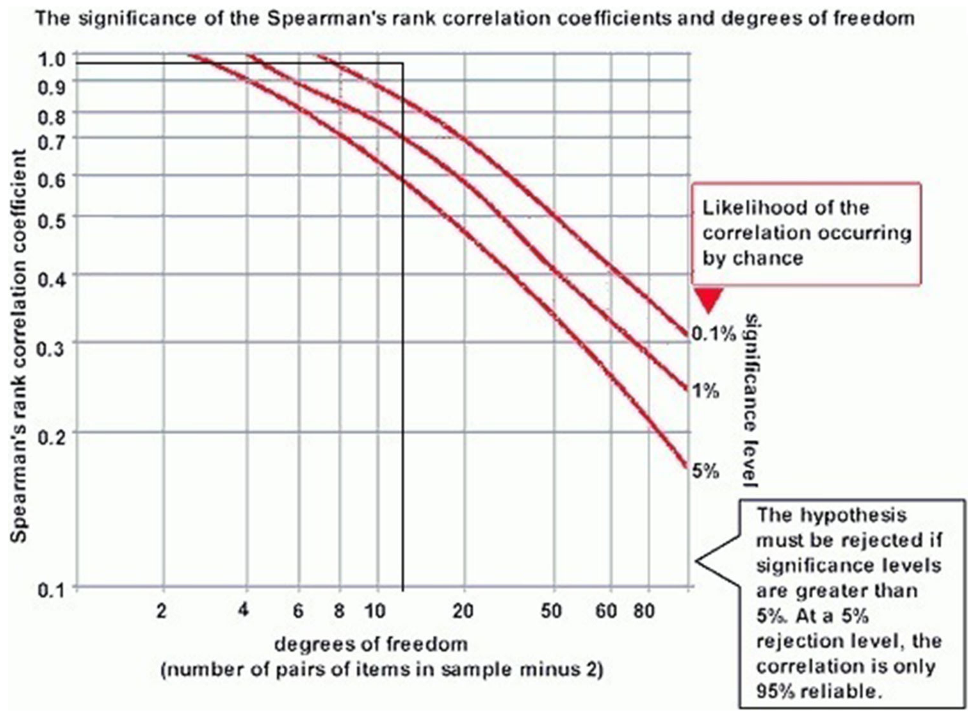

Fig. 3 Graph to test the significance level of Spearman's Rank correlation (Spearman's Rank correlation coefficient—Excel guide, Royal Geographical Society)

processes observed in the study. And the scores of instruct and hazard remained the same for all the disassembly steps in each of the disassembly processes that was observed. This is because, in practice, scores for factors like instruct and hazard did not change at each disassembly step since they are usually assessed at product level and not at part level. Thus, apart from disassembly time, the other major factors that are potential determinants of disassembly effort for each product are tools, fixture, and force involved in that particular disassembly process. Thus, it can be concluded that factors such as time, tools, fixture, and force are those that are predominantly responsible for causing the variation in disassembly effort across products.

In the proposed DEI model, the two primary factors that are used for the assessment of disassembly effort are (i) overall disassembly time and (ii) total number of tool and hand manipulations. Thus, based on the insights obtained into all the factors that might potentially contribute to the disassembly effort, it could be concluded that apart from time, the 'tool and hand manipulation' calculated using Kroll and Hanft model and factors such as tools, fixture, force that are used in the evaluation of disassembly effort by Das et al. DEI model are the significant contributors to the disassembly effort. One interesting observation that was made in the study was that the above-mentioned factors that contribute to disassembly effort (tool and hand manipulations calculated using Kroll and Hanft model and factors such as tools, fixture, and force that are estimated by Das et al. DEI model) are closely related to each other. Thus, these could be the underlying reasons as to why the correlation is high between the disassembly effort determined by Das et al. DEI model in the form of a DEI score and the new DEI estimated using the proposed DEI model.

Conclusions

A new model for estimating the EoL disassembly effort at the early stages of product design has been proposed. The need for the development of the proposed model is explained. With the proposed DEI model, disassembly effort can be estimated not only for an existing product but also for a product at its early design stage, for multiple feasible sequences, using less data and time. This model could also be used to test a product for its ease of disassembly. Thus, the model proposed could be used not only as a support to enable designers to evaluate alternative designs for ease of disassembly and help them make reliable decisions on preferred designs but also as a design for disassembly tool that would enable designers to gain insights into designs of a product from its disassembly perspective. The novel contributions of the paper are as follows: (1) This is the first DEI model where results of a time-based disassembly model (Kroll model) have been translated into an effort score which is on par with the results of the existing Das DEI model. From this, a new finding has been made as follows: (i) long disassembly time is one of the two major factors that contribute to high disassembly effort and (ii) the second major contributor is the more number of tool and hand manipulations that leads to high disassembly effort. (2) The new DEI model has provision for determining disassembly effort for multiple feasible complete sequential disassembly sequences, which will enable designers to compare the disassembly effort among various alternative designs even when each product could be disassembled in its best possible way. The new DEI model thus in a way has a new ability of determining effort for multiple feasible sequences compared to other existing models which help in determining effort. (3) Unlike earlier models, where using DEI during the design process was very difficult due to the large amount of data, many of which could be found only for a manufactured product, our model can be used during embodiment design onward. This makes it a potential design tool. Two potential areas for future improvement are as follows: (i) the feasible disassembly sequences are derived based on certain constraints (complete sequential sequences only), and therefore, the proposed DEI model is handicapped in its inability to derive all the geometrically feasible sequences; and (ii) it is yet to be checked as to whether the proposed model might be useful for assessing disassembly effort for other recovery options: reuse, remanufacturing, etc. This is because the two models (Das et al. DEI and Kroll and Hanft ease of disassembly evaluation model) that have been used in the development of the new DEI model primarily focus on recycling as the EoL option. Unless the proposed DEI model is used for the estimation of the disassembly effort for other recovery options like reuse and remanufacturing, and the results validated, it cannot be claimed that the proposed DEI model could be used for other recovery options as well.

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