Design for Disassembly. Introduction to a New Design Issue

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Abstract
The paper presents a concept to take into account disassembly processes in the product design. While products are frequently design for easy of assembly, disassembly is often neglected although it demands another approach because of differences between used parts and a variety of demands for their further treatment. This fact is emphasized in the first part of the paper. It has been shown that disassembly processes are strongly connected with the life cycle engineering. Next, some principles of design for disassembly have been discussed including joints and material choice. Finally, evaluation of cost involved in the disassembly is considered and methods that can aid disassembly process planning are shortly characterized.

Keywords: product design, product end of life, product disassembly, disassembly process, disassembly economics, recommendations for design.

1 Introduction

There is a growing need to design new products that are easy at disassembling. While products are frequently design for easy of assembly, disassembly is usually more complex because of differences between used parts and a variety of demands for their further treatment. The purpose of the paper is to discuss how disassembly processes could be taken into account in design for the product life cycle. It is shown that disassembly processes are strongly connected with keeping materials in the closed loop operations. First, distinctions between assembly and disassembly are examined. Next a taxonomy of disassembly processes and fasteners is presented. A number of recommendations to design for disassembly is put forward and principles of design for disassembly are discussed, including important problems of material selection and economic issues. Four constituents of disassembly process costs are presented and a complexity metrix is proposed. Finally, importance of easy disassembly for cost and end-of-life product management is emphasized.

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2  Design of assembly versus disassembly

Figure 1 shows that assembly and disassembly are integral parts of the product life cycle. The assembly process (Fig. 2) belongs to the most important stages of the product manufacturing process. It consists of joining elements into units and the units into the complete assembly or product. It is commonly known that manufacturing costs generate major expenses of the product realization, whereas cost of assembly may reach even 30-50% of all manufacturing costs (Whitney [2004], Rohatyński [2009], Boothroyd et al. [1994]). This importance of assembly cost for the product realization and quality suggests that assembly process should be carefully considered during design. It should be made certain that this process is performed fast and error-free.

![Diagram of product life cycle](image)

**Fig 1.** The life cycle of a product from identification of needs to phase out.

Methodology ‘Design for Assembly’ (DFA) recommends reducing number of the product being designed parts, streamlining assembly operations, and minimizing their cost. This suggests that quality of the assembly process should be explicitly considered during design.
Implmentation of DFA methods have been accepted in many manufacturing companies in a form of manuals and special computer programs. In some enterprises (especially in USA) application of DFA is obligatory (Boothroyd et al., 1994). Some companies report that thanks to this approach they cut the number of parts and average assembly cost up to 40%. They saved of 15-35% of direct labor and material costs. It is to be noted that these savings were obtained for products which were regarded as being well designed, and with application of the value engineering approach. It has also been proven that DFA application allows avoidance even up to 80% assembly errors (Whitney, 2004; Boothroyd et al., 1994).

In relevant literature one can find a variety of DFA methodologies in which the authors address advantages of application of commonly known DFA tools in stages of the product realization, and especially in the early design phase. Efficient tools assisting design for assembly are recommended in a number of literature sources (Whitney, 2004; Boothroyd et al., 1994; Rohatyński and Sasiadek, 2008). It is important to recognize that the actual assembly sequence is not always the reverse of the disassembly sequence, and disassembly is not simple opposite of assembly. Thus, disassembly requires special considerations of its own. For example, one desirable property of components for assembly, for example easy of insertion, is different from the corresponding disassembly step, i.e. extraction. The net value added percentage in the disassembly is significantly less than in the assembly process. This implies that for a disassembly activity to be profitable, the labor time, equipment needs, energy needs, skill needs, and space requirements must be relatively small.
2.1 Taxonomy of disassembly processes

Comparison of the diagrams in Fig. 2 and 3 gives general information of differences between these two processes. Although applications DFMA and DFD philosophies in the design may sometimes to be contradictory, but they both are responsive for the product quality.

The disassembly process is a sequence of disassembling operations. These operations remove parts or subassemblies from the product. The initial state of the process is the complete product yet the final one has to be determined in advance. After disassembling the complete product has been divided into its parts and/or subassemblies that remain undestroyed or partially destroyed. Destructive operations are not counted among the process of disassembly.

Undestroyed disassembly operations can be:

- Reversible, that are easy for disassembly, e.g. screw joints, or
- Partially reversible that can be also undestroyed but their execution - although easy for assembly - is somewhat more difficult in disassembling, e.g. snap joints.

![Figure 3](attachment:disassembly_diagram.png)

**Fig 3.** Block diagram for a product disassembly (after Blanchard, 1992).

Partially destroying operations are irreversible because they damage the joint by means of cutting, breaking, bending, and so on. They usually happen during disassembling, and if the damage is not serious they are considered to be fit to the disassembly.

Complete disassembly separates all parts that constitute the product while the partial one also divides it but not all parts are separated.
Disassembly depth is the measure of degree of the disassembly execution. The disassembly process that satisfies some defined criteria is called the selective ones.

Disassembly process can be serial or parallel. It is serial if at least one operation results in disassembling of one integral part. It is parallel if it consists of at least one operation resulting in disassembling of two composite parts.

Disassembly processes occur not only in the post-consumer phase. Partial disassembly and reassembly are often carried out in maintenance service for periodical exchange of used or damaged parts.

2.2 Types of Fasteners

A variety of fasteners types are applied in complex products (Fig. 4). It can be simple elements like, for example, screws or compound, e.g. snaps. In principle, each fixing element can be considered a fastener. However, elements often perform also other functions so named them ‘the fasteners’ is not correct. In a multi-function part one can identify a ‘fastener surface’ or a ‘fastener feature’.

![Fig 4. Types of joints and their properties (after Beitz, 1990).](image)

Taxonomy of fasteners depends on accepted distinguishing criteria (Das et al., 2000). Commonly agreed classification is listed below.

1. Individual elements which are not deformable (e.g. screws, bolts, nuts, etc)
2. Individual elements which are deformable but reversible (e.g. clamps, cot- ters...)
3. Individual elements which are deformable and irreversible (e.g. rivets, adhesive tapes...)
4. Parts of elements; reversible connections (contact surfaces, joint snaps...)
5. Parts of elements; irreversible connections (deformable surfaces, washers, welts...)

3 Design for Disassembly

In case of very complex products disassembly poses difficult task. Even though it could be performed by means of undestroyed operations they take significant time and cost. Therefore a rational approach to the matter is taking it into account in advance i.e. during design. The DFD principles are based on the detailed analysis of the disassembly process. Although detailed presentation of these exceeds size of this paper, yet a selection of requirements which is given below may be useful.

In the disassembly the first actions is frequently the most important ones. The first step for separation can be destructive or not destructive, the second step is sorting or, sometimes, separating again. Then the three general design rules are:

1. Arrange the subassemblies for easy disassembly,
2. Use joints that are easy to separate,
3. The joints should have the same life span as the whole product.

From the point of view of ecology it may be useful for designers to regard any product as a set of 'ecomodules' where each object or module consists of a homogenous piece of material, a useful subassembly and the like. Each ecomodule is surrounded by its sorting border. Sorting border should be congruent with a separating surface in all multimaterial products (Rohatyński, 2016). There are four questions for sorting borders the designers should consider:

- Easiness of information what is inside the sorting border,
- Costs that may be caused by the sorting border,
- Possibility to reuse it second time,
- To what extent separating surface follows the sorting border.

Evaluation of different design solutions requires information on a specific joint load case and on specific sorting objects that are surrounded by sorting borders. Moreover, designers are required to design joints that are easy to disconnected. The typical joint load cases are:

1. What tools are needed to release the joint,
2. What force is needed to release the joint,
3. How much time is needed to release the joint.
3.1 Principles of material selection

- Parts should be made from homogeneous materials (if possible),
- Number of different materials should be limited, particularly in case of plastics,
- Harmful substances as for example asbestos should be excluded,
- Substances that could potentially generate hazard should be avoided,
- Substances not amenable for recycling (for example composites) should be prohibited,
- Elements made from plastic materials should be labelled of their composition,
- Data on the product and its element (structure, material properties, mass, geometry etc.) should be easily accessible.

In general, the goal of material selection in DFD is to reduce the disassembly labor. By reducing the total number of materials, the designer decreases separation time and increases the product’s value to the recycler. Although cost may initially increase but the disposal expenses will soon be decreasing. Other material selection options include substituting equivalent materials to suit performance specifications or using two compatible materials that can be recycled together.

A recyclable material is not necessarily easily recycled. Some materials can only be recycled if a sufficient mass of a relatively pure content can be collected. The majority of the material recycling processes are limited in the amount of impurity they can accept. In a complex assembly this implies that a considerable degree of disassembly must be achieved to gain the required purity. Impurity determines the quality of the recycled material and its market price and is the most widespread roadblocks to more recycling. With present recycling technology a large part of the purification process must be accomplished by physical disassembly and sorting.

Using recycled materials in products will create and support the markets for these materials in the future. Unfortunately, designers often refuse to use recycled materials because they do not believe in their quality.

3.2 Recommended mechanical properties and structure

- Structure of the product should be transparent, that means joints that have to be disconnected should be unambiguously pointed out and effortlessly accessible,
- Product should have hierarchical and modular structure in order to be easily disassembled into its functional units,
- All connections should be accessible and, if they demand force, appropriate tools should be available,
• Joints should be reversible (if possible),
• Number of types of joints should be limited,
• Number of tools necessary to disassembly operations should be minimal,
• Number of directions of motions at disassembling should be limited.

Many of above suggestions are common for assembly and disassembly but reversibility and reduction of the material variety pertain to DFD only (Chen, 2001; Kuo et al., 2001).

By conforming to these recommendations and questions designers and managers can make right decisions about the disassembling functionality.

4 Disassembly economics

Assessment of the overall economics of disassembling process is still not easy task, yet there are four primary constituents contributing to the disassembly cost.

First, there is the direct labor time associated with the operation. When the products have been disassembled the labor can be estimated by means of time and motion analysis. There are several approaches by which this can be done (Das, 2002; Fang et al., 2014). In an effort to standardize disassembly operation times Dowie and Kelly (Dowie and Kelly, 1994) conducted a series of disassembly experiments with simple operations. Vujosevic and al. (Vujosevic et al., 1995) used a work measurement tool to estimate disassembly times in developing a simulator for maintainability analysis. Earlier, Kroll (Kroll and Carver, 1999) developed a method for estimating the disassembly time using work measurement analysis.

One primary principle in design for assembly and disassembly is the adoption of minimum number of fasteners in an assembly. In manual disassembly, especially without the assistance of properly designed disassembly fixtures, each fastener needs to be disassembled separately. Different fastener types may require different types of unfastening tools and different accessing directions, resulting in an increase in the disassembly time as well as disassembly cost. Therefore, the disassembly complexity of an individual part can be assessed based on (1) the variation of the fasteners types, and (2) the number of fasteners for each type. It is reported that the effect of the number of fasteners to the complexity is nonlinear, and can be modeled using entropy in information theory (Mathieson and Summers, 2010). When the count is low, the addition of a fastener is significant, while the opposite is true of high-count systems. The logarithmic function, which is monotonically increasing but concave, can model the impact of the number of fasteners.

The number of fastener types is modeled using the summation function, considering that the effect of the variation of the fastener types could overweighs that of the number of fasteners, since each fastener type may require a different unfastening
tool during disassembly. The disassembly complexity metric $M_{COM}$ can be given in equation (1), in which $N_j$ is the variety of the joining types, and $N_f(i)$ is the number of fasteners or connectors in type $i$.

$$M_{COM} = \sum_{i=1}^{N_j} \log_2(2 \times N_f(i))$$

(1)

The second cost element is the disassembly effort. This includes the associated tooling and fixturing needs, part accessibility, worker’s skill and instructions, process hazards, and force requirements. Das et al. (2000) and Chen (2001) proposed a multifactor model for estimating the disassembly effort index (DEI) for a product. The final weights distribution was as follows: time 25%; tools 10%; fixture 15%; access 15%; instruction 10%; hazard 5%; and force 20%. The sum of the DEI scores for all steps gives the overall score. The greater the number of steps the higher the DEI score will be.

The third cost element is the logistics cost. It includes the cost to collect the device from the point of disposal and convey it through the consolidation facility. Typically, this cost is equivalent to the price a disassemble will pay for the disposed vehicle on receipt.

The fourth and final cost is the inventory carrying cost associated with the disassembly activity. This includes the cost of the occupied space and the associated regulatory cost. Disassembly facilities located in high population density areas tend to have high carrying costs. A facility, for example, can delay the disassembly of a vehicle until there is sufficient demand for its parts.

To sum up, among factors contributing to higher cost of the disassembly are: The labor cost, the time to disassemble the product, indirect and overhead cost, the purchase and logistics cost associated with the product, and the inventory carrying cost for the product.

4.1 Methods for disassembly planning

Disassembly sequencing is one of the important task for design and planning the process since it much influences cost. In order to accomplish the optimal sequence the following three types of methods can be used.

**Heuristic methods.** These methods apply some general qualitative rules and instructions, which are relatively easy and quick but do not guarantee optimal solution (Góralski, 1989). Sometimes they may lead to erroneous effects.

**Computer metaheuristic methods.** To this group belong evolutionary and genetic algorithms, neural networks, tabu search, simulated annealing, ant colony, swarm intelligence and others. They are applied to complex problems of large size, which can not be solved by exact methods. Usually algorithms of metaheuristic methods terminate after predefined number of operations or after accomplishment some given value of the objective function. They have many advantages but also share common
drawbacks: (i) they need special computer programs; (ii) they usually work long; (iii) it is unknown how much their suboptimal solution is worse from the optimal one (Michalewicz and Fogel, 2002).

**Exact mathematical methods.** This group of methods uses mathematical programming. Principally, there are two kinds of these methods: the first systematically checks all possible solutions, while the second one applies some methods that accelerate search without visiting all possibilities. The latter are based on simplex algorithms or branch and bound algorithms, which eliminate some parts of the solution space from the search. Application of named methods to generation of disassembly sequences can be found for example in (Langella, 2007; Rekiek et al., 2002).

5 Conclusions

The general intention of the paper has been description of the disassembly as a part of the product end of life and explain and present reasons for importance of the design for disassembly (DFD) as a proactive action towards generation of modern, ecological products. This extensive problem has been taken based on analysis of thoroughly selected literature. It has been shown that purposeful decomposition of the disassembly process based on its taxonomy leads to important recommendations for DFD. Owing to these recommendations it becomes possible to define principles of design for disassembly including selection of materials, fasteners choice, and cost of the process. It has also pointed out that there is a need of the disassembly quality metrics. This question will be the subject of a further work.

References


