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Towards a framework for automatic disassembly supporting circular economy

Daniel Schmid^a, Simon Merschak^{b,*}, Silvan Lack^a, Peter Hehenberger^b^aZHAW Zurich University of Applied Sciences, Gertrudstrasse 15, CH-8401 Winterthur, Switzerland^bSmart Mechatronics Engineering, University of Applied Sciences Upper Austria, Stelzhamerstraße 23, 4600 Wels, Austria* Corresponding author. Tel.: +43-5-0804-44478; fax: +43-5-0809-44478. E-mail address: simon.merschak@fh-wels.at

Abstract

This paper provides an in-depth study of Design for Assembly (DfA) and Design for Disassembly (DfD) concepts and related challenges to facilitate the vision of a fully automated production line being capable of assembling and disassembling on the very same production line. The gained insights play an instrumental role in fostering the paradigm of the circular economy. Therefore, it enables the easy decomposition of product components at the end-of-life stage, facilitating efficient repair, recycling, reuse, and recovery. The circular economy, characterized by closed-loop resource utilization, depends immensely on structured product disposal and resource recovery systems, thus rendering DfD a critical component within this remanufacturing-framework.

A framework considering all lifecycle phases based on existing design strategies is presented. Product data management and their effectiveness in amplifying a circular economic system is assessed. Challenges and barriers in employing DfD (economical, ecological, technological, and operational) are discussed, along with potential solutions. Furthermore, advancements in technology including Industry 4.0 and smart manufacturing which can enhance DfD capabilities are explored, thus expediting the journey towards a more circular economy in product development.

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1. Introduction

The policy framework for new products is evolving significantly. They must fulfil the future sustainability requirements according to the circular economy. The European Union (EU) launched the European Green Deal [1] in 2019, striving to be the first climate-neutral continent, and published “Industry 5.0, a transformative vision for Europe” [2] in 2022, where sustainability is one of the three pillars. The direction is set by the EU’s circular economy action plan [3], which transforms the legal framework of the economy and affects the industry significantly. Therefore, product developments must fulfil those sustainability standards in the future.

The linear economy pushes the product from development via production into operation. Optimization took place considering e.g. design for assembly (DfA), design for environment (DfE), and design for manufacturing (DfM), summarized as design for X (DfX) [4]. Further elements under this DfX umbrella are design for test and maintenance (DfTM), verification (DfV), and reliability (DfR).

Within this overview paper, the vision is described as a fully automated production line which is capable of reversing the direction. Therefore, the same product can be disassembled, dismantled and sorted in its parts, modules, or sub-assemblies. To achieve this vision, DfX has to be enriched with a circular economy related focus regarding design for disassembly (DfD). Consequently, the following research question has been raised:

“What challenges must be overcome to achieve a fully digitalized and automated assembly and disassembly process that meets the requirements of the circular economy, encompassing repair, refurbishment, remanufacturing, repurposing, recycling, and recovery?”

2. Background

2.1. Circular economy and product development

With the aim of transforming the linear economy into a circular economy, the EU is requesting industry to significantly change its approach to product development. To fulfill the requirements, new fields need to be explored and known design methods must be adapted accordingly. Already the use of an alternative material for a bicycle helmet, which replaced expanded polystyrene (EPS) foam as an effort towards (circular) bioeconomy [5], forced to adapt a wide range of DfX [6]. In this specific case changing the base material to mycelium required adapting the Design for Manufacturing (DfM), Reliability (DfR), Test and Maintenance (DfTM), Assembly (DfA), Verification (DfV), and Environment (DfE).

- DfM: development of a new process letting the mycelium grow into the related helmet shape
- DfR: achieving reliability, e.g. to withstand environmental conditions such as precipitation
- DfTM and DfV: e.g. fulfilling the standard test procedures to comply with given laws
- DfA: e.g. combining a pulp shell with the mycelium base construction
- DfE: achieving a better product life cycle performance to enhance sustainability

Furthermore, the circular economy changes business cases and plans [7], e.g., subscription, pay-per-use, or renting; therefore, the requirements must be fulfilled. Products are in use for a longer time and repair and refurbishment are hard requirements, e.g., described as the 9Rs [sic] (R0 to R9) circular strategies [7]: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover. The EU's directive promoting the repair of goods [8] highlights the increased importance of “repair” and changes how products have to be designed.

This step by the EU emphasizes the proposed extension of DfX by “design for disassembly”, DfD. In the future not only an effective and efficient assembly has to be achieved by product development but also the disassembly and exchange of parts, sub-assemblies, and modules. [9] Therefore, DfD is key to the industry fulfilling the demands and staying in the market. The vision of a fully automated production line capable of running in reverse raises a wide range of questions and challenges, for example:

- Which connection technologies are suitable for automated assembly (DfA) and disassembly (DfD)?
- What is the impact of a reversible production line on investments and operation?

- How should related product lifecycle data (e.g., master data) be reflected?
- How can the Rs “remanufacture”, “repair” and “recycle” be integrated into a reversible production line enabling the replacement of single parts, modules, or sub-assemblies?

2.2. Remanufacture

At the end of a products life cycle, there are various ways to bring the product back onto the market. The product can be remanufactured, reconditioned, repaired, re-used or it can be recycled to make a new product. It is often difficult to draw a clear line between these end-of-life options. Remanufacturing is defined as the process of building a product to the specifications of the original manufactured product using a combination of re-used, repaired and new parts. This process includes disassembly, cleaning, testing and reassembly steps and requires the use of remanufactured or new parts. [10]

It is a form of product recovery that differs from other recovery processes in its comprehensiveness. A remanufactured product should meet the same customer expectations as a new product and receive a warranty at least equivalent to the original product. In contrast, reconditioned or repaired products often come with only a limited warranty. Typically, the warranty for reconditioned products applies to all major wearing parts, whereas it only applies to the repaired component in the case of repaired products. In addition, remanufacturing generally involves more labor than the other options, resulting in products that are generally of higher quality and performance compared to repaired products. Remanufacturing also requires the evaluation of all product components, whereby those that cannot be returned to at least the original specification are replaced with new components.

Remanufacturing can also involve improving used products beyond the original specification, which is not the case with reconditioning and repairing. [11]

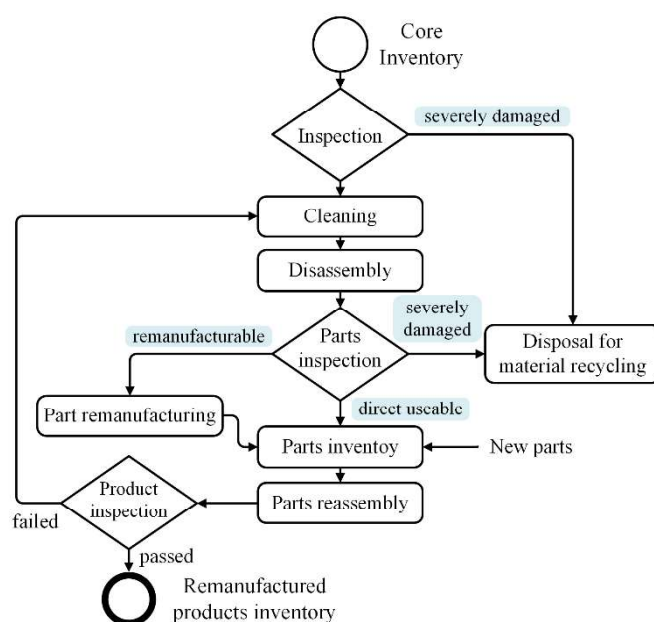


Fig. 1 Remanufacturing process steps

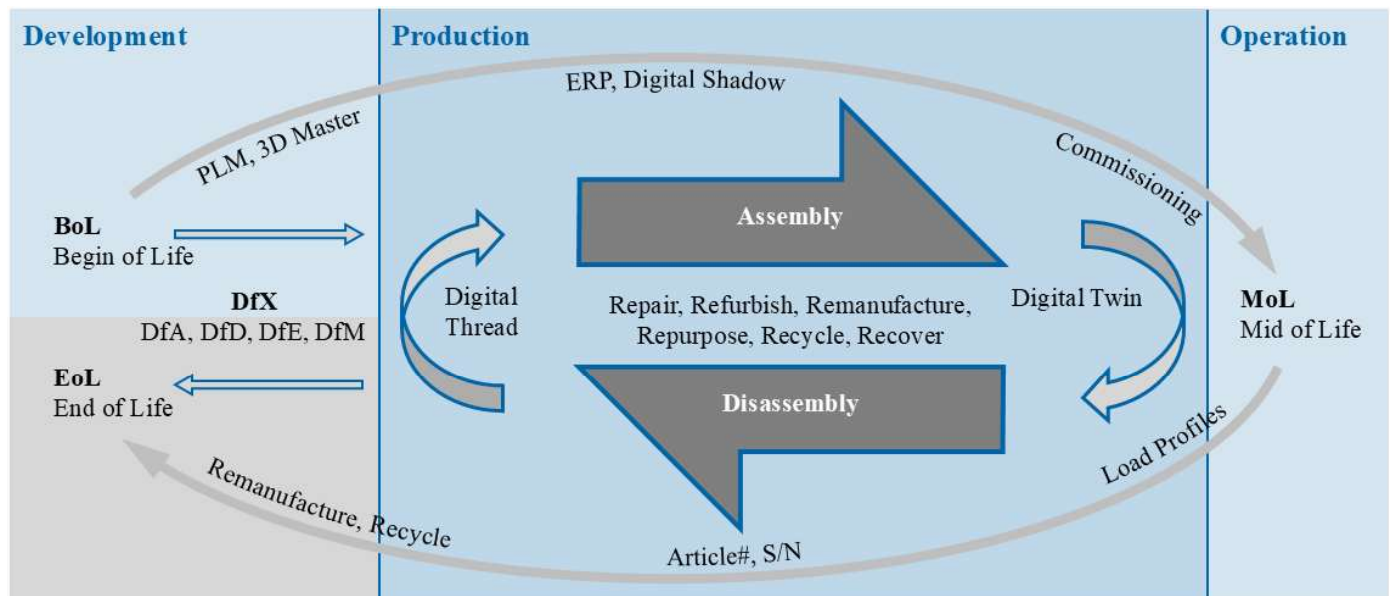


Fig. 2 Illustration of the vision of a merged automated assembly and disassembly production line and the related impact on the whole life cycle (DfA: Design for Assembly, DfD: Design for Disassembly, DfE: Design for Environment, DfM: Design for Maintenance)

A typical remanufacturing process consists of several steps which are shown in Fig. 1. [12] As a first step the products from the core inventory, which is the stock of parts that are returned after the use phase, are inspected. After dismantling, the sub-systems and parts are checked. Severely damaged components are sent for material recycling, reprocessable parts are sent for reconditioning and directly usable parts are stored in the parts inventory. In the subsequent reassembly process step, new parts, direct usable parts and remanufactured parts are combined to create a product as good as new. A final inspection ensures a high quality of the remanufactured part.

3. Overview of vision

The vision is a fully automated, reversible production line for products or related modules. Running forward means that parts are supplied, and the product gets assembled. In contrast, for a reverse operation of the production line, the product is fed at the end of the production line resulting in its parts, modules, or sub-assemblies disassembled. The reversible production line forms the core of the vision, with a wide range of topics from different life cycle phases coming into play. Fig. 2 shows relevant considerations for the vision of a merged automated assembly and disassembly production line.

3.1. Product lifecycle – BoL, MoL, and EoL

The product lifecycle is split into the phases of begin-of-life (BoL), mid-of-life (MoL), and end-of-life (EoL). [13]

The vision of a fully automated, reversible production line has an impact on each phase of the product lifecycle as design for disassembly (DfD) adds new requirements for the product and the data handling and availability (master data, variant

management). These requirements have to be reflected within the begin-of-life (BoL) phase while affecting MoL and EoL.

Mid-of-life (MoL) covers production and product usage and has to be advanced as the production line requires it to be reversible. Furthermore, data has to be allocated considering how the product has been used. Wear and tear might challenge the disassembly process significantly.

And finally, end-of-life (EoL) must cover how components are brought into the process of recycling and remanufacturing into other elements.

3.2. Main focus “production”

The main focus of the vision is on production, in particular the automated assembly line which, while running reversed, disassembles the related products. It is the core of the vision fulfilling elements of the circular economy and is key to enabling the Rs “remanufacture”, “repair” and “recycle”. The fundament is figuring out connection technologies suitable for automated assembling and automated disassembling.

3.3. The R-principles

The following R-principles [7] are applicable for the vision:

- *R0 Refuse* → not applicable
“Make product redundant by abandoning its function or by offering the same function with a radically different product.”
- *R1 Rethink* → not applicable
“Make product use more intensive (e.g., by sharing product).”

- *R2 Reduce* → not applicable
“Increase efficiency in product manufacture or use by consuming fewer natural resources and materials.”
- *R3 Reuse* → not applicable as the product does run again through the assembly/disassembly line after production
“Reuse by another consumer of discarded product which is still in good condition and fulfils its original function.”
- *R4 Repair* → applicable as the assembly/disassembly line is required for replacing parts, modules, or sub-assemblies
“Repair and maintenance of defective product so it can be used with its original function.”
- *R5 Refurbish* → applicable as similar to R4 parts, modules, or sub-assemblies can be substituted by the same type of refurbished item
“Restore an old product and bring it up to date.”
- *R6 Remanufacture* → applicable as valid parts of a disassembled part can be reused in a newly assembled product
“Use parts of discarded product in a new product with the same function.”
- *R7 Repurpose* → applicable as discarded parts (disassembled) are required for this R
“Use discarded product or its parts in a new product with a different function.”
- *R8 Recycle* → applicable as disassembly is required for adequate recycling
“Process materials to obtain the same (high grade) or lower (low grade) quality.”
- *R9 Recover* → applicable as disassembly is a prerequisite
“Incineration of material with energy recovery.”

4. Selected technological aspects

In this section, selected aspects of relevance for the implementation of a fully automated, reversible production line are explained and discussed in greater detail.

4.1. Product lifecycle phases

The lifecycle of products and their production systems encompasses the whole journey, from the extraction of raw materials to end-of-life disposal. This process involves various interconnected stages, including resource extraction, manufacturing, distribution, transportation, product usage and disposal. Each lifecycle phase has its own environmental, economic and social impacts, making it crucial to consider sustainability across the entire product lifecycle. Once in the hands of consumers, products are utilized, which involves energy consumption, maintenance, and potential repair. Finally, products reach their end-of-life phase, where disposal or recycling comes into play. Efficient and sustainable disposal methods are vital to mitigate environmental impact, while recycling is crucial for minimizing waste and promoting a circular economy [14].

Energy consumption, waste generation, emissions, and resource utilization across production processes all contribute to the overall environmental impact of products. Sustainable production systems emphasize resource efficiency, emission reduction, and waste minimization.

The pool of information during the development and production phase of any product is critical for ensuring efficiency and quality. This data is often generated by design engineers and available in a detailed description. During the development phase, information guides the conceptualization and design of products. It involves detailed specifications and requirements that shape the subsequent stages of the product lifecycle. In the production phase, information continues to be indispensable. Supply chain data, material specifications, and production schedules are essential for efficient and cost-effective manufacturing processes. Digital twins, for instance, enable the virtual representation of physical products and processes, facilitating in-depth analysis and optimization in real time. Furthermore, data obtained from production phases is utilized for continuous improvement through feedback loops that inform future designs and production iterations. This iterative process benefits from an abundance of information derived from the development and production phases, resulting in products that are more aligned with customer needs, market trends, and sustainable practices.

In summary, information generated during the development and production phase is fundamental for the disassembly phase. Access to accurate, timely, and comprehensive data, coupled with advanced technologies and analytics, enables informed decision-making, process optimization, and continuous refinement throughout the product.

Generating information about the usage phase of products is crucial for understanding their real-world performance, identifying opportunities for improvement, and ensuring that they effectively meet user needs. Gathering usage data allows an easy disassembly, but often this information is not available. Opportunities to collect this data are:

- The improvement of the product with integrated sensors or utilizing the Internet of Things (IoT) enables the collection of valuable usage data. These sensors can capture information about environmental conditions, usage patterns, energy consumption, and user interactions, providing insights into how products are being utilized.
- Another possibility is the process of evaluating and analyzing a returned product, which is essential to understand customer satisfaction, identify recurring issues, and implement product improvements.
- Combination of both options.

4.2. Bidirectional assembly line

Bidirectional manufacturing refers to a process that integrates both the creation and the deconstruction of products. It emphasizes designing products in a way that makes them easier to disassemble and recycle at the end of their life cycle. The idea is to minimize waste and maximize the reuse of components and materials. For the envisioned automated assembly and disassembly of products, bidirectional assembly lines could provide several benefits. Currently, there is not much information about bidirectional assembly available in scientific literature.

The idea is to use the same machinery for both assembly and disassembly of products. But for the implementation of bidirectional assembly lines, several requirements must be met by the product and the assembly line. Regarding the product, design for disassembly (DfD) is a key aspect. Products must be designed with the intention of being easily taken apart, which facilitates repairs, upgrades, and recycling.

Automatic disassembly of products could be very useful if large quantities of the same or similar products are to be processed. Especially for small and medium companies, which currently do not offer remanufacturing of their products, this could be a new business opportunity. The ability to use the same machinery for assembly and disassembly could also lead to a higher utilization of the production system. At times when less production activity is required, used products returned by the customer can be dismantled by simply reversing the direction of the bidirectional assembly line. Therefore, a high flexibility of the production system is required.

A challenge for each automated disassembly process are products which have been manipulated by the customer. An inspection of the returned products could be one solution to ensure that the product has not been modified. A possible modification that hinders automatic disassembly could be a repair with non-original parts.

4.3. Digital backbone

The envisioned production line being capable of assembling and disassembling products in a fully automated way requires a strong digital backbone that covers the whole product lifecycle. Products and product families are typically under continuous change through adaptations, improvements, and extensions. Examples of those three elements are:

- *Adaption* – A supplier faces out a component, e.g., an FPGA (field programmable gate array) unit on the product's PCBA (printed circuit board assembly), therefore, a related substitution is required. While disassembling one needs to differentiate between products with the previous and the substituting FPGA.
- *Improvement* – The product changes as a flange connection is rearranged to ease assembling and maintenance. Therefore, for disassembling the different locations of the screws need to be known.
- *Extension* – The product family (type), e.g., for pressure sensors [15], gets extended by an additional type of process connection (configuration). The disassembly has to be able to handle the new mechanical element and has to recognize related instances.

Therefore, the master data [16], typically managed in a product lifecycle management (PLM) or product data management (PDM) system and according to the 3D Master method [17] bridging development and production, is a required source of information to enable disassembling. It is advantageous if the production has been serial number-based, therefore each single instance can be traced back to its original bill of material. If products are changing during the mid-of-life (MoL) phase, e.g.

due to maintenance requirements or functional extensions, applying the concept of the Digital Thread [15] is fruitful enabling full traceability. This can include also load profiles, how a product has been used, and environmental information (under which conditions the product has been used).

A further applicable method is applying a Digital Twin Framework, especially digital shadow of the products in operation, to the reversible production line. It is of economic interest to run an assembly-disassembly line most efficiently. Therefore, predictive maintenance of the installed base can predict the quantity of returning products to optimize the operations management. The sequence of assembly and disassembly has an impact on costs as reversing requires a certain time due to start-up and face in/out procedures.

In summary, it is a prerequisite to have an adequate data management system as it is an enabler for automated disassembling. It covers at least the master data while the applied method of the Digital Thread ensures full traceability, ideally employing serial numbers, and the Framework Digital Twin for advanced operation management and forecasting. If such kind of digital backbone is missed, countermeasures must be taken, such as imaging processing that identifies the product.

5. Economic impact for companies

The envisioned automatic assembly-disassembly line requires a critical assessment of its economic impact on companies and their businesses. For example, the investment (capital expenditure, CapEx) and due to increased functionality and usage also the operational costs (operational expenditure, OpEx) for such a production line will be increased as a higher quantity of function is incorporated. However, in combination with the business case, especially related to the circular economy, there is the potential to increase the value chain significantly. Therefore, CapEx and OpEx might decrease in proportion to the generated turnover. For example, the return on investment (ROI), as the proportion between “net project benefit” and “project costs” [18], is increased as the benefit grows over-proportional due to an increased value chain compared to the costs (function integration and increased overall equipment effectiveness, OEE [19]). Alternatively, the payback period as the proportion between “project costs” and “annual project benefits” [18] is reduced due to the same reason as for a better ROI. Therefore, the total cost of ownership (TCO [20]) also gains in importance. Examples from industry for changing the value chain with a focus on TCO and circular economy are:

- Large wooden boxes for transport that protect machines: As an alternative to metal nails, wooden nails (e.g., Ligno-loc [21]) can be used. While wooden nails are more expensive, they eliminate the need for material separation during wood reuse, potentially reducing overall costs.
- Home compostable coffee capsules [22]: Unlike traditional plastic or aluminum capsules, home compostable capsules break down naturally in household compost bins, reducing landfill waste and microplastic pollution. Since they can be composted at home, they elimi-

nate the need for waste transportation and complex recycling systems or industrial composting, making waste management more efficient.

- Refurbishment of used scales at Bizerba [23]: Defined modules (sub-assemblies) of scales in the B2B market are returned to the company Bizerba and repaired for further use. These exchange modules offer customers a cost-effective alternative to new modules [24].

6. Conclusion and Outlook

This paper aims to present a framework that supports design for disassembly and explores how production systems can facilitate this process. Analyzing and providing the necessary information and data for all phases of the lifecycle plays a central role. The vision is presented and discussed based on specific aspects and examples for economic potentials are shown.

For sure there are many obstacles to achieve the described vision. These obstacles cannot be addressed all at once but have to be elaborated step-by-step.

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