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An Integrated Framework for supporting decision making during early design stages on end-of-life disassembly

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A B S T R A C T

Product life cycle (PLC) is a series of life cycle phases which a product will go through in its lifetime. There are several issues with the life cycle of a product when looked from the environmental impact perspective. These issues impact resource scarcity, cause adverse effects on the environment and loss of embodied energy as waste. Some of the potential solutions to these issues, as proposed in literature, are to carry out various End-of-Life (EoL) recovery processes on products including their recycling, reuse and remanufacturing. These EoL recovery processes help in reclaiming materials, components and sub-assemblies from used products and make them available for new products, or extend life of the products as a whole. In order to efficiently carry out these EoL recovery processes, a pre-requisite is disassembly. Disassembly processes are closely related to the design specifications of a product. Therefore, designers should incorporate disassembly considerations into a product during its early design stage itself in order to make disassembly of the product easier when it reaches the EoL phase. Therefore, the objective of the work reported in this paper is to support designers in evaluating some of the major factors influencing disassembly, both individually and together, so as to assess the trade-off among these in an integrated manner during early design stages of the product's life cycle, thereby helping designers compare and select alternative designs of a product that have better disassembly potential at the EoL phase. An Integrated Framework has been developed to support designers in the above evaluation process. For practical application, the Framework has been implemented into a computer based tool called *IdeAssemble*, and the usefulness of the tool is tested with a design experiment. The results indicate that the tool supported designers in decision making on alternative designs better than when designers evaluated without the tool. IdeAssemble tool could be used as early as during the embodiment design stage of a product when information on materials, geometry, disassembly tools and types of disassembly task are available to the designer.

1. Introduction

Traditionally product development involves improvements in design with respect to cost, functionality and manufacturability. But increasing importance of the environmental issues forces product designers to consider certain environmental criteria in the design process (Ilgin and Gupta, 2010). Eco-design in product development has been discussed widely in literature by several research studies including Bhander et al. (2003), Wimmer et al. (2004), Heijungs (2010), Gaha et al. (2014), Wang et al. (2015), Lacasa et al. (2015) and Andrae et al. (2016). Every product has a life cycle where it contains a series of phases from its introduction to eventual demise. Product life cycle (PLC) has six main phases: 1) Extraction of raw materials, 2) Manufacturing and production, 3) Packaging and distribution, 4) Purchasing, 5) Use and maintenance, and 6) End of Life (EoL). Some of the major impacts on environment that the life cycle of a product typically has are: 1) depletion of natural resources due to the use of virgin materials for production (Alting and Legarth, 1995); 2) consumption of energy in machinery operations while manufacturing components and assembling into complete products (Ijomah et al., 2007); and 3) production of a large amount of waste during the EoL phase, clogging the landfills (Hula et al., 2003). A potential solution to these issues, according to many researchers [Ijomah et al. (2007); Alting and Legarth (1995);

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Crowther (1999); Das and Naik (2002); Jovane et al. (1993); Ron and Penev (1995); Chiu and Kremer (2011)], is to carry out the following EoL recovery processes: recycle, reuse, repair and remanufacture. This, they suggest, would help not only in reducing the quantity of waste ending up in landfills but also in utilizing, in new products, the embodied energy stored in used products (Crowther, 1999). In order to efficiently carry out these recovery options, a pre-requisite is ease of disassembly (Kroll and Hanft, 1998) (Motevallian et al., 2010) (Das and Naik, 2002). Ease of disassembly is the ability to separate the components and sub-assemblies of a product with less effort and time (Brennan et al., 1994). defined product disassembly 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”. The need for disassembly is to assure an efficient separation of hazardous materials, or the accumulation of worthy ingredients for further recovery (Feldmann et al., 1999).

Disassembly activities are primarily carried out in two phases of a product's life cycle: use phase and EoL phase. In the use phase, disassembly helps to enable maintenance, and enhance serviceability; it allows selective separation of desired parts during repair. In the EoL phase, disassembly makes the parts of a product available for different material and part recycling processes at the end of its useful life; it promotes an increase in the purity of recovered material fractions; it aids in safe disposal of hazardous parts; it aids in recovery of subassemblies for reuse or remanufacturing; and helps in making the recovery processes economically viable. Our study focuses on the major enablers of disassembly encountered at the two major recycling sectors (formal and informal) of developing countries during the EoL phase of a product's life cycle, and supports designers in considering these together in decision making, so as improve the chances of appropriate disassembly during EoL and reap the above benefits.

Design for Disassembly (DfD) is a design approach that incorporates disassembly considerations into a product during its design and development phase. DfD is defined as “designing a product that can be readily disassembled at the end of its life and thus optimize the reuse, remanufacturing or recycling of materials, components & sub-assemblies” (Bogue, 2007). A prerequisite to incorporating disassembly considerations into a product during its early design stage, for enabling better disassembly at the EoL phase, is determination of the major factors that influence disassembly during the EoL phase.

In this study, an analysis of literature followed by identification of major research issues in disassembly has been used to determine the major factors influencing product disassembly at its EoL phase. For a designer to decide among multiple product and disassembly process options as to which would maximize the chances of disassembly at the EoL phase, designers need to be supported to analyse the above factors, vis-à-vis each product and disassembly process option, both individually and together, in an integrated manner. The need for assessment of the major factors in an integrated manner is echoed in literature as follows: “disassembly concerns must be balanced against each other. Industrial firms complain about the continuously increasing layers of complexity imposed upon the product design and it is often impossible to handle too many different methods & tools for assessing design” (Gkeleri and Tourassis, 2008). The paper, focuses on development of an Integrated Framework that supports both individual assessment of the factors and their trade-off analyses, with the aim of supporting decision-making on EoL disassembly options of electronic and mechanical products during their early stages of design. The Framework could be used as early as during the embodiment design stage of a product when information on materials, geometry, disassembly tools and types of disassembly task could be extracted from an assembly drawing of a product.

The paper is structured as follows. Sections 2 and 3 review literature on existing methods for disassembly evaluation during early design stages, and the issues with these methods in disassembly evaluation. Section 4 identifies the major factors, and develop new measures for their assessment. Section 5 discusses development of the Integrated Framework. Section 6 discusses the Implementation of the Integrated Framework into a computer based tool called IdeAssemble. Section 7 focuses on evaluation of effectiveness of IdeAssemble tool. Discussion and conclusions are given in Sections 8 and 9.

2. Existing methods for disassembly evaluation during early design stage

Existing methods for evaluation of product disassembly processes during early stages of design are discussed below.

Subramani and Dewhurst (1994) introduced time standard charts to support disassembly evaluation. A number of researchers [e.g. Zussmann et al. (1994); Ishii (1995); and Geiger and Zussmann (1996)], have developed end-of-life approaches for DfD. For instance, Srinivasan et al. (1997) developed a disassembly framework with design modules embodied in a geometric DfD tool.

Kroll and Carver (1999) developed a time-based DfD metric to be used for comparing alternative designs of a product during the design stage. Kroll and Hanft (1998) developed a method for evaluating ease-of-disassembly of products during early design stages. The method uses a catalogue of task difficulty scores. Veerakamolmal and Gupta (1999) introduced a Design for Disassembly Index (DfDI) to measure the efficiency of alternative designs from a disassembly perspective. Rose and Ishii (1999) developed an internet based tool called End-of-Life Design Advisor (ELDA), that guides product developers to specify appropriate end-of-life strategies.

Kuo (2000) proposed an approach to be used during design for enumeration of disassembly sequences and their cost analyses for electromechanical products. Das et al. (2000) proposed a Disassembly Effort Index (DEI) for estimating disassembly costs and effort; the DEI uses seven factors: time, tools, fixture, access, instruct, hazard, and force requirements. Lee et al. (2001) developed a method, for identifying, during its early design stage, the extent to which a product should be disassembled. Viswanathan and Allada (2001) developed a formal model, called the Configuration-Value (CV) model to evaluate the effect of configuration on disassembly. Ferrer (2001) proposed economic measures of recyclability, and a framework to use these, for determining disassembly and recovery processes of a product.

Desai and Mital (2003) developed a methodology, which assigns time-based numeric indices to each design factor to assist in easy and quick determination of disassembly time during the design stage. Villalba et al. (2004) proposed a recyclability index of materials (R) for use to determine economic feasibility of disassembling a product. Sodhi et al. (2004) stated in their work, “… designers are frequently challenged today to address the concept of effort of disassembly during design stage”. Motevallian et al. (2010) proposed six factors that influence ease of disassembly. Disassembly effort is one of those six factors. Banda and Zeid (2006) developed a computational methodology to support designers to perform disassembly cost analysis during the design stage of a product. Kuo (2006) modelled disassembly and recycling within LCA to perform disassembly and recycling planning for product designs.

Gkeleri and Tourassis (2008) presented a set of requirements for developing novel disassemblability metrics for specific product families. They pointed to the need for a simple yet rich index,