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Evaluation of disassemblability to enable design for disassembly in mass production

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Abstract

A comprehensive methodology to enhance disassemblability of products has been presented in this paper. Disassemblability of a product is a function of several parameters such as exertion of manual force for disassembly, degree of precision required for effective tool placement, weight, size, material and shape of components being disassembled, use of hand tools, etc. The study of relevant literature indicates the presence of disassembly evaluation criteria and methodologies that address the problem partially such as disassembly sequence planning or economic analysis. As far as design for disassembly is concerned, there is a plethora of literature on rules *to improve recycling* end-of-life components. A systematic methodology to incorporate disassembly considerations in product design and enable quantitative evaluation of the design is absent. The current methodology assigns time-based numeric indices to each design factor, which make for easy and quick determination of disassembly time. A higher score indicates anomalies in product design from the disassembly perspective. Addressing these anomalies can result in significant design modifications rendering an overall increase in disassemblability of the product. Decisions regarding design modifications are based on weighing several factors such as technical and economic feasibility, overall functionality and structural rigidity of the product as a whole.

Relevance to industry

A comprehensive Design for Disassembly methodology is developed which is intended to act as a tool in life cycle engineering.

Keywords: Disassemblability; End-of-life products; Design for X (DfX); Design for disassembly; Disassembly evaluation metrics

1. Introduction

In the engineering context, disassembly may be defined as the organized process of taking apart a systematically assembled product (assembly of components). Products may be disassembled to enable maintenance, enhance serviceability and/or to affect end-of-life (EOL) objectives such as product reuse, remanufacture and recycling.

In the present era of environmental awareness, EOL objectives such as component reuse (components from a retired product being used without up gradation in a new product), remanufacture (components from a retired product being used in a new product after technological up gradation)

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and recycling (reuse at the material level, e.g. recycling of plastics) constitute some of the most important reasons for disassembling products. This can be attributed to the staggering impact of industrial and domestic waste on the environment. Widespread diffusion of consumer goods and shortening of product life cycles has lead to an unprecedented number of used products being discarded. For example, every family in the USA is expected to own a computer by 2005. In 1991, Carnegie Mellon University estimated that by this time, some 150 million obsolete PCs, *none with readily recoverable materials*, would require more than 8 million cubic meters of land fill space at a cost of around US$400 million (Lee et al., 2001). However, the number of potential landfill sites for non-hazardous solid wastes has seen an exponential decrease. In the United States alone, landfill sites have diminished from 18,000 in 1985 to 9000 in 1989. According to a recent study, the United States had lost more than 70% of its landfill sites by 1997 (Zhang et al., 1997) with landfills in many states reaching their permitted capacities at an alarming rate. EOL products contain extensive amounts of reusable material, which is too expensive to dispose of, retrieval of, which would be beneficial to the manufacturer as well as the environment.

Due to the gravity of the situation, products will be expected to derive minimal energy and resources from the environment and *discharge minimal amount of wastes during and after their life cycles*. Unrecyclable material is required to be disposed of without causing any harm to the environment or to human health (Choi Athelstan, 1994). Disassembling products for EOL objectives allows *reusable, non-recyclable and hazardous subassemblies to be selectively separated from recyclable ones* (Gungor and Gupta, 1997).

From the manufacturers'/reclaimers' perspective, the process may be clearly distinguished into two categories based on the method of disassembly:

- Destructive disassembly or brute force approach, e.g. incineration, metal cutting, etc.
- Non-destructive disassembly or reverse-assembly.

In the case of non-destructive disassembly, if a fastener is screwed in, then it is screwed out. If two parts are snap fit together, then they are snapped out. In the case of destructive disassembly, parts are just pulled or cut (Kuo et al., 2001). This paper focuses on non-destructive disassembly as part of environment friendly manufacturing. Depending on the extent of disassembly, non-destructive disassembly can be further classified into two categories as follows:

- *Total disassembly*: The entire product is disassembled into its constituent components. This is sometimes not economically feasible due to the imposition of external constraints such as time, economic factors, presence of hazardous materials, etc.
- *Selective disassembly*: Selective disassembly is defined as the *reversible dismantling* of complex products into less complex subassemblies or single parts (Lambert, 1999). It involves the systematic removal of *desirable constituent parts from an assembly* while ensuring that there is no impairment of parts due to the process (Brennan et al., 1994).

Quantitative design information is the single most important source of information available to the designer. Research efforts in addressing this issue of the disassembly problem have been few. With the exception of a couple of independent researchers, little has been done to enable quantitative evaluation of a design from the disassembly perspective.

Most algorithms focus on the theoretical part of the product disassembly process. Examples of these include optimization algorithms; algorithms based on economic analysis, CAD-based algorithms, etc. They fail to consider crucial factors such as:

- The magnitude of manual force required to effect disassembly.
- The need for specialized manual tools in order to facilitate disassembly.
- Accessibility issues to enhance quick and easy disassembly.
- The need for the assumption of irregular working postures for a prolonged period of time.

This is where the ergonomic aspect of the disassembly process comes into picture. Special provisions need to be incorporated into the algorithm in order to account for these factors. The disassembly process is still largely manual in nature. It is therefore imperative that a variety of ergonomic factors such as the ones mentioned above come into play in the mass disassembly of consumer products. An effective disassembly algorithm should consider the effect of such factors on the disassembly process as a whole. By doing so, the algorithm introduces the much-needed 'practical' aspect into disassembly evaluation. Such considerations would also facilitate the subsequent automation of the disassembly process in the future.

Quantitative design data coupled with systematic application of the general design for disassembly (DfD) methodology would be instrumental in arriving at a feasible and practical solution so far as designing products for disassembly is concerned. To this end, a new comprehensive methodology for DfD based on quantitative analysis of design parameters affecting disassembly has been presented in this paper.

This paper is divided into two sections. Section 2 presents an overview of background and current status of disassembly algorithms. Section 3 presents a new methodology for DfD. It is supplemented by a case study experiment on a common consumer product in order to highlight the usability and significance of the methodology.

2. Background and current status

2.1. Disassembly algorithms

The major bulk of research conducted on disassembly has concentrated more on such issues as disassembly sequence planning, disassembly evaluation and analysis and product recovery. This section attempts to review various approaches addressing these and related issues.

Thierry et al. (1995) proposed a product recovery management (PRM) approach wherein returned products could be recovered at four levels: product, module, part and material level (in that order). Product recovery options achievable by disassembly may be classified into the following categories (Table 1).

Krikke et al. (1998) considered the problem at the tactical management level to *determine an optimal product recovery and disposal (PRD) strategy*. Retrievable parts, modules and subparts were identified and represented at various sublevels. The aim of disassembly was to make separate recovery or disposal possible for every single subassembly.

A disassembly sequence plan (DSP) is a sequence of disassembly tasks that begins with a product to be disassembled and terminates in a state where *all the desired parts of the product are disconnected* (Gungor and Gupta, 1998). A DSP aims to optimize product recovery through the minimization of cost, maximization of material

Table 1
Product recovery options after disassembly

Options	Objective	Level of disassembly	Result
Repair	Restore working condition	Product level (limited disassembly and fixing)	Some parts repaired
Refurbishing	Improve quality level (though not like new)	Module level (some technological upgrading)	Some modules repaired/replaced
Remanufacturing	Restore quality level as new	Part level	Used and new parts in new products
Cannibalization	Limited recovery	Selective disassembly and inspection of potentially reusable parts	Parts reused and/or recycled/disposed of
Recycling	Reuse materials only	Material level	Materials used in new products

Source: Thierry et al. (1995).

recovered, minimization of disassembly time using mathematical techniques such as linear programming, dynamic programming and graphical tools. Chandra (1994) described product recovery using a CAD tool (ReStar) to find a recovery plan that *balanced the amount of effort put into recovery and the amount of effort saved by reusing parts and materials* through the use of breakeven analysis. The traveling salesman methodology is used to solve the problem. Zussman et al. (1994) addressed the problem of dealing with future uncertainties of recycling options using the utility theory. Attributes such as technology refinement, prices or dumping fees are bound to change with time (dynamic) and as such involve uncertainty for the designer/policy maker. Two algorithms were presented by Taleb and Gupta (1997) to obtain a scheme for disassembling multiple product structures having common parts. The Core algorithm determined the number of root items to be disassembled in order to minimize disassembly cost. The Allocation algorithm was used to determine a disassembled schedule for the roots and subassemblies by allocating the disassembly requirements over the planning horizon. Gungor and Gupta (1997) presented an evaluation methodology to choose the best disassembly process from among several alternative processes based on total time for disassembly. Penev and DE Ron (1994) proposed an algorithm for designing processes and systems based on the detection and removal of *preferred* components. *The Dynamic programming approach was used for optimization.* Lambert (1999) addressed the problem of selective disassembly sequence generation using the linear programming approach. Sequences that combined maximum net revenue with environmental requirements were selected.

Feldmann et al. (1999) touched upon the issue of disassembly costs. Recycling costs and benefits differ for specific fractions of recovered materials. The more important economic considerations to be taken into account during the disassembly process include such factors as value added to products and materials during manufacturing, disassembly cost and revenue per operation and the penalty if poisonous materials are not completely removed (Ad de Ron, 1995). The EOL economic value of components can be computed using the costing technique suggested by Lee et al. (2001). The role played by economic factors in the determination of an optimal recycling and disassembly strategy is illustrated below (Fig. 1).

de Ron and Penev (1995) devised a disassembly strategy based on the economic validity of the disassembly process. The main drawback of disassembly evaluation based solely on economic criteria is that it does not present a comprehensive strategy to optimize disassembly. Lee et al. (2001) proposed guidelines for determining feasible EOL options including the economic value of products and their components (Table 2).

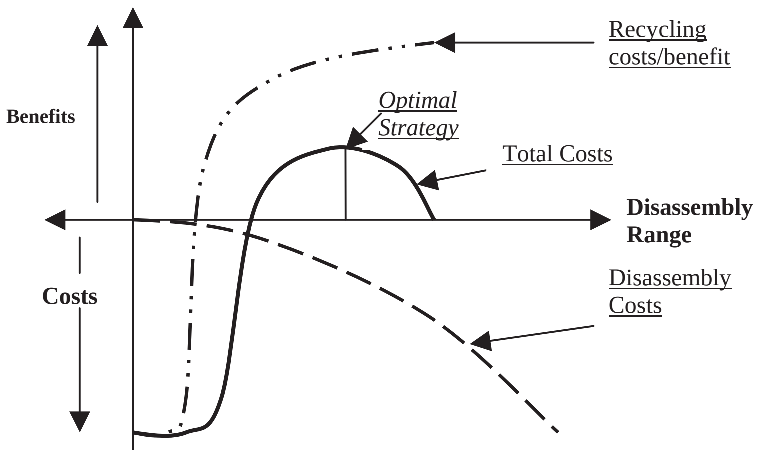

Fig. 1. Determination of optimal recycling and disassembly strategy. *Source*: Adapted from Feldmann et al. (1999).

Table 2
Type of recycling according to component composition

Type of recycling	Definition	Composition of the component
Primary recycling	Recycling on a comparable quality level	No alloy present in the component Polymer content in the component
Secondary recycling	Recycling on a lower quality level *Down cycling*	Presence of an alloy in the component No polymer content Ceramic content
Tertiary recycling	Decomposition	Elastomer or composite material
Quaternary recycling	Incineration with energy retrieval	No polymer content Ceramic content

Table 3
Technical feasibility and economic attractiveness of automation of electrical and electronic goods disassembly technology

Year	Technical feasibility (%)			Commercial feasibility (%)		
	Full	Partial	Limited	Full	Partial	Limited
1998	2 (6)	7 (6)	29 (22)	4 (0)	2 (0)	12 (16)
2000	7 (2)	28 (14)	40 (35)	5 (0)	23 (4)	25 (16)
2005	26 (4)	39 (33)	24 (22)	11 (2)	25 (24)	39 (35)
2010	30 (28)	14 (29)	3 (18)	14 (15)	28 (31)	14 (16)
2015	11 (17)	11 (12)	2 (0)	23 (17)	5 (12)	2 (4)
2020	9 (15)	2 (4)	2 (2)	12 (17)	5 (10)	5 (4)
Later/never	16 (28)	0 (2)	0 (0)	32 (49)	14 (18)	4 (8)

Note: Feasibility for automotive products is indicated in parentheses.
Source: Adapted from Boks and Templemon (1998).

Srinivasan and Gadh (2002) addressed the issue of disassembling a geometrically constrained assembly of components. Two types of constraints were considered: spatial constraints and user defined constraints. A geometric algorithm to selectively disassemble a product was presented by Srinivasan and Gadh (1998). The algorithm utilized the principle of wave propagation by analyzing the assembly from the component outwards and ordering the components for disassembly. Srinivasan et al. (1999) presented another CAD-based selective disassembly algorithm. Shyamsundar and Gadh (1999) addressed the problem of determining a valid assembly for which at least one disassembly sequence existed. Two methodologies were presented: (1) assembly topology graph (ATG) and (2) set of boundary components (components most easily accessible for disassembly).

The issue of automation of disassembly and recycling technology was dealt with in a recent Delphi study. The conclusions of the study point to the fact that the main obstacles facing future disassembly and recycling technology are more economic than technological in nature (Boks and Templemon, 1998). Automatic disassembly (for a limited product variety only) was expected to gain importance. Results of the study are tabulated as follows (Table 3).

2.2. Design guidelines for design for disassembly

Life cycle analyses indicate that a large chunk of the entire cost associated with the product can be attributed to the product design process. It has been proved that disassembly process optimization accounts for a meager 10–20% of all disassembly related gains. *The major chunk of disassembly related gains (80–90%) tends to be determined at the product design stage*. Hence, it is in industry wide interest to develop methods and tools to incorporate environmental considerations into product design (Kriwet et al., 1995). DfD, is therefore, a key strategy within the larger area of Sustainable Product Design and development.

DfD initiatives lead to the correct identification of design specifications to minimize the complexity of the product structure (Gungor and Gupta, 1999). This is done by achieving numerous objectives such as minimizing the number of different parts, increasing the use of common materials, optimizing the spatial alignment between various components to facilitate disassembly *without jeopardizing assemblability, functionality and structural soundness*.

Gu and Sosale (1999) developed a methodology to modularize a product for Life cycle analysis (LCA). The methodology considered various LCE objectives such as assembly, maintenance, reuse and recycling. Parts were clustered such that interactions between modules are minimized.

Ong and Wong (1999) described a methodology for *the automatic generation of disassembly sequences* by modularization of components using computer software.

2.3. Defining and evaluating disassemblability

Disassemblability is defined as *the degree of easy disassembly* (Mok et al., 1997). The following factors affect disassemblability:

- Use of force: Minimal use of force is recommended. This enables the disassembly process to be carried out quickly without the use of excessive manual labor.
- Mechanism of disassembly: A simple mechanism is preferable.
- Use of tools: Ideally, disassembly should take place without the use of tools. Examples of such processes would include simple push/pull processes or processes in which components become disengaged merely by the exertion of direct manual force. This factor is in agreement with factor 1 above.
- Repetition of parts: Part repetition should be minimized to enable quick and easy identification of parts at each stage of disassembly.
- Recognizability of disassembly points: Disassembly points are defined as those joints, which need to be disjointed so as to affect disassembly. Easy recognizability of such points is advisable especially in the case of complex product structures or products that incorporate snap fits as well as in the case of products that accumulate internal dirt during their useful life.
- Product structure: The simpler a product structure, the better it is from the disassembly point of view.
- Use of toxic materials: Since most disassembly is still manual in nature it is advisable not to incorporate toxic materials in the design of parts since they may pose health hazards to the operator performing the disassembly.

When a product is designed from the DfD perspective, a number of changes may be incorporated which would render the product technically faulty or structurally unsound. Product redesign would be necessary in such a situation. This may be affected by redesigning components, standardizing parts, materials and subassemblies, devising innovative joining methods, etc. This is one of the most critical arguments made by Mok et al. System parameters classified by disassemblability factors have been provided as illustrated below (Table 4).

Shu and Flowers (1999) presented an application of a *design-for-remanufacture* framework to the selection of product life cycle fastening and joining methods. The issue of accessibility of joints not otherwise used in routine maintenance operations was addressed at length.

Kroll and Carver (1999) attempted to develop time-based DfD metrics *to be used when designing new products to simplify their disassembly for recycling*. Difficulty in product disassembly can be attributed to the following factors:

- Accessibility: Measure of ease with which a part can be reached by hand or by a tool.

Table 4
Disassembly system parameters

Part parameters: structural aspects			
Contact condition	Center of gravity	Weight	Joint point
Symmetry	Grip point	Strength	Roughness
Interlocking	Joining element	Size	Rounding
Color	Material	Shape	Tolerance
Part parameters: organizational aspects			
Product structure	Standardization	Variant	Number of parts
Process parameter: pre-process			
Working space	Alignment mechanism	Degree of automation	
Disassembly information	Transport mechanism	Presence of hazards	
Inspection mechanism	Disassembly sequence		
Process parameters: in-process			
Disassembly direction	Handling mechanism	Interference	Joining force

Source: Adapted from Mok et al. (1997).

- Positioning: The degree of precision required to place the tool or hand.
- Force: Measure of effort required to perform the task.
- Base time: The time required to do the basic task movements without difficulty.

Though disassembly evaluation metrics play a very important role in product DfD, time is the only metric this paper considers. The one factor that this paper fails to address is the weight to be assigned to specialized tools if they are to be used. More important is the fact that the methodology relies heavily on specialized disassembly task analyses only. It would be relegated to obsolescence in case of an entirely new, more efficient disassembly operation. As such, this methodology decreases the degrees of freedom as far as innovative disassembly operations and therefore fastening methods are concerned. Similarly, the researchers have stopped at trying to compile a scoring system to estimate disassembly time of a disassembly operation. A systematic methodology to use these scores to enhance product design from the disassembly perspective has not been devised.

An optimal disassembly strategy should optimize such attributes as use of manual labor, use of specialized tools, etc. Efforts therefore need to be undertaken to adapt knowledge from the theoretical realm to work in the practical realm. In the light of the above discussion, it is clear that researchers have managed to find only partial solutions.

The following section describes a DfD methodology based of quantitative analysis of design parameters affecting disassemblability.

3. Evaluation of disassemblability

The methodology being described in the following paragraphs assigns weightage to numerous factors such as size and shape of components being disassembled, weight, frequency of disassembly tasks, requirement of manpower, postural requirements and material handling requirements. A number of human factors in addition to design and economic factors merit consideration due to high labor intensiveness of the disassembly process. *These factors directly affect the disassembly process and had hitherto been neglected* in the formulation of both disassembly algorithms and DfD methodologies.

Every disassembly operation is subdivided into basic elemental tasks. It has been observed that only a fraction of all the tasks in the entire disassembly operation are actually responsible for performing disassembly.

For example, consider a simple unscrew operation that may be subdivided into the following elemental tasks:

Operation: unscrew

1. Constrain the product to prevent motion during disassembly.
2. Reach for tool (power screwdriver).
3. Grasp the tool.
4. Position the tool (accessibility of fastener).
5. Align the tool for commencement of operation (accessibility of fastener).
6. Perform disassembly (unscrew operation: force exertions in case of manual unscrew operation).
7. Put away the tool.
8. Remove screws and place them in a bin.
9. Remove the component and put it in a bin.

Clearly, task numbers 4, 5 and 6 actually affect disassembly. Task numbers 1, 2 and 3 are preparatory tasks. Altering these tasks would have little or no effect on the efficiency of the disassembly process. Assuming all other conditions such as operator dexterity and speed of operation, weight and size of tool and workplace conditions to remain constant, the efficiency of the disassembly process can be directly attributed to task number 4, 5, 6 and 9 above. Examination of these tasks reveals that they are directly affected by design configuration of the product. For example, some designs would allow easy access to components for disassembly while others may not. Accessibility of components and fasteners is a design attribute that enables effective positioning and alignment of a tool for disassembly purposes. Similarly, task no. 9 can also be shown to be directly affected by product design. Component removal is influenced by design attributes such as size, shape, weight and material of the component. Large, unsymmetrical and heavy components as well as minute and sharp components are difficult to manipulate and handle and result in decrease in disassembly efficiency. Similarly, all the above-mentioned tasks require the adoption of a particular posture during the disassembly process. If a large number of such operations are to be performed during the work shift (frequency of operations) and the worker is forced to adopt an unnatural posture resulting in the onset of static fatigue, the long-term effects can be devastating.

Meaningful disassembly evaluation criteria should therefore include all the above-mentioned factors since they are directly related to product design. Other factors that affect the disassembly process include weight and size of tool (large, heavy and unsymmetrical tools are unwieldy and difficult to operate) and any preparation operation such as cleaning and degreasing prior to disassembly.

The new methodology consists of the following distinct elements:

- A numeric disassemblability evaluation score.
- Systematic application of DfD methodology.

The numeric disassemblability evaluation index is a function of several design parameters that directly or indirectly affect the process of consumer product disassembly. Numerical scores are assigned to each of these parameters depending on the ease with which they can be attained. The following parameters have been addressed:

Degree of accessibility of components and fasteners: Easy access is a prerequisite for quick and efficient disassembly operation. The less accessible a component or fastener, the higher numerical score it receives.

Amount of force (or torque) required for disengaging components (in case of snap fits) or unfastening fasteners: The lesser the amount of force required, the better the design. The amount of effort required is directly proportional to the value of numerical score received.

Positioning: This attribute reflects the amount of precision required to place a tool for disassembly purposes. The greater the degree of accuracy required, the more the time. This leads to a higher numeric index being assigned.

Requirements of tools: An ideal disassembly operation constitutes reaching for an easily grasped object and removing it without the exertion of much force without the use of any tools. Ideally, disassembly should be attainable without the use of any tools. However, in most

Table 5
Comparison of EOL options based on cost considerations

EOL option	Definition	Associated costs of implementation
Reuse	Component is disassembled from the product structure and is used on an "as is" basis, without any technological up-gradation/down-gradation or being subject to any design modifications	Disassembly costs
		Cleaning costs
		Assembly costs
Remanufacturing	Component is disassembled from the product structure and is subject to certain design changes which result in technological up-gradation/down-gradation	Disassembly costs
		Cleaning costs
		Redesign costs
		Remanufacturing costs
		Assembly costs
Recycling	Only the material of the component is used again to perform another function	Disassembly costs
		Cleaning costs
		Recycling costs
		Material processing costs
		Manufacturing costs
		Packaging costs
		Assembly costs

Table 6
Attributes affecting decision of EOL options

Attributes	
1.	The level of technological complexity of the component
2.	Functional importance of component
3.	Cost associated with manufacturing and assembling the component
4.	Level of manufacturing expertise associated with manufacturing and assembling the component
5.	Cost associated with taking the component apart and recycling it
6.	Component life
7.	Probability of component design undergoing fundamental changes in the near future that fundamentally affect its functionality, efficiency and/or performance

cases, product disassembly entails the use of common tools such as screwdriver, etc. Under special circumstances, special tools may be required.

Design factors such as weight, shape and size of components being disassembled: This can be a crucial consideration in product disassembly especially since it involves the use of special fixtures and apparatus or simply more manpower. For example, the CRT of a 25″ television set can be quite heavy and large for a single person to manipulate efficiently.

The ascertainment of a numeric disassembly score consists of two distinct parts:

- Assignment of discrete EOL options to each component.

Table 7
Scoring system for numeric analysis of disassemblability

Design attribute	Design feature	Design parameters	Score	Interpretation
Disassembly force	Straight line motion without exertion of pressure	Push/pull operations with hand	0.5	Little effort required
			1	Moderate effort required
			3	Large amount of effort required
	Straight line and twisting motion without pressure	Twisting and push/pull operations with hand	1	Little effort required
			2	Moderate effort required
			4	Large amount of effort required
	Straight line motion with exertion of pressure	Inter-surface friction and/or wedging	2.5	Little effort required
			3	Moderate effort required
			5	Large amount of effort required
	Straight line and twisting motions with exertion of pressure	Inter-surface friction and/or wedging	3	Little effort required
			3.5	Moderate effort required
			5.5	Large amount of effort required
	Twisting motions with pressure exertion	Material stiffness	3	Little effort required
			4.5	Moderate effort required
			6.5	Large amount of effort required
Material handling	Component Size	Component dimensions (very large or very small)	2	Easily grasped
			3.5	Moderately difficult to grasp
			4	Difficult to grasp
		Magnitude of weight	2	Light (<7.5 lb)
			2.5	Moderately heavy (<17.5 lb)
			3	Very heavy (<27.5 lb)
	Component symmetry	Symmetric components are easy to handle	0.8	Light and symmetric
			1.2	Light and semi-symmetric
			1.4	Light and asymmetric
			2	Moderately heavy, symmetric
			2.2	Moderately heavy, semi-symmetric
			2.4	Moderately heavy, asymmetric
			4.4	Heavy and symmetric
			4.6	Heavy and semi-symmetric
			5	Heavy and asymmetric

Table 7 (*continued*)

Design attribute	Design feature	Design parameters	Score	Interpretation
Requirement of tools for disassembly	Exertion of force		1	No tools required
			2	Common tools required
			3	Specialized tools required
	Exertion of torque		1	No tools required
			2	Common tools required
			3	Specialized tools required
Accessibility of joints/grooves	Dimensions	Length, breadth, depth, radius, angle made with surface	1	Shallow and broad fastener recesses, large and readily visible slot/ recess in case of snap fits
			1.6	Deep and narrow fastener recesses, obscure slot/recess in case of snap fits
			2	Very deep and very narrow fastener recesses, slot for prying open snap fits difficult to locate
	Location	On plane surface	1	Groove location allows easy access
		On angular surface	1.6	Groove location is difficult to access. Some manipulation required
		In a slot	2	Groove location very difficult to access
Positioning	Level of accuracy required to position the tool	Symmetry	1.2	No accuracy required
			2	Some accuracy required
			5	High accuracy required
		Asymmetry	1.6	No accuracy required
			2.5	Some accuracy required
			5.5	High accuracy required

- Evaluation of numeric indices affecting disassemblability.

This methodology is described in detail as follows:

3.1. Assignment of EOL options to components

Each component is assigned a discrete EOL option: Reuse, Remanufacturing and recycling. Incineration and land filling are not considered as EOL options since this methodology is being formed to enable non-destructive disassembly of product structures (Table 5).

The following factors are considered while deciding EOL options for each component (Table 6).

The logic in assigning EOL options to components early on during the evaluation process is to take advantage of the 'Vital few, trivial many' philosophy. This means that components destined

Table 8
Correlation of need for unnatural postures to specific design anomalies

Posture	Design anomalies
Prolonged gripping of a tool	Large number of fasteners Need for large amount of disengaging force Need for sustained exertion of disengaging force Large number of disengaging points
Prolonged bending and twisting the neck	Need to reach obscure components/fasteners (location) Need to reach obscure components/fasteners (size) Complex and twisted disassembly path Need to perform a highly accurate disassembly operation on a sensitive component Need to avoid hazardous components in the disassembly path

Table 9
Provision of allowances for adoption of atypical postures to incorporate ergonomic considerations in product design

Posture	Score
Prolonged gripping	3
Prolonged arm extension forwards	3
Prolonged bending and twisting the neck	4
Prolonged bending and twisting the entire torso	4
Prolonged wrist flexion	3

for reuse, being the most important are considered first for design changes. Design changes made to these components may in turn require changes to be made to other components as well. It is advisable to have more important components to be the focal point in design analysis.

3.2. Numeric evaluation of disassemblability

Each component is evaluated for each of the above-mentioned attributes directly affecting disassemblability.

Each of the above factors is further subdivided into causal design parameters alteration of which can result in significant improvement in disassemblability of the component. The scoring system as presented below is based on the MTM predetermined time system. The simplest disassembly task of removing an easily grasped object without the exertion of much force by hand by a trained worker under average conditions has been considered as the basic disassembly task. A score of 73 TMUs was assigned to this task, which corresponded to time duration of approximately 2 s. Subsequent scores were assigned based on the detailed study of most commonly encountered disassembly operations (Table 7).

3.3. Posture allowances

Allowances have been made for the need of specialized postural requirements. Unnatural postures commonly encountered are listed in Table 9. In addition, product design characteristics leading to the need for the adoption of some such postures are also listed in Table 8. These allowances may be viewed as an appendix to the main algorithm.

Product disassembly may be viewed under two different scenarios: Low volume and high volume. In the case of low volume disassembly, economic considerations may not always justify the additional costs to be incurred through the design of specialized disassembly fixtures. Yet the product volume is high enough to entail operator fatigue and in extreme cases may hasten the onset of posture related MSDs. In this case, posture allowances may be incorporated into the

Table 10
Design modifications to enhance disassemblability from the perspective of the design attribute: accessibility

Design attribute	Design feature	Remedial measures	Component redesign required?
Accessibility	Deep fastener recesses	Redesign recess to facilitate tool access	Y
		Select a different fastening method	Y
	Narrow fastener recesses	Redesign recess to facilitate tool access	Y
		Select a different fastening method	Y
	Small fastener head	Increase fastener head size	N
		Select a different fastening method	Y
	Obscure fastener	Choose standard fastener sizes	N
		Increase fastener size	N
		Select a different fastening method	Y
	Deformed fastener	Improve fastener rigidity to withstand stresses during operation	N
	Deformed component	Improve component rigidity to withstand stresses during operation	Y
		Redesign weak component cross sections	Y
	Deformed bearing surface of component	Improve component rigidity to withstand stresses during operation	Y
	Need for cleaning before access	Redesign component/fastener interface	Y
		Change component material	Y
	Obscuring components	Redesign assembly sequence based on disassembly priority of components	N
	Insufficient clearance for effective tool manipulation	Redesign component recesses/slots	Y
		Redesign fasteners	N
		Select a different fastening method	Y

disassemblability evaluation. This DfD methodology has been developed for medium sized consumer products and appliances. As such, it is understood that most disassembly tasks would be performed sitting down at bench level.

3.4. Design diagnostics

Once design attributes with high numeric scores have been identified for each component, causal effects need to be diagnosed. A detailed and in depth diagnosis of these effects results in the formation of alternative design configurations. Thus, the design diagnostics part of the algorithm is indispensable as far as effective application of the methodology is concerned. A few of the design diagnostics for the design attribute 'Accessibility' are as outlined in Table 10 below.

As is evident from the above diagnostics, a variety of alternative design configurations can be generated corresponding to each remedial measure. Each of these configurations may in turn be

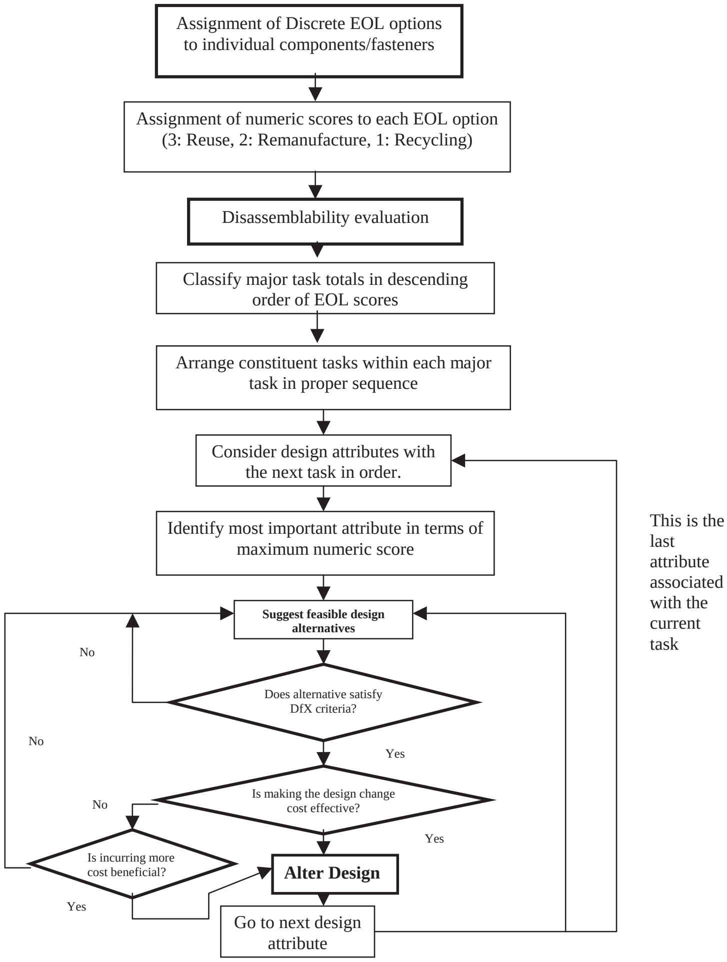

Fig. 2. Hierarchical reasoning of the DfD algorithm.

analyzed for cost effectiveness and in turn tested for functionality, assemblability, manufacturability and structural rigidity under working conditions. The following is a hierarchical representation of the proposed DfD algorithm as depicted in Fig. 2.

3.5. Applications in design

An experiment was conducted on an electric drill set to gauge the effectiveness of the current methodology in the objective evaluation of disassemblability. The parts list for the drill set is as given in Table 11.

Table 12 is only a random assortment of some disassembly tasks and tools. The tasks and tools listed do not necessarily correspond to one another.

From the results of the experiment of Table 13, it is clear that the total disassembly time equaled approximately 1.94 min.

3.6. Comprehension of design evaluation

As is evident from the numeric evaluation chart presented in the preceding section, the task involving removal of component 4 from the assembly comprises the highest score of the

Table 11
Parts list for electric drill

Part no.	Component name	Material	Quantity
1	Front and rear screw	Steel	6
2	Middle screw	Steel	2
3	Upper housing	Plastic	1
4	Sub assembly of parts 7–20	Mixed	—
5	Brush	Carbon	2
6	Lower housing	Plastic	1
7	Bushing	Bronze	1
8	Insulating washer	Phenolic	1
9	Sub-assembly of parts 18–20	Mixed	—
10	Rotor	Mixed	1
11	Spring washer	Steel	1
12	Washer	Steel	1
13	Bushing plate	Steel	1
14	Chuck assembly	Steel	1
15	Support plate	Steel	1
16	Shaft	Steel	1
17	Gear	Steel	1
18	Brushes wire	Mixed	1
19	Trigger assembly	Mixed	1
20	Stator	Mixed	1

Table 12
Sample list of commonly encountered disassembly tasks and disassembly tools

Task	Code	Tool	Code
Unscrew	Un	Power screwdriver	Ps
Pry open	Pr	Pry bar	Pr
Pull	Pu	Screwdriver	Sd
Invert	In	Adjustable wrench	Aw
Push	Ps	Allen key	Ak

entire disassembly operation for components with the highest EOL value. This is followed by the task involving removal of component 9 and so on.

The next step involves identifying the most important design anomaly in terms of maximum numeric score for the first task in the list. For example, in the case study performed in the preceding section, the task involving removal of component 4 would be the first task considered for scrutiny. The following design anomalies (those receiving the highest scores) are involved in performing the task:

- need for excessive force (design factor),
- component shape, size and weight (design factor),
- accuracy of tool positioning (design factor).

3.7. Advantages of the new design methodology

The new methodology offers several distinct advantages over existing DfD techniques. These advantages are enumerated as follows:

1. The system of assigning numeric scores to varying degrees of difficulty of a particular criterion has been kept simple and straightforward. Each scoring criterion has been correlated to a list of possible design flaws. This enables quick and ready interpretation of numeric disassembly scores.
2. The scoring system can be readily adapted to suit any disassembly operation involving any kind of tool, and disassembly actions.
3. Since the new methodology couples disassemblability evaluation with DfD criteria, numeric scores obtained from the former can be readily identified as design flaws, which can be corrected using appropriate DfD criteria.
4. Additional allowances for human factors such as assumption of unnatural postures while performing particular disassembly tasks can be readily correlated to a design flaw. For example, a highly repetitive task of accessing and positioning a tool in a narrow and deep recess requires much attention and entails visual fatigue.

4. Conclusion

The disassemblability evaluation methodology strives to include all relevant factors that directly or indirectly affect the process of non-destructive disassembly of products. To attain this objective, numerous ergonomic evaluation categories have been included in addition to conventional design attributes while compiling the methodology. The assignment of objective numeric indices to

Table 13
Evaluation of disassemblability for a hand-held electric drill set

Task no.	Component no.	Task	Tool	EOL option (rank of component)	Disassembly force			Material handling			Requirement of tools		Accessibility of joints		Positioning	Task total	Remarks
					Inter-surface friction	Inter-surface wedging	Material stiffness	Component size	Component Weight	Component Symmetry	Force exertion	Torque exertion	Dimensions	Location	Accuracy of tool placement		Key: EOL options Reuse 3 Remanufacturing 2 Recycling 1
Major task #1					Disassemble component 3 (1) 'Upper Housing'												
1a	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew first of six front and back screws
1b	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew second of six front and back screws
1c	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew third of six front and back screws
1d	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew fourth of six front and back screws
1e	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew fifth of six front and back screws
1f	1	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew sixth of six front and back screws
1g	2	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew first of two middle screws
1h	2	Un	Ps	1	2.5	—	—	2	2	0.8	—	2	1.6	2	2	14.9	Unscrew second of two middle screws
1i	3	Pu	—	1	—	1	—	3.5	2	1.4	1	—	1	1.6	1.6	8.6	Pull out upper housing
Major task # 2						Remove subassembly 4 (3) 'Subassembly of parts 7–20'											
2a	4	Pr	Pr	3	—	4.5	—	4	2.5	2.4	2	—	2	2	2.5	21.9	Pry out subassembly out of the lower housing
Major task # 3					Disassemble subassembly 4 (3) 'Subassembly of parts 7–20'												
3a	7	Pu	—	1	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out bushing
3b	8	Pu	—	1	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out insulating washer
3c	9	Pu	—	3	3	—	—	4	2.5	2.4	1	—	1.6	1.6	2.5	18.6	Pull out subassembly 9
3d	10	Pu	—	1	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out rotor
3e	11	Pu	—	1	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out spring washer
3f	12	Pu	—	1	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out washer
3g	13	Pu	—	1	1	—	—	2	2.5	2	1	—	1	1	1.2	11.7	Pull out bushing plate
3h	14	Pu	—	3	1	—	—	2	2.5	2	1	—	1	1	1.2	11.7	Pull out chuck assembly
3i	15	Pu	—	3	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out support plate
3j	16	Pu	—	3	1	—	—	2	2	0.8	1	—	1	1	1.2	10	Pull out shaft
Major task # 4					Disassemble subassembly 9 (3) 'Subassembly of parts 18–20'												
4a	18	Pr	Pr	1	—	3	—	2	2	1.4	2	—	1.6	1.6	2.5	16.1	Pry out brushes wire
		Pu	—	1	1	—	—	2	2	1.4	1	—	1.6	1.6	2.5	13.1	Pull out brushes wire
4b	19	Pr	Pr	3	—	3	—	4	2.5	2.4	2	—	1.6	1.6	2.5	17.1	Pry out trigger assembly
		Pu	—	3	1	—	—	4	2.5	2.4	1	—	1.6	1.6	2.5	16.6	Pull out trigger assembly
																324.6	

Note: Total disassembly time = 3246 TMUs = 3246 × 0.036 s = 116.8 s = 1.94 min.
Task # 1 for disassemblability analysis: Task # 3: Disassembly of subassembly 4.
Task # 24 for disassemblability analysis: Task # 1: disassemble upper housing.
Most important design anomaly: force required wedging out subassembly # 4.

component design attributes provides the designer with much-needed (but sorely missing) quantitative design information. Design attributes such as accessibility, force exertion and positioning have been expanded to include design specifics such as location and dimensions that affect each of these attributes.

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