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# Approaches and Challenges in Product Disassembly Planning for Sustainability

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**Abstract**

Due to the vast variety of products and end-of-life uncertainties of used products, product disassembly remains as a challenging research area. This paper aims to address the gap between sustainable product development and product life cycle through optimizing disassembly in each stage of the product life cycle. Firstly, a comprehensive review on design concepts for product development and relevant disassembly planning methodologies at the different phases of a product life cycle, such as Design for Disassembly (DfD), product service system (PSS), disassembly sequence generation (DSG), and reconfigurable disassembly systems (RDS) is presented. Next, a conceptual framework that leverages on emerging technology driven by Industry 4.0 and product family approach to facilitate product disassembly planning for sustainability is proposed. Lastly, a short summary on different challenges presented as well as the respective future work are elaborated.


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## 1. Introduction

Existing environmental issues, such as pollution, climate change and resources depletion have exerted great pressure on the manufacturing industries to develop sustainable growth plans. The main role of manufacturing is to transform raw materials into readily sellable items, known as products. Nowadays, our lives are highly dependent on the vast variety of products, such as the vehicles we drive, clothes we wear, gadgets we use and groceries we consume. Conventionally, profit-driven industries mainly focus on optimizing the development process of their products that ranges from conceptual design to mass production. Once the products are sold, consumers will hold full responsibility of the products. Depending on the consumer's behavior, government's legislations, etc., some products are offered a second chance to be reused or recycled while other products eventually end up in landfill [1].

Undeniably, landfill, as a waste disposal option, offers better short-term benefits since it is easier and requires the least cost compared to other alternatives, such as incineration, and resources recovery plans that require expensive infrastructure and manpower investment. However, the fast-growing trend of landfill globally has resulted in numerous environmental problems, such as contamination and greenhouse gas pollution [2]. In the long run, these methods are unsustainable and the best solution is to close the loop of a product life cycle through a cradle-to-cradle product design approach [3]. In other words, used products should be returned to the life cycle in the following pathways, namely, recycling, reusing and remanufacturing [4]. Recycling refers to the conversion of products into raw materials that will be used for next production while remanufacturing refers to production of new products using parts recovered from the old products. Notably, these end-of-life (EOL) operations as well as routine maintenance of the products require disassembly.

Product disassembly is formally defined as the systematic separation of components. It can be categorized into several types, namely, destructive or non-destructive and partial (selective) or complete (full) disassembly [5]. For remanufacturing, complete disassembly may often be required as the product has reached its EOL. For maintenance and repair, partial disassembly is conducted since only certain parts require servicing. Generally, non-destructive


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disassembly is preferred because destructive disassembly is an irreversible operation. Unlike product assembly that occurs during the manufacturing stage, disassembly operation is performed after a product launch and is often considered as a non-value added operation; hence, the companies or remanufacturers have to be incentivized to perform disassembly [6]. Depending on the scale, disassembly research can be divided into two types, namely, (1) disassembly process planning, such as automated disassembly line in factory settings for different batches of product [7-9] and, (2) disassembly sequence planning for individual product, such as optimal sequence generation based on product ontology information [5].

Given the importance of disassembly planning optimization in achieving effective sustainable product life cycle, this paper describes a conceptual framework that aims to efficiently inject different disassembly planning research that has been conducted independently in the past into different stages of a product life cycle. A brief history of design methodologies in product development and manufacturing is first presented followed by a review on disassembly planning methodologies at both the sequence level and process planning level with respect to their functioning roles in a product life cycle.

## 2. An Overview of Design Methodologies in Product Development

Over recent decades, advanced technological and computing developments have contributed to a rapidly changing world. Similarly, new design methodologies are constantly being proposed to meet the changing demands of the consumer market, manufacturing industries and government regulations. Motivated by corporate interest in profit gain, cost reduction, and pressure to achieve sustainability, relevant design concepts, such as Design for Manufacture (DfM), Design for Assembly (DfA), Design for Disassembly (DfD), etc., have been introduced in the industries and are summarized in Table 1.

Product design and development are closely coupled with manufacturing and production that convert raw materials into actual end products. Hence, DfM methodology is first introduced during early design stages to access and improve the overall manufacturability of products so that the desired product attributes can be met [10]. In particular, ease of assembly is an important criterion for good manufacturability because products are usually formed by assembling many components into one functional system, which leads to the concept of Design for Manufacture and Assembly (DfMA).

Notably, DfA allows quantification of assembly costs at early stages of product design and provides an efficiency score to identify possible design improvements. After a product is assembled and sold, it will require regular servicing to maintain its intended function. Therefore, serviceability that affects lifetime servicing costs is another important consideration that leads to another design concept known as Design for Service (DfS). DfS utilizes previous maintenance and service information to optimize the design of new products for greater reliability and lower maintenance cost in the future [10].

While assessing the serviceability of products, the ease of disassembly of the items to be serviced is the main factor since disassembly is necessary before servicing, maintenance and repair can be performed [11]. Thus, DfD has been introduced to ease the disassembly of EOL products. Similar to DfA, for DfD, the manufacturers need to consider the disassemblability of their products as early as from the initial design stage to minimize the cost of EOL options, which involve remanufacturing, recycling and only dsiposal if the components are completely unusable [7, 12]. DfD methodologies and technologies that are applied commonly include increasing product modularity, reducing the number of fasteners and tools needed for disassembly as well as incorporation of embedded design and usage of smart materials in products for active disassembly [13].

Table 1. Design concepts in product design and development [10, 13, 14]

| Design concept | Description |
|---|---|
| Design for Manufacture (DfM) | Design to improve manufacturability of products |
| Design for Assembly (DfA) | Design of products so that they are easy to assemble |
| Design for Manufacture and Assembly (DfMA) | Design of products to address both DfM and DfA |
| Design for Disassembly (DfD) | Design to facilitate disassembling of products |
| Design for Service (DfS) | Design to reduce maintenance cost of products using previous service information |
| Design for Remanufacturing (DfReman) | Design to retrieve and refurbish core components during EOL stage |
| Design for Sustainability (D4S) | Design of products with sustainability criteria |

Starting from '90s, increasing research on disassembly has been conducted to establish efficient disassembly sequence planning (DSP), which is also applicable in DfD, maintenance or repair because these operations always require at least partial disassembly of the products to retrieve or repair certain parts [11-13]. In addition, disassembly is an inevitable step in remanufacturing which is gaining popularity as one of the preferred EOL strategies. The main goal of remanufacturing is to restore the performance of a used product and bring it back to the market through a series of activities, such as core retrieval, disassembly, sorting, inspection, cleaning, reconditioning and reassembly [6]. The functionality of the remanufactured products should at least match or even exceed the specifications set by the Original Equipment Manufacturer (OEM) using latest technologies.

Therefore, Design for Remanufacturing (DfRem) is introduced to facilitate remanufacturing of products at early product design stage through incorporation of good remanufacturability properties, such as core protection and