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Analyzing Conflicts between Product Assembly and Disassembly for Achieving Sustainability

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Abstract: Environmental performance of a product could be increased throughout its life cycle by incorporating design requirements which consider Design for Disassembly (DfD) from a life cycle perspective by aiding ease of disassembly of the product across its life cycle. These design requirements, including DfD for different life cycle phases, should be made compatible with Design for Assembly (DfA) requirements within an integrated framework. Using such an integrated framework should reduce various layers of complexity introduced in to design and should help designers to develop products that are easy to both assemble and disassemble, without compromising the product's functionality. Prerequisites to developing the integrated framework are to: understand the requirements for DfD and DfA, identify if they are in conflict with one another, understand the underlying causes, and develop means to resolve these. To determine whether DfD and DfA requirements conflict one another, various existing products are analyzed, for conflicts among their assembly and disassembly processes. Various conflicts are found to be present among these processes. These conflicts are outlined, and possible causes for these are identified.

Keyword: Disassembly, DfD, DfA, conflicts

1. Introduction

Sustainability is a growing concern among all countries. This is due to various factors, such as the following: manufacturers continue to introduce huge quantities of products without considering future reuse during their development, and customers often get dissatisfied with their products even through these are in good working condition. Factors such as these lead to a wide variety of products being disposed rather than being recovered and reused.

Society has started realizing the likely environmental threats that might result from disposal; for instance, governments are enacting strict legislations for disposal of products in an environmental friendly manner. One impact of these regulations is increased responsibility on the part of manufacturers in the End-of-Life (EoL) phase of their products. This scenario makes manufacturers rethink about the decisions taken during their product design and manufacturing stages. Decisions taken during the design stage are critical because it is during this stage that most product attributes are decided (Motevallian et al. 2007) and most of the considerations that have the potential to resolve environmental issues are incorporated. Designing products with reduced impact on environment in their EoL phase is a far better option than products that are not designed for this purpose, and hence destined to end in disposal. However, in order to achieve environmental sustainability, it is not enough to focus only on the EoL phase of the product. Impacts caused by the product in its other life cycle phases also add to its environmental consequences. Therefore, it is crucial to improve the environmental performance of a product throughout its life cycle (Alting and Legarth, 1995). The product should be developed in such a way that its likely impact on the environment is minimized in each of its life cycle phases.

One way to improve the environmental performance of a product throughout its life cycle is to design the product such that it aids ease of disassembly in all its life cycle phases. Design for (ease of) Disassembly (DfD) is one of the strategies to improve disassemblability of the product. It is an approach in which disassembly considerations are incorporated into the product at the design stage itself (Veerakamolmal and Gupta, 2000), thereby increasing the product’s ease of disassembly. While doing this, DfD should be balanced against other design considerations (Gkeleri et al. 2008) such as DfA in order to avoid new problems being introduced into the design; evidence for this can be found in Chiu and Kremer (2011), who observed that introducing Design for X guidelines for one aspect (e.g. assembly) without considering other often led to new problems.

This paper emphasizes the need for developing an integrated framework for DfD. Prerequisites to this are: to understand the requirements for DfD and DfA, to identify whether or not they are conflicting, identify the reasons behind the conflicts, if any, and develop means to resolve the conflicts. Existing products were analyzed for conflicts in their assembly and disassembly processes to understand DfD and DfA compatibility. We found that various conflicts exist among assembly and disassembly processes of these products. In this paper, these conflicts are outlined, and possible causes are discussed.

Section 2 elaborates the importance of carrying out disassembly in each life cycle phase; Section 3 explains what DfD is and how DfD needs to be different for each life cycle phase; Section 4 reviews existing literature on the relationship between DfD and

DfA, and establishes the need for an integrated framework for DfD; Section 5 reports on a pilot study carried out to determine whether conflicts exist among ease of assembly and disassembly processes of existing products and what cause these conflicts; conclusions and future work are presented in Sections 6.

2. Disassembly

(Brennan et al. 1994) defined disassembly as ‘‘the processes of systematic removal of desirable constitute parts from an assembly while ensuring that there is no impairment of the parts due to the process”

“Ease of disassembly” is one of the requirements for achieving easy transportation, easy service and maintenance (Desai and Mital, 2003), easy recovery of parts at EoL (Kroll and Hanft, 1998 and Desai and Mital, 2003). We argue, therefore, that disassembly has the potential to improve environmental performance of a product throughout its life cycle by improving efficiencies of the operations carried out during all the life cycle phases of the product. Henceforth, we refer to this objective as “disassembly for all life cycle phases”.

2.1 Disassembly for various life cycle phases

2.1.1 Disassembly for production

During assembly, the possibility of parts ending up in a wrong fitting is high when parts have similar geometric structure and multiple possible ways of being fitted. In such cases, disassembly would be necessary for removal of those parts for reassembly in the same product, thus preventing the use of new parts. Another reason is that testing may reveal issues with functioning of the product; to resolve these, product must be disassembled.

2.1.2 Disassembly for distribution

Some complex products are difficult to distribute, because their product architecture will not allow their components to get separated during transportation and later reassembled for use. Disassembly of such products could improve the distribution efficiency by making products occupy less storage space during transportation.

2.1.3 Disassembly for use

Disassembly enables maintenance and enhances serviceability (Desai and Mital, 2003). Thus it increases the life of a product **(**Motevallian et al. 2007).

2.1.4 Disassembly for EoL

The recovery processes are often economically unviable if the products are originally designed with no consideration to their future reuse. So, very often, disposal is the only option for such products. To resolve this issue, products should be variously remanufactured, reused or recycled, so as to maximally recover its sub-assemblies, components or materials, from used products, in order to make these available for new products. Disassembly is necessary in carrying out these recovery processes.

3. Design for disassembly

According to Giudice et al. (2006), DfD is a design approach with the objective of optimizing the architecture and all other constructional characteristics of a product in relation to the following main requirements: limiting the time and costs of disassembly; simple and rapid separability of parts to be serviced or recovered. DfD can also be defined as "the consideration of the ease of disassembly during the design process" (Veerakamolmal and Gupta, 2000).

3.1 DfD for various life cycle phases

Production phase:
The objective of DfD for production is to design such that the parts having similar geometric structure and ambiguous fitting possibilities are easily accessed, disassembled and assembled in order to rectify the assembly, if applicable.
Distribution Phase:
The objective of DfD for distribution is to design the product with high modularity, i.e., easy access, disassembly and reassembly of all modules, with all functional requirements satisfied after reassembly.
Use phase:
The objective of DfD for service and maintenance is to make design choices that most efficiently ease accessibility, disassembly and reassembly of certain predetermined components that require servicing intervention.
EoL phase:
The objective of DfD for EoL is to design a product such that its subassemblies, parts and materials, at the end of its useful life, are easily accessible and separable (and in some cases re-assemblable) from their adjacent subassemblies, parts and materials, so as to make them amenable to appropriate EoL treatments e.g. remanufacturing, reuse, or recycling.

4. Compatibility between DfD and DfA

4.1 Literature on relationships between DfD and DfA

Boothroyd and Alting (1992), Jovane et al. (1993), Penev and De Ron (1996), and Gupta and McLean (1996) have studied DfA methods and discussed research opportunities in

DfD. Shu and Flowers (1995) showed that joints designed for ease of assembly and recycling may not facilitate remanufacturing. One problem with disassembly of existing products, reported by Alting et al. (1995), is that it requires a large number of steps to take products apart as joining techniques are directed towards assembly and not disassembly.

Harjula et al. (1996) identified that though DfA redesigns could be beneficial in simplifying disassembly, additional design changes have to be incorporated for simplifying removal of critical items. Several differences between assembly and disassembly have been identified, such as 1) irreversible operations like welding, riveting or breakage of components (Lee et al. 1996), 2) selective disassembly (Srinivasan and Gadh, 1997). Based on the implications of these differences, Srinivasan et al. (1997) concluded that the most economical assembly sequence need not be the most economical disassembly sequence. Kroll et al. (1998) pointed out that DfD and Design for Manufacture and Assembly (DfMA) may seem similar in intent, but are often quite different in practice. They reported that many products designed for assembly are very hard to disassemble, e.g, those with certain types of snap-fit joints.

Westkamper et al. (1999) have compared assembly and disassembly for different EoL options (including repair), based on following criteria: productivity, quality, lead time, time to delivery, process time, and flexibility. Their study highlights how to integrate assembly and disassembly given that logistics, systems, technical installations, flexible automation, management of product life cycle data were to be made common for both assembly and disassembly. While this work focuses on integrating assembly and disassembly systems for existing products, the focus of our work lies in integrating assembly and disassembly requirements at the design stage.

Nof and Chen (2003) argued that Design for assembly and disassembly (DFAD) involves integrating the specific domain knowledge of manufacturing, design, and decision-making. They have developed an approach called Cooperation Requirement Planning (CRP), the output of which is analyzed for conflicts among task assignments and assembly planning in CRP. The focus of our work is distinct from this work by resolving conflicts among DfA and DfD requirements to achieve sustainability rather than resolving conflicts among task assignments and assembly planning in CRP to achieve optimum utilization of cooperation among robots. Also our definition of DfAD is to design products such that it enables easy assembly and easy disassembly. But Nof and Chen considers disassembly as reverse of assembly. DfAD is approximately equal to DfA in their work.

Motevallian et al. **(**2007) have modified the DfMA process, and incorporated DfD into a framework; however, this integrates DFMA and DfD in a serial manner, allowing possibility for conflicts among these to remain in the final product. Gkeleri and Tourassis (2008) pointed out that disassembly concerns must be balanced against other design considerations. They also mentioned that industrial firms complained about the increasing layers of complexity imposed upon the product design process. Integrating various DfX concepts into a single framework is required (Chiu and Kremer, 2011).

4.2 Need for an integrated framework for DfD

As discussed in Section 2, a major means for improving environmental performance should be to support “disassembly for all life cycle phases”. From literature (Section 4.1), it can be argued that substantial differences can exist between requirements for DfD and DfA; design requirements that enable easy assembly can be different from those that enable easy disassembly. There is a need to balance disassembly concerns with other design considerations, and a need to integrate various DfX concepts into a single framework. The overall objective is therefore to develop an integrated framework that supports consideration of design requirements for ease of disassembly for all phases of product life cycle while being compatible with requirements for ease of assembly in these life cycle phases.

To achieve this, the following steps are necessary:

1. Understand the requirements for DfD and DfA,
2. Identify whether they conflict one another,
3. Understand the underlying causes for conflicts or their absence, and
4. Develop means to resolve or learn from these.

To carry out Steps 1-3, a series of existing products are taken, and their assembly and disassembly processes are analyzed to answer the following research question: Are there any conflicts among the assembly & disassembly processes for the same product, if yes, what are the conflicts, and why do they occur?

5 Conflicts among assembly & disassembly processes

As a preliminary investigation to answer the research question in Section 4.2, two studies were undertaken. The first was a literature based study, where existing cases in literature that report conflicts among assembly and disassembly processes of a product are analyzed to identify the underlying causes. The second is a pilot study that was conducted with data collected using a semi-structured questionnaire (with both open and close-ended questions) among Masters and PhD students with formal engineering training at Indian Institute of Science and in some cases with industrial experience; the students were asked about products known to them that have conflicts among assembly and disassembly processes, and according to the subjects, what the causes might have been. Three products (each of them a mechanical assembly) from literature and associated information about their assembly and disassembly processes, were selected for analysis.

A further four products from participants in the questionnaire survey, feedback on these from 12 participants on 12 questions (answered over a period of 15 days) are also analyzed. The results from these seven products are shown in Table 1-2, respectively.

Table 1 Results of Literature based study – Conflicts in Assembly and Disassembly processes

Products (Mechanical assemblies)	**Assembly process**	**Disassembly process**	**Conflicts**	**Causes of conflicts**
Rivet in Aircraft structure (from literature AFS-640, 1998)	-Rivet is passed through the holes in the parts and then forming (upsetting) a second head in the pin on the opposite side. -The deforming operation can be performed hot or cold and by hammering or steady pressing.	-Support the structure to prevent distortion and permanent damage to the remainder of the structure. -Undercut rivet heads by drilling. -Drilling must be exactly centered and to the base of the head only. -After drilling, break off the head with a pin punch and carefully drive out the shank. -Inspect rivet joints adjacent to damaged structure for partial failure	More effort and longer time to disassemble than to assemble.	-Use of many disassembly tools (bucking bar, drill, pin punch). -Fastener design did not consider disassembly. (deforming the second head).
Retaining ring in Gear assembly (from literature Ref 1**)**	Installation is manually carried out using hammer.	-These rings with no lug holes are impossible to remove without either destroying the ring or warping it out of specified tolerances. -Once installed, the rings become tamper proof and make it difficult to be removed.	More effort to the extent of destruction is required in disassembly unlike in assembly.	-Fastener design did not consider disassembly (e.g. without lug holes). -Becomes tamper proof.
Shrink fit in Shaft hub assembly (from literature Ref 2)	-The external part is heated to enlarge by thermal expansion, and the internal part either remains at room temperature or is cooled to contract its size. -The parts are then assembled and brought back to room temp so that external part shrinks and internal part expands to form a strong interference fit.	-If evenly distributed heat is used to remove parts from shafts. This will increase the time cycle and create heat buildup in the shaft that can result in both parts expanding thus causing difficulty in removal. -In this case, it is often best to shock that particular component with a rapid heat. -This should be done carefully to prevent expansion of both the parts	More effort to disassemble than to assemble.	-Evenly distributed heat leading to expansion of both parts. -Accessibility and visibility influence the shock given since shock needs to be given only for a particular component.

Table 2 Results of Questionnaire based study - Conflicts in Assembly and Disassembly processes

Products	Assembly process	Disassembly process	Conflicts	Causes of conflicts
Welding in Levers (from questionnaire)	-Connection between parts to be welded is established using an agent that together with the material of the parts undergoes phase transition.	Usually destructive disassembly is used to separate welded joints.	More effort and longer time to disassemble than to assemble.	-Difficult to access the parts -Low clearance for tooling.
Cotter and nut in Bicycle pedal crank (from questionnaire)	-Slide in pedal crank in to axle. -Align cotter in to the pedal and hammer it for tight fit. -Screw in the nut on to the cotter from other end of the cotter head.	-The process of removal of the cotter from the pedal crank requires reversal of the tight fit between them. -Since they had rusted and joined up with each other, power drill was used to drill out. -Cotter and pedal got damaged while trying to separate them	More effort and longer time to disassemble than to assemble.	-Corrosion
Snap fit in Laptop Key (from questionnaire)	-Used fingers to carefully engage the projection in one part to other.	-Used nail to force open the snap fit. However, it was difficult to take apart.	More effort to disassemble than to assemble.	-Parts were hidden. -Joints were invisible. -Structure was delicate to handle.
Snap fit in Wrist watch (from questionnaire)	-A small hammer was used to establish snap fit between back cover and dial of the watch.	-A strong blade was to disassemble.	More effort to disassemble than to assemble.	-Low clearance for tooling. -Fit design has little. consideration to disassembly (back cover and dial are almost jammed).

5.1 Results and Discussion

The above studies showed the existence of conflicts among assembly and disassembly processes of existing products. In all cases, conflicts seemed to occur in the amount of effort and/or the time required to carry out assembly and disassembly processes. Causes behind the effort and/or time to disassemble are interpreted to be among the following:

Design Issues:

1. **Fasteners:** The fastener or fit design did not consider (or considered little) the disassembly requirements. Additional conflicting requirements (e.g. tamper proof) forced the design to be difficult to disassemble.
2. **Product architecture**: Accessibility and visibility of parts and joints were low, or structure of parts was delicate to handle during disassembly.
3. **Materials**: Rust formed due to corrosion and made disassembly difficult.

Other Issues:

1. **Tooling**: Use of many tools, and/or low clearance for tooling made disassembly difficult.

6 Conclusions and future work

Existing products were analyzed for conflicts among assembly and disassembly processes using two studies. It seemed that conflicts occurred in the amounts of effort and/or time required to carry out the assembly and disassembly processes. Various causes for these conflicts were identified: these came either from the product (parts, interfaces and their materials), or from joining elements or associated tools. The study indicates that conflicts exist among assembly and disassembly processes, and all of the causes identified could be addressed during the design process. However, this is only a pilot study, with relatively few subjects and products, and with subjects who are not assembly/disassembly professionals. The goal is to expand this study in to a comprehensive study involving professional engineers and assemblers from industry.

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