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Drone design for Circularity

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Abstract. The transition toward a circular economy requires systematic design strategies that incorporate disassembly needs into product development, making end-of-life processes more efficient and cost-effective. While Design for Disassembly (DfD) supports reuse, remanufacturing, and recycling, its manual execution is often inefficient and expensive. Design for Automated Disassembly (DfAD) extends DfD by adding requirements for robotic handling, including standardised joining techniques, improved accessibility, and simplified processes, enabling scalable and economically feasible circular strategies.

This paper applies and refines DfAD principles for a lightweight and complex mechatronic product—a drone. A two-stage analytical approach combining Hotspot Mapping and Disassembly Mapping has been developed to assess the disassembly process and systematically identify critical design weaknesses. These insights have been validated and expanded through an interdisciplinary expert workshop, leading to specific design adaptations guided by DfAD. The results show how DfAD can be used early in product development to improve automation potential and process efficiency. This study contributes to the theoretical and methodological development of DfAD and offers transferable insights for extending existing guidelines from large-scale systems to smaller, lightweight mechatronic products.

1. Introduction

The global challenges of climate change, resource scarcity, and environmental degradation emphasise the necessity for a fundamental transformation of production and consumption patterns. The concept of a circular economy is predicated on the objective of maximising the longevity of products and materials, thereby preventing waste, reducing resource consumption, and promoting ecological and economic sustainability [1]. The design phase is recognised as a key factor in the implementation of circular economy strategies [2]. For this reason, the European

Union has established binding requirements in 2024 for durability, reparability, reusability, and resource efficiency through the Ecodesign Regulation for Sustainable Products[3].

At the same time, contemporary product development is characterised by rising customer demands for performance, quality, and cost efficiency, as well as by shorter development and product life cycles [4]. These trends create highly dynamic development environments, frequent product updates, and the integration of advanced technologies, thereby increasing the number of components and interfaces and, consequently, complexity [5]. Yet, this complexity poses significant challenges for implementing circular strategies. Products are typically designed with a strong focus on efficient assembly and manufacturing, often resulting in architectures that complicate disassembly, reuse, and recycling [6]. Limited accessibility, high diversity of joining techniques, hierarchical structures, and sensitive component interactions can substantially increase disassembly time and effort [7]. This creates a growing mismatch between regulatory requirements for circularity and the realities of contemporary, assembly-oriented product architectures, including joining strategies.

Design for Disassembly (DfD) addresses these challenges by promoting modularity, accessibility, and standardised, reversible joining techniques to facilitate end-of-life processes [8],[9]. However, the growing complexity and volume of returned products make purely manual disassembly economically and operationally impractical, particularly under increasing cost and efficiency pressures [10]. Design for Automated Disassembly (DfAD) extends DfD by incorporating requirements for robotic handling, such as standardised joining techniques, simplified motion sequences, and improved component accessibility. Automation can thus transform disassembly into a scalable and economically viable process [11].

To apply DfD in a way that also captures requirements for automated end-of-life processes, this paper uses a structured analytical approach applied to a drone, a representative mechatronic product. The product is first analysed in its current configuration using Hotspot Mapping and Disassembly Mapping to systematically identify disassembly-related challenges arising from product complexity, without assuming prior DfD compliance. By systematically linking disassembly-oriented product analysis with the derivation of automation-relevant design adaptations, this study offers a structured approach to operationalising DfAD in the early stages of product development. Based on the identified hotspots and structural characteristics, design adaptations are then derived and discussed, with a specific focus on DfAD. The drone serves as an example of how the proposed analytical approach can be applied to a concrete product, and the methodology is transferable to other lightweight, highly integrated mechatronic systems.

2. Related Work

Approaches to product design optimisation are collectively termed Design for X (DfX), where the "X" denotes the specific objective to which the product design is oriented [12]. In the context of the circular economy, particular emphasis is placed on the handling of products after their first life cycle and the disassembly procedure required for this purpose. Consequently, concrete design guidelines have been developed under the concept of DfD, which have been further refined to address the requirements of automated disassembly [13].

2.1 Design for Disassembly (DfD)

The primary objective of DfD is to design products in a manner that enables their systematic and efficient disassembly at the end of their lifecycle, thereby facilitating the recovery of materials and components through downstream R- strategies (Repair, Reuse, Recycle, etc). The ease of disassembly depends on several factors, such as the overall product design: the type and number of joining techniques used, the properties of individual components, the materials involved, and the condition of the product upon its return [8]. To address these factors, specific design guidelines have been proposed in the literature [8],[9]:

- *Product structure:* A modular design with a reduced number of parts, limited variety, and a high degree of standardisation is recommended. Moreover, components should be designed to ensure good accessibility, facilitating the replacement of defective elements, and they should combine low weight with sufficient robustness.
- *Joining techniques:* The number of connections should be minimised, designed to be visible and easily accessible, and limited to a few standardised types. Reversible joining techniques, such as screws, are particularly recommended, as they can be removed without destruction and allow for component reuse, whereas adhesive or welded joints should be avoided.
- *Material selection:* A high level of material homogeneity should be pursued to facilitate separation and recovery. Recyclable materials should be prioritised, while the use of toxic or safety-critical substances should be avoided.
- *Disassembly conditions:* The efficiency of disassembly is also influenced by the process environment. Ideally, the design should allow disassembly with simple, standardised tools and be structured in a way that enables the potential automation of disassembly processes.

2.2 Design for Automated Disassembly (DfAD)

The automation of disassembly is becoming increasingly important due to the growing volume of returns and the need to develop economically viable end-of-life processes. Simultaneously, the growing variety of products makes it more difficult to develop standardised automated methods, highlighting the need to adapt product design based on DfAD principles [13].

DfAD builds on the principles of DfD and improves them by adding specific requirements for robotic integration. These requirements are designed to facilitate robotic handling, such as by using standardised joining techniques, enhancing sensor-based detection of features such as ArUco markers and barcodes, and improving design elements such as gripping surfaces. Therefore, DfAD is a key approach to ensuring the efficiency, reliability, and economic viability of circular strategies on an industrial scale [11]. The consideration of these factors motivates the need for specific design guidelines, which must be adapted to the capabilities of the respective robotic system. These robotic and process-related requirements translate into concrete product-level design principles, which can be structured into four main categories [14],[15]:

- *Product structure*: Components should be arranged such that robotic arms can access them with minimal movement sequences. Adequate clearance between parts should be ensured to prevent collisions, and component geometries should enable secure handling.
- *Joining techniques:* Standardised and non-destructive joining techniques should be preferred, as they can be reliably gripped and released using automated tools. Adhesives, welds, or poorly accessible connections should be avoided wherever possible.
- *Component properties:* The weight and dimensions of individual parts should remain within the load and gripping limits of the robotic system. Surfaces and gripping edges should be designed to allow reliable handling with suction or mechanical grippers.

- *Disassembly conditions:* Process complexity should be minimised by reducing tool changes and enabling the use of standardised tools. Furthermore, designs should support the automated detection of component position and orientation to ensure precise and reliable disassembly operations.

2.3 Existing Areas and Applications of DfD and DfAD

DfD has been applied across a broad range of product domains. Reported application areas include architecture and construction, where reversible building components enable material recovery [16], mechanical- and plant engineering, with a focus on maintainability and component reuse [17], modular furniture systems designed for repeated assembly and disassembly [18], household appliances optimised for repair and recycling [19], and automotive products that support remanufacturing and end-of-life treatment [20].

Reported DfAD studies are currently largely limited to specific electromechanical and electronic products, including LEGO® motors [11], electric vehicle battery systems [14], consumer electronic devices such as remote controls [21], laptops [22] and selected automotive components [23]. Despite existing research on DfAD addressing individual products and automation scenarios, there is currently no widely established methodology that systematically links disassembly-oriented product analysis to the derivation of automation-relevant design adaptations. A structured integration of analytical disassembly assessment, architecture-oriented visualisation, and interdisciplinary validation has not yet been established. This study addresses this gap by proposing a structured approach that integrates analytical disassembly assessment, architecture-oriented visualisation, and interdisciplinary validation to support DfAD-guided product design decisions.

3. Methodology

In this work, a structured analytical approach has been developed to evaluate a product's disassembly potential and identify necessary design modifications, based on the principles of DfD and DfAD. The following section describes the two-stage analytical process and its validation through an interdisciplinary expert workshop.

The Hotspot Mapping method is used to identify weaknesses in the product architecture that hinder its disassembly. The product is comprehensively disassembled in a real-world physical teardown, with each step being meticulously documented. This process encompasses the capture of various parameters, including activity (comprising the utilisation of tools and the duration of the process), accessibility, functional sensitivity, and material data. Considering the data, a quintet of indicators is derived: disassembly time, activity difficulty, priority parts, environmental impact, and economic value [24].

The Disassembly Map is then used as a visualisation method based on the Maynard Operation Sequence Technique (MOST) [25] and the ease of Disassembly Metric (eDiM) [26],[27]. This method captures disassembly sequences, times, tool requirements, and the reusability of joining techniques. These are represented as nodes (components) and edges (disassembly steps). The application of colour and symbol coding serves to emphasise dependencies, difficulties, and target components, thereby enabling the evaluation of existing product architectures and the derivation of concrete design principles for disassembly-oriented (re-)design [28].

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Together, the Hotspot Analysis and Disassembly Map enable the systematic identification and visual prioritisation of critical individual components and their connections, providing a comprehensive foundation for developing and evaluating DfD strategies within circular approaches.

To validate and further develop the analytical methods and design guidelines, an exploratory expert workshop was conducted as a qualitative research activity. The workshop involved 25 academic participants from five disciplines: product development and design, production engineering and manufacturing systems, materials science, architecture with a focus on circular construction, and energy and environmental engineering. The participant group comprised a mix of PhD candidates and Master's students, ensuring both methodological depth and exploratory perspectives. All participants attended the entire workshop.

The workshop was held over five consecutive days to validate the proposed analytical approach and design guidelines. As illustrated in Figure 1, participants engaged in a sequence of activities that combined methodological input with the collaborative application of the analytical methods to the considered use case (drone), with a focus on disassembly aspects relevant to automation. Based on insights from these sessions, DfAD-oriented design adaptations were developed and discussed. The workshop outcomes were used to further refine the analytical approach and align the derived design guidelines with practical design and automation requirements.

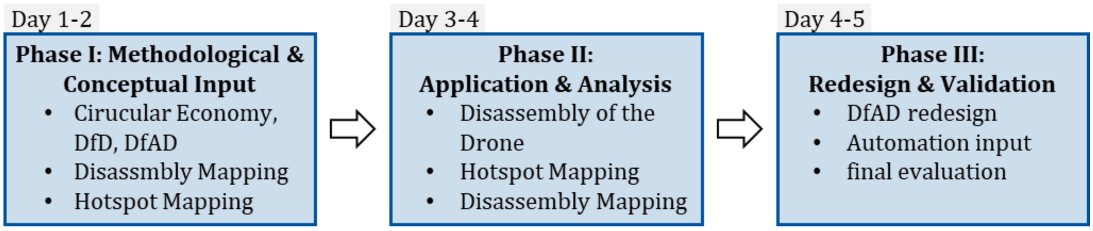

Figure 1. Overview of the structure and phases of the five-day expert workshop

4. Use Case: Drone Design

The drone was selected as a representative use case due to its highly integrated mechatronic architecture, hierarchical product structure, and limited access to key components. These characteristics make it well-suited to illustrating how disassembly-related challenges can be systematically identified using the proposed analytical methods and then translated into DfAD-guided design adaptations. Importantly, the drone is not considered an example of an existing DfD-optimised product; instead, it serves as a baseline configuration to demonstrate the applicability of the theoretically derived design guidelines in combination with Hotspot Mapping and Disassembly Mapping. As illustrated in Figure 2, the drone comprises standard components that can be assembled into different configurations, and its current assembly and disassembly are performed manually.

The product consists of 42 individual parts, comprising 13 primary components and 29 joining elements realised as screw joints. In the design process, the utilisation of solely screw connections, comprising bolts and nuts, was employed. These connections varied in terms of nominal diameter and shaft length. The process of assembly and disassembly necessitates a set of tools, namely hex keys in sizes 2.5 mm, 4 mm, and 5 mm, as well as open-end or socket wrenches with widths across flats of 8 mm and 10 mm.

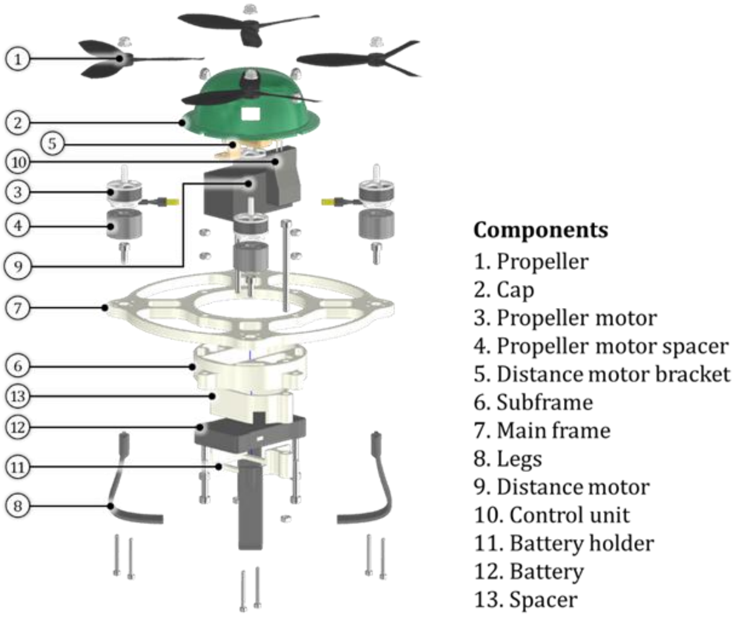

Figure 2. Exploded view of the drone illustrating the arrangement and numbering of the individual parts.

5. Results

This chapter presents the results of the analysis that was conducted. First, it outlines the hotspots identified within the drone design and the outcomes of the product architecture analysis. Based on these findings, design adaptations are developed in accordance with the previously outlined guidelines of DfD and DfAD.

5.1Identification of Hotspots

The stepwise disassembly was documented using the Hotspot Mapping Datasheet, following the previously defined categories presented in Chapter 3 [24]. Figure 3 shows an example of one of these datasheets from a workshop group, illustrating how the hotspots were identified and documented.

General				Activity					Accessibility			Functional		Material		HotSpot Indicators				
Step number	Name	Subassembly?	Part of ...	Type of activity	Required tool	Tool size	Task frequency	Total time to disconnect (sec)	Force	Accessibility	Positioning	Failure Likelihood	Functinoal relevance	Material group	Weigth (g)	Time	Activity	Priority part	Environmental	Economic
1	13. Propeller screw	no	main assembly	Unscrew	Screwdriver	8x125n	4	20	level 0 -	level 0 -	level 1 -	level 1 -	level 1 -	Steel	0.6	⚑				
2	11. Propeller	no	main assembly	Remove	Hands	N/A	4	8	level 0 -	level 0 -	level 0 -	level 2 -	level 2 -	Thermoplastic	3.3			⚑		
3	9. Hatmutter M5	no	main assembly	Unscrew	Hands	N/A	4	20	level 0 -	level 0 -	level 1 -	level 1 -	level 0 -	Steel	2.4	⚑				
4	8. Tophat	no	main assembly	Remove	Hands	N/A	1	2	level 0 -	level 0 -	level 0 -	level 0 -	level 1 -	Thermoplastic	16.8					
5	7. Mutter M5	no	main assembly	Unscrew	Screwdriver	8x125n	4	24	level 0 -	level 0 -	level 1 -	level 0 -	level 1 -	Steel	1.3	⚑				
6	6. Screw M5x30 Hex	no	main assembly	Remove	Hands	N/A	4	8	level 1 -	level 1 -	level 1 -	level 0 -	level 1 -	Steel	5.5		⚑			
7	Sub 1	yes	main assembly	Remove	Hands	N/A	1	5	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Mixed materials mainly plastics						
8	5. Screw M3x30 Hex	no	main assembly	Unscrew	Screwdriver	2.5	8	160	level 0 -	level 1 -	level 2 -	level 1 -	level 1 -	Steel	1.9	⚑	⚑			
9	10. Motor Z2207 2400KV	no	main assembly	Remove	Hands	N/A	4	4	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	E-motor	33.8				⚑	⚑
10	4. Motor spacer	no	main assembly	Remove	Hands	N/A	4	4	level 0 -	level 0 -	level 0 -	level 0 -	level 2 -	Steel	6.5					
11	2. Screw M5x12 Hex	no	main assembly	Unscrew	Screwdriver	4	4	20	level 1 -	level 0 -	level 1 -	level 0 -	level 0 -	Steel	1.9	⚑				
12	3. Legs	no	main assembly	Remove	Hands	N/A	4	4	level 0 -	level 0 -	level 0 -	level 1 -	level 1 -	Thermoplastic	6.1					
13	9. Screw M6x12 Hex	no	Sub 1	Unscrew	Screwdriver	5	1	8	level 1 -	level 0 -	level 1 -	level 0 -	level 1 -	Steel	4.9					
14	6. Battery Holder	no	Sub 1	Remove	Hands	N/A	1	2	level 0 -	level 0 -	level 0 -	level 0 -	level 0 -	Thermoplastic	3					

Figure 3. Example of a section of the Hotspot Mapping Datasheet from one workshop group, illustrating categorisation and the identification of time-, activity-, functional-, material-, environmental-, and economic-related hotspots. [24]

The evaluation of the hotspot indicators reveals that the primary weaknesses in the Time category are primarily due to the use of screw connections. On average, loosening a screw takes about five seconds. However, significantly longer disassembly times of around 20 seconds per screw are observed for the screws used to secure the motor ③. This is because of the limited accessibility of these joining techniques. As a result, this connection is a critical weakness not only in the Time category but also in the Activity category.

The remaining categories refer to the components. The analysis identifies the propellers ①, the battery ⑫, and the control unit ⑩ as priority parts, as they are essential for the drone's fundamental functionality. These components are therefore designed to ensure both accessibility and replaceability. Additionally, the battery ⑫, control unit ⑩, and distance motor ⑨ are identified as major factors influencing the environment and economy categories. Because both categories are driven by the same components, they are treated jointly in the following evaluation.

The assessment relies on a multifactorial analysis of material composition and weight. Both the economic value (EUR/kg) and the embodied environmental impacts (CO_2 footprint in kg/kg) are considered [24].

5.2 Analysis of the Product Architecture

Using the Disassembly Map method, the product architecture and the accessibility of individual components are systematically analysed. The disassembly sequence is illustrated, showing which parts must be removed successively or can be detached simultaneously. Additionally, the actions needed to separate the components are identified. Since the drone consists solely of screw- and plug-based joining techniques, a distinction is made between the tools used: screwdriver, open-end wrench, and manual handling. Tool changes between steps, as well as necessary rotations of the assembly to access specific connections, are also taken into consideration. Furthermore, the previously identified hotspots are marked with symbols defined in earlier chapters. A complete overview of the analysis is provided in Figure 4.

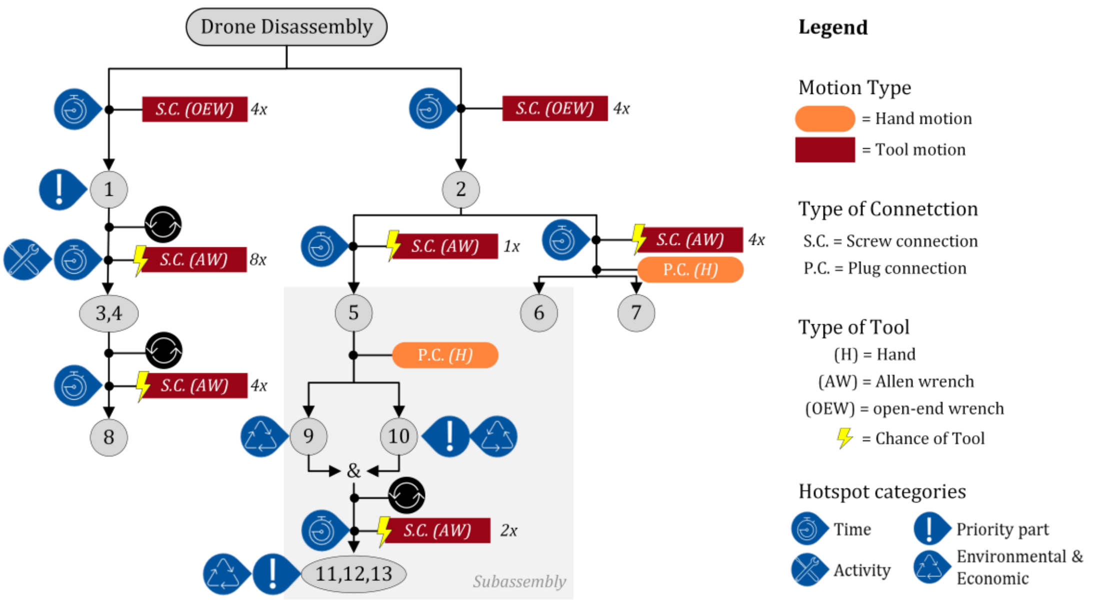

Figure 4. Disassembly map summarising the results of the workshop-based hotspot analysis, showing the sequence of disassembly steps, subassemblies, and the identified process- and component-related hotspots.

The figure highlights the strongly hierarchical structure of the drone as well as the mandatory sequence of disassembly steps. Already at the first levels, it becomes apparent that the propellers ① and the cap ② must be removed before access to the underlying subassemblies (e.g., propeller motors ③ or subframe ⑥) is possible. Moreover, the analysis reveals that almost every step necessitates reorientation, either through a change in motion type (manual vs. tool-based), a tool change (e.g., Allen wrench, open-end wrench), or by rotating the entire assembly to make the respective connection accessible. This not only increases the disassembly time but also the complexity of potential automation, as a robotic system would need to adapt and reposition continuously. In addition, specific components, particularly ⑪, ⑫, and ⑬, fall freely once the screws are removed, without further fixation. This presents a considerable challenge for automated disassembly, as suitable measures must be implemented to catch or detect the parts and prevent loss or damage. Considering the identified hotspots, it becomes evident that both the battery ⑫ and the control unit ⑩ are only accessible after several preceding disassembly steps. This limited accessibility reinforces the identified weaknesses.

In summary, the combination of hotspot analysis and the Disassembly Map reveals, on the one hand, the highly hierarchical structure of the drone, which makes replacing priority parts more complex, and, on the other hand, the related process challenges associated with tool changes, accessibility, and part handling. These findings are essential for developing efficient and potentially automated disassembly processes and can be addressed through the design improvements outlined in the following chapters.

5.3 Derivation of DfAD-guided design adaptation

The results of the expert workshop offered valuable insights into how the analytical approach and the DfAD guidelines can be used to develop product-specific design adjustments. The workshop served to validate and prioritise analytically derived findings rather than to generate independent results. Accordingly, the following design adaptations are concept-level proposals derived from the workshop and have not been physically implemented or prototyped. From the interdisciplinary group discussions, three key areas for improvement were identified that have a significant impact on the level of automation in disassembling the drone system.

1. *Product structure:* Limited accessibility and frequent reorientation during disassembly were identified as significant obstacles to robotic implementation. Improving accessibility reduces tool complexity, motion planning effort, and the risk of collisions. To address these challenges, participants recommended using modular and symmetrical subassemblies that allow uniform tool access and minimise reorientation requirements. Additionally, a one-sided disassembly orientation was identified as a key requirement for automation, since a product architecture that enables all relevant joining techniques and components to be reached from a single direction simplifies tool handling, shortens process times, and improves the overall stability of robotic operations.
2. *Joining techniques:* The current design comprises a large number of screws that differ in diameter and length, resulting in frequent tool changes and increased process complexity. The experts therefore recommended reducing both the quantity and diversity of joining techniques to simplify toolpath planning and minimise setup times. In this context, plug connections were highlighted as a promising alternative to screw joints, as they offer significant advantages in terms of process time, accessibility, and potential for automation. Plug connectors enable geometrically guided disassembly motions that can be executed using universal robotic tools, such as multifunctional or vacuum grippers. This simplifies robotic operations by reducing the need for specialised tools and complex tool-change procedures. In

particular, the bayonet lock was identified as a suitable solution for attaching, for example, the drone's legs ⑧ and cap ②, as illustrated in Figure 5.

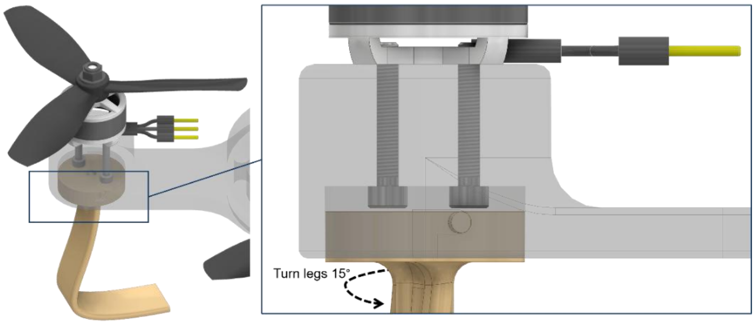

Figure 5. Conceptual illustration of a bayonet lock connection between the frame ⑥ and the legs ⑧, proposed as a DfAD-guided design adaptation to replace screw joints and improve automated disassembly.

3. *Component properties:* The experts focused on the main ⑥ and subframes ⑦ as well as the spacers (④ and ⑬), which act primarily as mounting aids without independent technical functionality. Since these components mainly serve structural support purposes, their material selection and geometric design are particularly relevant from an efficiency standpoint. The workshop results revealed potential for structural simplification by integrating these elements into a single part. Using additive manufacturing, the main and subframes, along with the spacers, can be consolidated, reducing the number of disassembly steps from six to one while also lowering the overall weight. An initial concept that combines the individual components into a single unit, unlike the previous ones, is illustrated below.

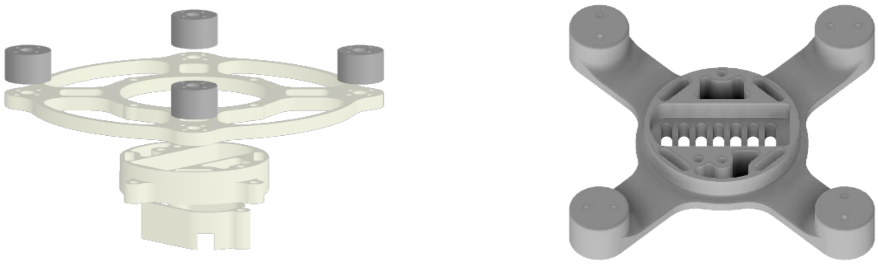

Figure 6. Comparison of the previous multi-part frame structure (left) and the consolidated design concept (right).

In conclusion, the design adaptations from the expert workshop are crucial in improving the disassembly automation of the drone system studied. The identified measures, ranging from improved accessibility and standardised joining techniques to structural integration and material optimisation, demonstrate how DfAD can be purposefully implemented at early stages of product development. The results underscore that a comprehensive approach to product architecture, encompassing technology and material selection, is crucial for systematically enhancing both process efficiency and disassembly. Accordingly, this result not only provides concrete strategies for transferring the developed design guidelines to a specific product but also contributes to the empirical substantiation of DfAD as an integral component of circular product development.

6. Conclusions and Critical Reflection

The results of this study demonstrate that applying Design for Automated Disassembly (DfAD) principles to lightweight mechatronic products can significantly enhance their potential for automated disassembly in circular product development. By systematically combining Hotspot Mapping and Disassembly Mapping, this research shows that limited accessibility, excessive diversity of joining techniques, and hierarchical product structures are key barriers to automated disassembly.

Beyond these product-level findings, this study contributes to the conceptual development of DfAD by extending its application beyond large-scale products, such as electric vehicle batteries, to smaller, highly integrated assemblies, such as drones. While core DfAD principles, including accessibility, standardisation, and modularity, remain valid across product scales, the results indicate that their implementation must be adapted to specific geometries and functional constraints. Limitations related to robotic gripping, perception, and part handling in lightweight systems require different design trade-offs compared with heavy industrial products.

From a methodological perspective, integrating analytical disassembly methods with qualitative expert input proved essential. The interdisciplinary workshop validated and prioritised analytically derived findings and confirmed that collaboration among product designers, automation engineers, and manufacturing planners is necessary to translate theoretical guidelines into actionable design adaptations. This integration positions DfAD not only as an analytical concept but also as an operational design approach.

Despite these contributions, the study has inherent limitations. The analysis is based on manual disassembly processes, and the feasibility of the proposed design adaptations for automated disassembly has not yet been experimentally validated. Moreover, while the analytical approach effectively captures disassembly-related complexity, economic and lifecycle considerations remain only partially integrated. Addressing these limitations is essential for establishing DfAD as a comprehensive and scalable design approach.

7. Future Work and Outlook

Building on these conclusions, future research should focus on experimentally validating the proposed design adaptations. This involves developing physical drone prototypes and implementing a robotic disassembly cell to evaluate the achievable level of automation under real-world operating conditions. In addition, the integration of DfAD principles throughout the product development process should be further explored to ensure continuous alignment among design, assembly, and disassembly considerations.

Furthermore, additional research is required to assess the economic implications of the proposed design measures. While technical feasibility and automation potential have been demonstrated, increased manufacturing and assembly effort may currently be a limiting factor. A techno-economic assessment is therefore essential to quantitatively analyse trade-offs among production costs, automation efficiency, and circularity benefits. In this context, an integrated consideration of Design for Assembly (DfA) and Design for Disassembly (DfD) emerges as a key enabler for developing products that are both efficiently assembled and automatically disassembled, thereby supporting environmentally and economically viable circular manufacturing systems.

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