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Review

Manufacturing and Assembly for the Ease of Product Recycling: A Review

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Abstract: Design for manufacturing, assembly, and disassembly is critical in manufacturing. Failing to consider this aspect can lead to inefficient performance and material overuse, which significantly impact cost and construction time. Production with a high capability for recycling is a method to help conserve natural resources. This article is compiled with a review method and has evaluated the recent and related articles that consider design for production, design for assembly and disassembly, design for recycling and reuse, and sustainable design. This review, moreover, aims to focus more on the relationship between using a design approach for production and assembly in the ease of recycling and preservation of raw materials and reuse of materials. The survey for the design methods conducive to achieving ease of recycling is one of the crucial issues that fill the gap in the literature in this respect. Google Scholar was selected as a database, and the keywords "DFMA", "design", "facility of recycling", "recycling", "EoL", and "product design" were considered to collect related articles. At first, 115 articles were identified, and 26 articles with a high focus on the subject were selected. Finally, nine articles were considered for final evaluation, 33% of which focused on the design approach for assembly. Many of the issues evaluated are about reducing the number of components and reducing complexity in design, materials, environmental impact, manufacturing cost and time, repair, reuse, end-of-life, remanufacturing, recycling, and non-recyclable waste. According to the mentioned materials, compiling a category of crucial information along with sustainable design indicators and approaches, as well as identifying and explaining the strategic actions of the researchers in this field, will benefit the experts and help them to obtain better insight into environmentally friendly production. This, moreover, helps to substantiate a circular economy by increasing the percentage of recycling materials and parts with various methods and reducing costs and the use of raw materials.

Keywords: design for manufacturing and assembly; DFMA; recycling; EoL; ease of recycling

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1. Introduction

The production sector could be important to every nation's economic activity. It adheres to sustainability principles and includes a wealth generation mechanism to assist societal progress via job creation. There have been numerous production modifications since the advent of the industrial revolution. Design for Assembly/Disassembly (DFAD) and Design for Manufacturing (DFM) are modifications that deal with waste containment, cost reduction, and remanufacturing. The assembly design approach attempts to limit the number of components to reduce assembly time, parts inventory, fasteners, and the total product cost. Boothroyd and Dewhurst [1] introduced DFA in the 1980s with the emergence of design software for manual and automatic assembly. Afterward, this idea was given the name DFM and was expanded to include manufacturing features. DFM's primary goal is to promote shared product production and design knowledge.

Minimizing the process's form and complexity at the design stage makes it apparent how crucial DFM approaches are for reducing production time and operational problems. Achieving this goal requires a detailed design and commissioning plan. An optimal commissioning plan depends on several factors, like the type and form of raw materials, machinery and tools availability, production quantity, cost, desired tolerance, and management policy [2–4]. Due to repair, maintenance, and recycling, DFAD seems to be crucial for a product. This involves repairing End of Life (EoL) or rejected product components to lessen contamination [5]. The two-disassembly techniques, destructive and non-destructive, vary in those destructive techniques are mainly concentrated on material recovery than parts recovery, and non-destructive techniques are highly concentrated on parts recovery than material recovery [6]. This method emphasizes the relevancy of design for manufacturing and assembly of components that finally form part of the final asset [7]. Tiwari et al. [8] examined the assembly and disassembly of opposing and distinct parts by regulating the parts' quality, quantity, and reliability. As a result, they concluded that designing products to be as easily disassembled as possible is important for recovering and reusing product parts and components. Product recovery, reuse, restoration, and recycling strategies have developed due to rising environmental protection awareness worldwide and stronger environmental regulation enforcement [9]. In addition, using EoL strategies during sustainable product design may assist organizations in decreasing environmental effects and complying with stringent requirements, boosting global manufacturing competitiveness, cutting production and disposal costs, and increasing economic growth [10]. Closed-loop systems require businesses to commit to managing the whole product life cycle, in contrast to open-loop systems that dispose of things when they reach the end of their useful life [9]. Using product EoL recovery strategies, such systems seek to reduce the usage of new energy and energy input sources, increase the effectiveness and lifetime of materials, and decrease waste and greenhouse gas emissions [11]. A closed-loop system is necessary to warrant sustainable production and consumption [12]. Allwood and Cullen [13] proposed improving product life, material efficiency, and recycling efficiency as three product design techniques compatible with the circular economy vision. All approaches for extending a product's life, including reuse, repair, and product harvesting for parts reuse, necessitate availability of the product components. In order to enhance access to internal parts for maintenance, inspection, and disassembly of regularly damaged and valuable components, it is essential to establish requirements relating to the ease of disassembly of structural components. This will enable repair by replacement of damaged components and recovering parts for remanufacturing or reuse. It is extremely significant. Consequently, lowering the separation time minimizes the efforts and expenses associated with such activities. DFMA provides a solution for the problems by considering technicians and manufacturers upfront at the design and taking to account issues in manufacture and assembly [14]. The environmental advantages of product remanufacturing or component reuse over recycling or disposal might make them the preferable EoL approach [15,16].

Furthermore, in industrialized nations, the primary methods for recycling complicated products like electronic products include mechanical crushing and automatic material separation. High recovery rates of certain materials, like steel and aluminum, characterize this recycling program. However, it has a lower performance for recovering precious metals, essential metals [17–20], and several plastics [21,22] that are of significant environmental and economic importance [23]. It may greatly enhance the recovery rate of precious and vital metals and plastics and the separation of parts during the product's life.

2. DFMA Historical Development

DFMA evolved during the second world war when Ford and Chrysler accepted it as a principle for weapons production; it was originally employed in manufacturing. In the late 1960s, formal methods to design for assembly and design for manufacture arose, as documented in the 1975 British Standards on Design Management for Economical Manufacturing. Boothroyd and Dewhurst's study of DFMA [1] also represented the beginning of academic studies of DFMA. Since then, DFMA has undergone significant expansion in the industry. DFMA offers a method for evaluating and enhancing product design according to the manufacturing and assembly procedures downstream [24]. Consequently, it illustrates a change from traditional design thinking to non-linear methods.

Implementing DFA and DFM may have considerable advantages, including decreasing manufacturing and assembly costs, enhancing product quality, and shortening production time by simplification of products. Nevertheless, they are solely manufacturing efficiency issues. In regard to sustainability considerations, several researchers have started to address separation and recycling during the design process and have shifted their attention to environmental design, recycling, and the life cycle. Such investigations have been regarded as design for excellence (DFX) [25], which emphasizes excellence in aspects including testability, conformance, manufacturability, reliability, variability (DFV), inspection (DFI), and cost (DFC). For instance, DFX techniques may increase design quality, productivity, efficiency, and flexibility and lower life cycle costs by reducing existing design ideas. DFX attempts to offer a consistent philosophy, methods, and tools for optimizing a design [26–28]. Early on, DFX research addresses all design goals and associated constraints.

3. Design for Production

Design for Manufacturing has become a key issue in product development in the last three decades. Design for manufacturability, production design (DFP), design for variability (DFV), design for environment (DFE), and design for additive manufacturing (DFAM) have been intensively studied by scientists. DFM's primary goal is to provide a link or integration between manufacturing and product design [29]. Scholars consider DFM as a method of thinking that simplifies and reduces the cost of production by integrating manufacturing input into the primary design stage of components or complete products [30–32]. Stoll [33] initially introduced the term DFM to the research community by developing the notion of design for assembly. A study was carried out to explore the utilization of DFM tools and practices in industries. The study results demonstrate that industry and universities should adjust the DFM work program and teach DFM skills by examining the advantages and effectiveness [34]. DFM aims to reduce manufacturing costs, product complexity, and production time [35]. DFM is also utilized to evaluate key areas, such as part features, to assess if they can be produced using machining operations [36]. Giachetti [37] created a database of material properties for the material selection and manufacturing process decision support system. Investigators employed the DFM ontology concept to organize design knowledge and production guidelines to develop a decision support system [38]. In creating a computerized integrated production system, DFM techniques were utilized to combine pipe bending design and feasibility analysis, process planning, manufacturing, and inspection [39]. DFM has also evolved into Design for Environment (DFE) to overcome the conflict between product performance and environmental effects in the conceptual design phase.

4. Design for Assembly/Disassembly

The advantages of disassembly for the economy and environment have made the design for assembly/disassembly more important over time. DFA is developed as a subset of DFM, which incorporates assembly reduction in costs, with the main goal of recovering invaluable materials and components from EoL that otherwise would be transported to landfills and cause air and body pollution. Additionally, it aids in resource conservation and decreases the requirement for fresh ingredients [40,41]. For most items, assembly represents a small part of the entire cost. Nevertheless, the emphasis on return on assembly costs exceeds its advantages significantly. Due to the significance of DFA, the total cost of support, the manufacturing complexity, and the number of components is decreased, along with the assembly cost. Even though the separation line resembles an assembly line in reverse, it is significantly more complicated. Divergence seems to be an obvious distinction between assembly lines, convergence, and disassembly lines, which split EoL products into their parts. Nevertheless, unlike the assembly line, components and subassemblies' quality, quantity, and reliability are not examined in separation lines [42]. DFA can be utilized in reverse engineering and the development of new products. The first outcomes of using DFA include a decrease in unit costs, a reduction in production time, and an increase in reliability. Since it is incomplete owing to technical and economic factors, disassembly may be a partial process. Technical limits may comprise the irreversible joining of parts, while economic restrictions may involve low revenue from recovered parts. Disassembly is conducted after the product life cycle; however, planning should be included in the product's design. Designing for disassembly may help develop products that facilitate a high reuse and recycling rate. Nevertheless, products are traditionally manufactured and developed only to enhance facilities' assembly and productivity [6]. An important challenge that has drawn the interest of academics in recent decades is the development of simply isolated products. Nevertheless, simple assembly and disassembly take time to complete.

Easy disassembly, improved adhesion to avoid permanent integration, modular design for simplicity of operation, and limiting variance in material consumption are a few factors that must be considered during the design phase [6,43]. Boothroyd and Alting [44] introduced the extensively utilized design strategy for assembly and disassembly, which attempts to lower the assembly cost and provide guidelines to enhance sustainable product performance via disassembly. Self-separation has drawn much interest, and the literature has tackled stochastic and deterministic issues for complete separation with no target component. For instance, Gungor and Gupta [45] examined separation sequences in the scenario of uncertainty when there is no specified target component, whereas Boothroyd and Alting [44] considered complete determinism. Kim et al. [46] engaged in selective separation, in which the objective was to separate target components from the discarded product by improving the investigation. Line design and balance are other components of DFA. Maximizing total profit considers the impact of partial separation when a task's processing time is uncertain [47]. The researchers claim that most literature publications emphasize complete separation while neglecting the financial benefits of an incomplete operation. Consequently, the authors represent the priority connection between tasks using an AND/OR diagram [47]. An algorithm and Monte Carlo sampling utilizing the average sample approximation are used to create and solve stochastic programming models utilizing an exact solution technique [48].

5. Evaluating the Ease of Disassembly

Absolute criteria, including energy, time, or entropy, and relative criteria, like design effectiveness, could be used to categorize evaluation criteria (degree) of ease of separation or separation [49]. The information necessary to derive the absolute criterion is simpler to find and define [50]. While other work measures, including energy, are believed to be challenging to acquire and understand, time has been acknowledged as a good sign of separability among absolute measurements [51,52]. Time has also been used as a useful parameter for separation modeling [53], for assessing the ease of different product designs [50], and as a performance measurement for recovery [54]. Additionally, disassembly time has previously been utilized to assess the disassembly simplicity in environmental labeling products [55,56]. "Extraction time" is considered an appropriate representation to assess the ease of disassembly in current JRC publications on integrating resource efficiency criteria in European product regulations [57]. The basis for evaluating the ease of disassembly for environmental design to assist the implementation of product requirements that simplify life-extension techniques and enhance EoL treatment is thus a standardized approach for estimating the disassembly time for component extraction.

6. Evaluating the Recycling and Product Separation

In recent decades, it has been acknowledged that separating parts is a necessary step for the cost-effectiveness of recycling. Designing a product that may be readily separated provides benefits throughout product disposal and storage [58]. As a result, numerous studies may be discovered on this topic. Design for disassembly (DFD) is the major driving force of design for recycling (DFR) since it enables parts to be removed for reuse and product recycling [59]. Several researchers [52,59,60] propose the separation assessment approach relying on the determination of the index based on the pertinent parameters in the dismantling operation in addition to the economic analysis and the durability of time. They consist of the work piece's position, the tool's accessibility, the force needed to separate the parts, the equipment needed, and the characteristics of the components (shape, weight, and size). The guidelines used for this procedure, such as the disassembly sequence, are significant for certain researchers in the case of disassembly. The disassembly sequence serves as the basis for developing an index to measure the effectiveness of product design compared to disassembly [61]. Developing algorithms that assist in selecting the best separation order is one technique to improve product separation [62,63].

7. Reproduction and Design for Isolation

The whole life cycle of the product, consisting of pre-production, manufacture, usage, and post-use phases, must be considered when designing a sustainable product [11]. Utilizing artifacts from the EoL chain to create a new product is known as "design from EoL." (For example, using recycled materials instead of raw materials or reusing modules or parts extracted during disassembly). The most well-known and popular design method is called "designing for EoL", and its objectives are:

- The improvement of the product is such that it can be recovered in the best possible condition after disposal.
- Promote the residues' elimination that cannot be recovered.

Currently, indirect production is one of the main approaches and a novel sustainable business model for managing the industrial products EoL, reducing the environmental footprint and the company's profit [64]. Remanufacturing is a reverse process in which the product is separated into its components (non-destructive separation) or components with automatic or manual components (destructive separation) [65]. The aim of remanufacturing operations is to quickly and efficiently separate the exact parts of the product and strengthen EoL closed-loop strategies like reuse, remanufacturing, and recycling [66]. Therefore, product separation plays a vital role in the production process. DFD is a target design method that provides guidelines to assist designers and engineers in the early product design stages. Effective product separation makes components separation easy for product storage or EoL treatment [67,68]; DFD makes the product and product manufacturing plans more efficient and influences EoL choices and strategies [69]; several studies have addressed product separation from various aspects. For instance, the separation depth concept has been proposed by Dewhurst [67] to provide adequate economic ease for separation processes via the separation index calculation.

Besides, selective disassembly focuses on the practical extrapolation of data from product structures or CAD models, like the best disassembly sequence or possible disassembly paths that minimize costs and disassembly time [70,71]. Nevertheless, the critical result of DFD analysis is the disassembly time approximation [71]. Separation time is one of the basic subjects for calculating the separation cost and, as a result, evaluating the EoL economic feasibility of separation [72]. DFD and Design for EoL are complementary and interactive design methods. EoL-based design methods need product analysis from a disassembly perspective. A substantial gap in the field is characterized by the need for more integration of the two methods, i.e., the absence of a specific tool required to support the design [73]. EoL indicators are a useful design tool for understanding the intact product architecture and selecting the most proper assembly connections between components.

8. Review Methodology and Discussion

The article examines the link between design and sustainability, as well as the implications of design on ease of assembly and disassembly, recycling, extending product life, and end-of-life treatments. This investigation used Google Scholar to examine the literature on design for manufacturing and assembly, easy recycling, and related topics. Keywords "DFMA", "facility of recycling", "EoL", and "product design" were used to collect related articles and information through the mentioned search engine. Initially, 115 articles that contained the necessary keywords in English were discovered. Furthermore, depending on the appropriate titles, 26 articles were chosen depending on the criteria. After reading the abstracts of the publications, 16 were selected for full-text examination. After reviewing the full text and removing irrelevant articles, nine were left for the final assessment. Figure 1 depicts the screening procedure for papers, and the characteristics of the final selected and included articles have been listed in Table 1.

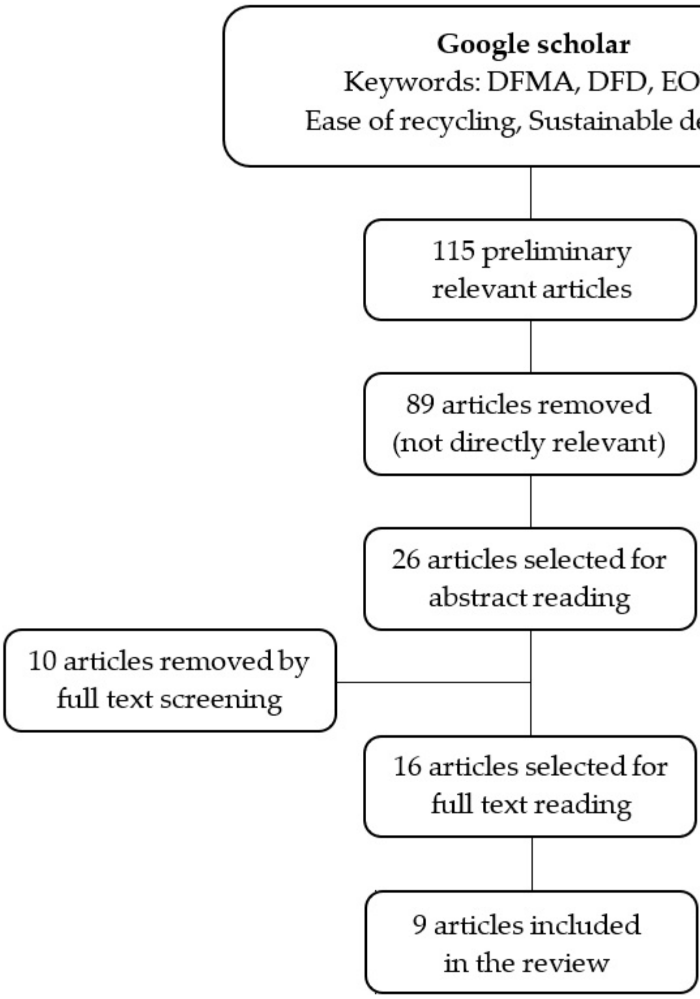

Figure 1. Articles' screening hierarchy.

Leal et al. [74] offered a design strategy relying on an innovative index that combines design from recycling and design for recycling to strengthen the circular economy by establishing a forward and targeted connection between EoL chain stakeholders and product designers. Design for recycling identifies the characteristics of a product with the lowest recycling performance and provides the most exact design guidelines for its development. Design based on recycling facilitates the utilization of recycled materials from economic, technical, and environmental perspectives. To strengthen the circular economy by establishing a forward and focused interaction between designers and stakeholders of the EoL chain, they have also offered a design method depending on a unique index that integrates design from recycling and design for recycling. Design for recycling enables us to determine the product aspects with the lowest recycling efficiency and offer the most accurate design guidelines for their enhancement.

Design based on recycling facilitates using recycled materials from a technical, economic, and environmental standpoint. Moreover, it may be objectively examined. Figure 2 demonstrates the possible ways between design and EoL stakeholders.

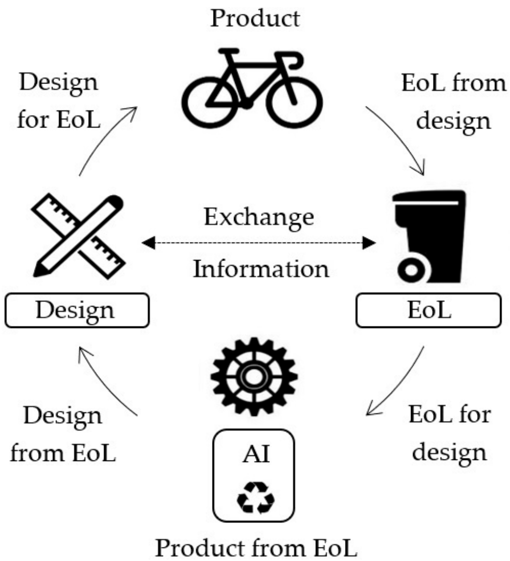

Figure 2. Approaches and possible exchanges between beneficiaries of EoL and designers [74].

In the vastly competing manufacturing world, waste disposal is repeatedly overlooked. There are measurable costs related to excess raw material, scrap parts, out-of-date materials, and insufficient resource use. All these terms contribute to a company's waste and should be taken into account in the cost of disposal calculation [75]. Battaia et al. [76] examined the development of DFM and DFA. In addition to examining the aims and reasons for utilizing such methods in product design, their function in optimizing product design for recycling and reuse was also explored. According to research, to address the contradiction between product performance and environmental implications at the concept design stage, DFM should be expanded to include DFE. Lu et al. [77] examined the historical evolution of DFMA, its prevalence, and the evolution of the status quo in construction. They revealed that DFMA as a philosophy is not new to the construction industry and that the practical application of several DFMA standards has started in the AEC sector. Nevertheless, it is possible to explore the notion that DFMA is not unique to the construction industry and is relevant to various innovative construction aspects [78–80]. Badurdeen et al. [81] addressed a substantial gap in the literature concerning the complete lifecycle-based design of product configuration. To create a sustainable product that encourages closed material flow, one should consider a product's complete life cycle and various life cycles. In this study, a strategy relying on several life cycles is suggested to address the design issues of multi-purpose products while considering the competing goals of minimum total life cycle cost, GWP, and water use. Vanegas et al. [82] developed a technique for determining the ease of product separation to hold up the circular economy. The suggested approach supports DVD assessment for repair, reuse, and recycling. This paper proposes a robust Ease of Disassembly Metric (eDiM) method that calculates the disassembly time according to the Maynard sequence of operations technique. eDiM seems to be a time measurement and estimating approach that applies to all product groups and determines the time required to eliminate a particular component using manual separation types. Additionally, eDiM may be utilized to model the disassembly time of new joints, giving the needed flexibility as a general way for merging different products and connectors. Aguiar et al. [83] suggested a design tool that facilitates the creation of recyclable items. The tool has been created to determine the product's level of recyclability, allowing the designer to choose a superior design. This tool offers a thorough review of the present stage of the design of a recyclable product, indicating its strengths and weaknesses and enabling the designer to concentrate on more fundamental problems. Consequently, product recycling will become simpler. Favi et al. [84] provided an approach to assist designers in evaluating and ultimately improving the EoL performance of a product depending on four unique indicators, one for each EoL scenario (reuse, remanufacturing, recycling, and incineration). Consequently, the designer may change the product's structure or interfaces to maximize the reuse, remanufacturing, and recycling of components and materials. The research confirms the efficacy of this method in assisting designers in decreasing the amount of material and industrial waste sent to landfills. Fatima et al. [85] proposed combining the DFMA approach using sustainable design. Since DFMA aids in reducing product complexity and expense throughout the manufacturing process, they have advocated employing 3D scanning and CATIA software to draw the essential parts of the product. Using the DFMA approach, the product is developed with fewer components and less complexity, which results in a more stable product. In this manner, the influence of various product parts on the stability of the analysis is considered. According to this report, the number of cases has decreased by 25%. Yadav et al. [86] examined how designers employ design for assembly factors to estimate a product's recyclability index on four items, resulting in tool development that designers may utilize to estimate the recyclability of a product during the concept design stage. Such results are employed to create a recyclability index that incorporates assembly design measures, enabling engineers and designers to identify recyclability early in the design procedure. Case study data demonstrated a high correlation between assembly time and product recyclability.

Table 1. The characteristics of the final selected and included articles for review.

No.	Title	Methodology	Conclusions
1	Design for and from Recycling: A circular eco-design approach to improve the circular economy [74].	The suggested design for the recycling technique enables product designers to determine the product aspects that are the least effective in recycling and offer the most suitable suggestions for their development.	The suggested method facilitates the development of connections between designers and EoL treatment chain stakeholders. This connection may also be enhanced by recommending a complementary strategy (i.e., a method that integrates recycling tools in and out of the design procedure).
2	Design for manufacturing and assembly/disassembly: joint design of products and production systems [76].	This article discusses the background of DFA, DFM, and related issues in today's manufacturing in an overview.	This research investigates the cost distribution degree for a competing market across the product's life cycle. Supply chain partners are expected to collaborate to produce the product at the present manufacturer and assembly plant.
3	Design for manufacture and assembly (DFMA) in construction: the old and the new [77].	In this investigation, a multistage research strategy comprised of brainstorming, a review of literature, and a comparative analysis was employed.	DfMA originated in manufacturing industries and has been utilized as a panacea for chronic issues in the AEC business, including high costs, long lead times, and lower productivity. This analyzes the notion of AEC, which is renowned for its project orientation.
4	A multiple lifecycle-based approach to sustainable product configuration design [81].	Creating a dependency diagram to characterize the optimization model scope, modeling EoL recovery techniques taking into account the flow of multiple life cycles, and formulating and solving multi-objective optimization problems with the Genetic Algorithm are the steps of the proposed method.	Decisions made throughout the design phase of a product have a substantial influence on its profitability and environmental impact over its entire life cycle. Implementing EoL techniques closes the material flow loop by reusing components and materials from one product life cycle into the next.
5	Ease of disassembly of products to support circular economy strategies [82].	Two methods were recognized to assess partial or total separation time: direct measurement and calculation depending on product attributes. The easiest technique is for numerous operators with varying levels of competence to directly measure the separation time of products of a similar grade.	This study outlines the methods developed to assess the simplicity of product separation in support of the circular economy. The suggested technique gives organizations that apply material efficiency criteria involving product disassembly with scientific support. It assists OEMs and electronics operators with a mechanism for evaluating DFD for repair, reuse, and recycling

Table 1. *Cont.*

No.	Title	Methodology	Conclusions
6	A design tool to diagnose product recyclability during the product design phase [83].	The research describes a design tool to facilitate the creation of recyclable items. This tool is intended to determine a product's level of recyclability and assist the designer in making better design choices.	The research describes a design tool to facilitate the creation of recyclable items. This tool is intended to determine a product's level of recyclability and assist the designer in making better design choices.
7	A design for the EoL approach and metrics to favour closed-loop scenarios for products [84].	Four new indicators evaluate the feasibility of each EoL scenario (reuse, remanufacturing, recycling, and incineration) to optimize product EoL management in the early design stages.	Designers can quickly assess whether predetermined goals have been achieved and whether the product, component, or part can be effectively recovered at the EoL. If targets are not met, deep or partial product redesign is necessary to improve EoL performance both environmentally and economically.
8	Design for manufacturing and assembly: A review on integration with design sustainability [85].	This section of the DFMA and sustainability design and process research are used to determine the flow of data collecting. This section describes the actions required to explore the research topic and the rationale for using the techniques or approaches to discover, select, and investigate the information utilized to comprehend the problem.	This research proposes utilizing the DFMA approach in combination with sustainable design. DFMA tackles just a part of sustainability effects, but its application reduces product complexity and development costs, which may contribute to environmentally friendly production.
9	Development of Product Recyclability Index Utilizing Design for Assembly and Disassembly Principles [86].	The article starts with a discussion of the fields of design for disassembly (DFD), assembly (DFA), remanufacturing (DfReman), and reuse (DfReuse).	This study provides a technique based on DFA principles for early product design recyclability prediction. The examination of which DFA characteristics impact product recyclability and to what degree was conducted using a case study approach. The case study data findings revealed a significant connection between the recyclability index of a part or subset and the insertion tables.

The articles reviewed in this research were selected with a focus on A. design for assembly and disassembly, B. design for EoL, C. design for ease of recycling, and D. sustainability of the final product. According to Figure 3, the design for assembly and disassembly has the largest frequency percentage among these four axes, indicating that the issue's relevance has been highlighted in the study. In the reviewed articles, with the design approach for assembly and disassembly, the importance of ease of assembly of product parts to reduce production time and cost and the importance of ease of disassembly for easy repair and disassembly of reusable parts or recyclable parts are discussed. This design approach helps reduce production and recycling costs, control product life, and increase sustainability. The articles that focused on design for EoL and design for remanufacture gained the least attention compared to the other subjects. Table 2 also lists the main focus of nine articles listed in Table 1, based on the results and conclusion section of each.

The indicators listed in Table 3 exist in the product life cycle. In the mentioned articles, indicators can be classified into four out of five stages (Here, the explanations about transportation and distribution have been omitted from stages of a product's life due to the lack of information in the reported literature) of a product's life as the following:

- Pre-production stage: In the design stage, it is imperative to consider all aspects to increase the product's life. Using the design approach for assembly and disassembly includes some principles of other approaches, such as design for end-of-life and recycling [74,84]. One of the most critical matters to be investigated in the pre-production phase is the selection of materials and their optimal use. Using the least diversity of materials in the design and production of a product and choosing suitable materials in such a way as to cause minor damage to the environment and reduce the growth rate of landfills is one of the reasons for the popularity and importance of the design approach for assembly and disassembly. This method also aims to minimize primary and recovered raw materials use which reduces the wastage of valuable materials and production costs. This method returns the used materials to the production cycle as raw materials or parts [83].

- Production stage: Applying an approach and producing a product only happens if it is economically profitable. The most crucial goal of the design approach for assembly and disassembly is to reduce production costs and increase the resulting net profit [85]. In this regard, various methods and models for cost estimation have been presented in the reviewed articles. Production time is also one of the influencing factors in production costs, which minimizes a significant amount of production costs. Most of the time required in production is wasted on assembling complex parts. This problem can be solved by following the design principles for assembly and disassembly and simple design with minimal components. Other features such as minimum complexity and a minimum number of components should also be considered in the design so that products can be assembled in the shortest time and disassembled efficiently and in less time, and also, if necessary, parts can be separated and re-entered into the production line with minor damage to the target parts [86]. Another result of observing design principles for assembly and disassembly is to reduce workstations and minimize operational problems in production lines [76].
- Consumption stage: every product enters its consumption stage after leaving the production line and presenting it to the market. Sustainable design approaches, intending to increase the lifespan of products, present product design with principles that can be repaired, reused, and reproduced [86]. Products designed with design patterns for assembly and disassembly are easily repaired due to the ease of opening and closing. If they are not repairable, their valuable parts are reused by disassembling and entering the consumption cycle again. A product's multiple life cycles lead to maximum resource use and waste reduction as well [84].

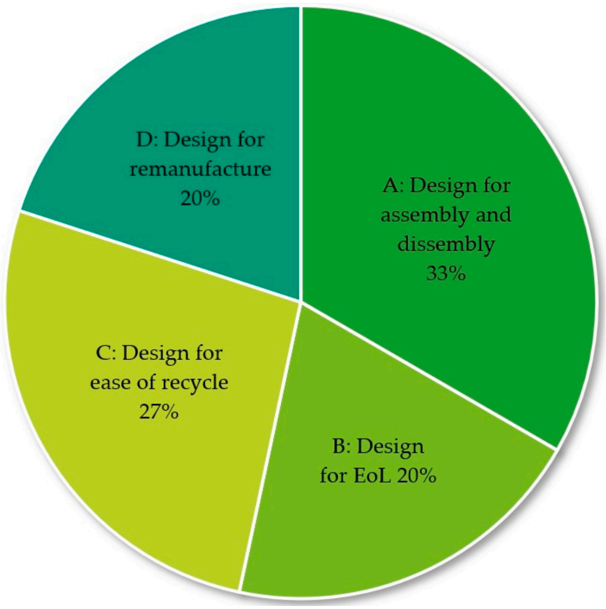

Figure 3. Frequency chart showing approaches of reviewed articles.

- Product death stage: After passing through several life cycles, the product enters its end-of-life period if it is impossible to reuse and reproduce. At this stage, the products are disassembled, and their entry into the recycling cycle begins by separating their valuable materials. In addition to economic reasons, material recycling has important environmental reasons, such as preventing the destruction of the environment because the raw materials extraction, preventing the growth of landfill environments, and preventing the depletion of limited resources of these materials. Finally, materials that cannot be recycled are thrown away. However, the design approach for assembly and disassembly minimizes the inevitable waste at the end of each product's life [74].

Table 2. The main article's themes, based on the results of the articles listed in Table 1.

No.	The Main Focus of Articles Listed in Table 1.			
	A	B	C	D
1			■	
2	■			
3	■			
4		■		■
5	■		■	■
6		■	■	
7		■		■
8	■			
9	■		■	

Table 3. The characteristics of the final selected and included articles for review.

Demographic Characteristics			Topics Raised in the Articles													
No.	Year	Research Place	Components Reduction	Complexity Reduction	Material Homogeneity	Environmental Considerations	Environmental Impact	Production Cost	Production Time	Repair	Reuse	EoL	Remanufacture	Recycle	Waste
1	2020	France	✓	✓	-	✓	✓	✓	-	✓	✓	✓	✓	-	-
2	2018	France	✓	✓	✓	✓	✓	✓	✓	✓	-	✓	✓	-	-
3	2021	Hong Kong	✓	✓	-	✓	✓	-	✓	✓	-	✓	✓	-	✓
4	2018	USA	✓	✓	✓	✓	✓	-	-	✓	✓	✓	✓	-	✓
5	2018	Italy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓
6	2017	Brazil	✓	✓	-	✓	-	-	-	✓	✓	✓	-	-	-
7	2017	Italy	✓	✓	✓	✓	✓	✓	-	✓	✓	-	✓	-	-
8	2018	Malaysia	-	✓	✓	✓	✓	-	✓	✓	✓	✓	-	✓	-
9	2018	USA	✓	✓	-	✓	-	-	✓	✓	✓	✓	✓	✓	-

The selected articles (Table 3) include studies in the field of design for production and assembly in five years, from 2017 to 2021. These studies, which started in Europe and then reached the continents of Europe and Oceania, examine an approach of sustainable design that reduces waste and harmful side effects on the environment and increases the products' life and the life cycle of the raw materials. With the spread of eco-friendly lifestyles in Europe, the demand for eco-friendly products has increased. Therefore, research on sustainable design approaches has gained more attention in recent years. The study on the components number reduction in the ease of assembly and disassembly and the ease of recycling was first conducted in Italy in 2017 and then in 2018 and 2021 in the United States and Hong Kong, respectively [77,81,82]. In other words, reducing the components' number and integrating the product leads to a more straightforward product design [85,86].

On the other hand, designing products with a small number of simple components reduces production time, which is one of the most important factors in design and production because it directly affects production costs. Production time, moreover, is considered to be an influential factor in applying the design approach for assembly and disassembly [81,82]. In the review process, it can be concluded that 100% of the selected articles include research in the field of production costs, and their estimation of this factor is one of the most fundamental reasons for using an approach in the process of design and production. The production should always be economical for investors and producers as well as consumers. In addition to economic reasons, the design approach for assembly and disassembly also addresses the ease of repairability of products. As the leading continent in sustainable and long-life products, Europe has paid particular attention to various practical aspects during the product's life, among which repairability can be mentioned. This issue was first studied in Italy and France in 2016 and then again in the same countries in 2017 and 2019 [74,76,82,84].

As one of the critical subjects in sustainable design, we face the concept of reuse, which is mentioned in almost 80% of the selected articles, according to Table 3. This issue was first studied in 2016 in Europe [74] before gaining attention in American and Malaysian researches in 2018 [85,86]. In 2020 and 2021, it was studied in France and Hong Kong, respectively [74,77].

A study on remanufacturing and EoL was performed in 2017 in Italy [84]. The end of product life and the ways to postpone it are among the crucial issues that almost all the selected articles have addressed. In addition, reproduction has been studied as one of the ways to deal with the end of product life. In Table 3, material selection has been studied in two categories: material homogeneity and environmental considerations. Almost 90% of the articles mentioned the selection of materials with environmental considerations, and 70% referred to selecting materials with high homogeneity. The importance of choosing suitable materials is determined when recycling products; if recycling and the end of product life are considered in the design phase, the recycling of materials or products will be performed with more efficiency, and less waste. All the articles presented in this research have mentioned the importance of product recyclability. If a part of the product or the materials used cannot be recycled, it is placed in the disposed of and waste category. The choice of materials, recycling, and the amount of non-recyclable waste are directly related to the environmental factor. With the movement of design towards sustainable design, the products must have minor damage and negative impact on the environment during the production, consumption, and end-of-life stages. The design to reduce the environmental impact was focused on in articles 2, 6, 8, and 9 of Table 3 [76,83,85,86].

As a result of human overexploitation of primary resources and indiscriminate extraction, the environment has faced much pressure in recent decades. On the other hand, the disposal of waste in nature and the increase of landfill sites are a great danger for both humans and the environment, which will be paid a heavy price if this trend continues. Since the 1960s, researchers have offered solutions to deal with this problem under different titles, and finally, these solutions have ended in the circular economy and sustainable design. Kirchherr et al. [87] have provided a broad definition of CE as "an economic system based upon business models that change the end-of-life concept with reuse, reduction, recovery, and recycling of materials. The circular economy has been welcomed by managers, economists, and students. In addition to reducing natural resources use and supporting their recovery, circular economy principles are based on repair, reuse, and recycling. The circular economy states that the environment can be restored by reducing raw material use and controlling waste through recycling materials, reusing products or their components, or reproducing used products at their end of life. These solutions are associated with a significant percentage of cost reduction by separating economic growth from negative environmental consequences, which makes it much more acceptable [88]. Ellen MacArthur Foundation Examining reports of successful circular economy implementation shows that numerous companies successfully implement circular economy solutions. Furthermore, the metrics used to monitor the success of circular economy solutions are successfully implemented by numerous companies. These companies adopted different policies to implement this method, for example, material focus, product focus, or redesign. Morseletto [89] has categorized the goals of the circular economy. This category includes: refuse, reduce, rethink, reuse, refurbish, repair, repurpose, remanufacture, recycle, and recover. It can be seen that the goals of the design approach for production and assembly align with the circular economy's goals. A circular economy is considered from the beginning to the product's end of life in design for production and assembly. The circular economy is an economic system representing a paradigm shift in the interaction of society with nature. Its purpose is to avoid resource depletion, close the energy and material loops, and facilitate sustainable development through micro-level implementation. Design for production and assembly is a design approach to reduce the consumption of raw primary resources and increase the life cycle of the product and the components and materials used in producing that product. Therefore, design for production and assembly is another form of circular economy and a solution for its implementation [90]. The circular economy promotes innovative systems for designing waste, increasing resource productivity, and reaching a balanced state between society, the environment, and the economy [91]. With all these interpretations, the circular economy has scattered limitations and unclear theoretical foundations, and its implementation faces structural obstacles. The circular economy is based upon an ideological agenda dominated by economic and technical accounts that brings undetermined contributions to sustainability [92]. Moreover, a circular economy future where there is no more waste, where material loops are closed, and products are recycled indefinitely is thus, in any empirical sense, impossible: Each loop around the circle creates waste, which leads to losses of quality and quantity. New material must be injected in every circle of circular material to overcome the losses [93]. Therefore, in future research, the shortcomings and obstacles of implementing the design approach for production and assembly and the circular economy should be widely addressed. Future researchers should provide constructive solutions to solve these obstacles.

9. Conclusions

Design for manufacturing and assembly is a design approach to help the environment and a solution to achieve circular economy goals by improving, simplifying, and making intelligent choices at the beginning of design. Many studies have been conducted in this popular field, which shows its importance and position at scientific and research levels. Briefly, in these research articles or library studies, researchers have discussed this approach's benefits, including environmental and economic benefits. In addition, the obstacles that the designers should take into account in the design process, such as the time of production and separation, have a significant impact on the costs and acceptability of this method, the ability of easy implementation, and the use of recyclable materials, have been mentioned. DFMA has been employed in the manufacturing sector as a remedy for the industry's chronic issues, including high costs, long-time delivery, and low productivity. The studies revealed that, according to the researchers, the most crucial aspects are the selection of materials, cost, end of life, and recycling, which were mentioned in each of the selected publications; In addition to this, the design strategy for manufacturing, assembly, and disassembly has an influence on waste. Numerous papers have examined the environment, production time, and reproduction of items with a high dispersion percentage. It seems that today the people living in the European continent and the new generation who live in these coordinates, due to being concerned about the environment, are more welcome to study in this field and to promote and use it, which is a higher percentage of investigations. Designing for production and assembly is a step towards helping the environment with economic goals, which is why it is functional. In order to realize the circular economy and make the recycling of materials more efficient as a result of using fewer raw materials, designers must consider the end of life of a product and its fate after that. Decisions made throughout the design phase of a product have a substantial influence on its profitability and environmental impact over its entire life cycle. In contrast, the material flow loop is closed when EoL techniques are implemented by employing materials and components from one life cycle in the subsequent life cycle of the product.

Nevertheless, the current literature demands product design tools that take into account multi-life cycle material flows across the product demand cycle to achieve competing goals at the same time. Recycling is a design technique that aims to promote the circular economy by enhancing and simplifying product design decision-making. The strategy for recycling is created by combining two tools:

- In contrast, the design proposal for recycling allows us to determine the product aspects with the lowest performance (in terms of recycling) and to offer the most specific design suggestions for their enhancement.
- On the other hand, designing from recycling enables us to simply and objectively assess the technical, economic, and environmental benefits of utilizing recycled materials.

This article attempts to review the primary and basic concepts of design for production and assembly by reviewing the research in this field. Additionally, the fields that this approach affects or affects them were briefly stated. Considering the speed of technological progress and the endless thirst of man for progress, if environmentally friendly approaches are not our priority, the end of this path will be nothing but disaster. Therefore, researchers and designers in the future should consider these approaches more until they become an integral part of our designs.

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