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Circular Design of Composite Products: A Framework Based on Insights from Literature and Industry

Jelle Joustra *, Bas Flipsen and Ruud Balkenende

Faculty of Industrial Design Engineering, Delft University of Technology, 2628 CE Delft, The Netherlands; S.F.J.Flipsen@tudelft.nl (B.F.); A.R.Balkenende@tudelft.nl (R.B.)
* Correspondence: j.j.joustra@tudelft.nl

Abstract: Composite materials are an attractive material choice as they enable lightweight, low-maintenance products with a long lifespan. Recycling these materials, however, remains a challenge. Homogeneous material composition and the use of thermoset matrices complicate reprocessing, and result in low-grade recyclate. This means that closing the loop for these materials in a circular economy remains challenging, especially for glass fibre-reinforced thermoset composites. For a circular economy, products need to be designed to preserve product functionality, material properties, and economic value for as long as possible. However, recovery strategies, design aspects and their interconnectedness are currently largely unexplored for products containing fibre-reinforced polymers. The aim of this study was to identify circular strategies and determine design aspects for products containing composites. To achieve this, we conducted a systematic literature review and consulted experts. The circular strategies are largely similar to generic circular economy strategies as far as product integrity is concerned. However, on a material level, we identified additional approaches, the most notable of which is structural reuse, which preserves the material quality and thereby value. The design aspects were clustered and positioned along the product design process to support implementation. Finally, the strategies and design aspects we identified were brought together in a framework to support product design and design research for products containing composite materials in the context of a circular economy.

Keywords: design; circular economy; composite materials

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1. Introduction

The current rate of consumption places excessive pressure on our global ecosystems, depleting resources and generating waste. The circular economy offers a promising alternative to lower the environmental burden [1,2]. It aims to prevent waste by design and to preserve economic and environmental value [3]. Product integrity is a key concept in the circular economy [4] and maintaining product functionality has preference over material recovery [4,5]. Product value can be preserved through long life, lifetime extension, and product recovery approaches, while material value can be preserved through recycling. Thus, the circular economy is a driver for achieving sustainable use of resources.

In the case of composites, the circular economy scheme can largely be applied as far as product integrity is involved, however material integrity has some distinct aspects [6]. Composite materials enable a long product lifetime because of the resistance to corrosion and fatigue [7,8] and provide opportunities for lifetime extension through maintenance and repairs [9,10]. However, no clear solutions have yet been found to close the loop at a material level. Composite recycling processes tend to break down the composite into its constituting materials, thus losing the specific composite material properties [7,11]. As recycling processes severely degrade materials, recycling is barely viable economically [11]. Consequently, the majority of composite material is landfilled or incinerated, losing the material and its potential for reuse [12]. Thus, while composite materials provide many advantages, we need to improve on their end-of-life treatment.

End-of-life treatment processes and their position in a Circular Economy are currently being developed from various perspectives. An increasing number of countries banned landfilling or stipulated gate fees to incentivise recycling activities [11,13]. Additional regulations to direct materials towards reprocessing activities, similar to the end-of-life vehicles (ELV) directive [14], are expected for large composite consuming sectors such as wind energy [13,15]. To answer these increasingly strict regulations, recycling processes are developed [16–19] and industrialised [20,21]. Project consortia from academia and industry aim to create closed value chains for composite products [22,23] or explore repurposing opportunities for current end-of-life material flows [24]. The increasing attention to reuse and recycling illustrates the necessity as well as the challenges, which can be attributed to the variation and complexity of composite materials.

Composites can be classified according to either their matrix or reinforcement fractions [25]. For the matrices, ceramics, polymers and metals are commonly used, of which polymers are by far the largest group [7] and form the focus of this study. Within polymer matrices, thermosets (mainly epoxides and polyesters) and thermoplastics can be distinguished. The market share of thermoplastic composites, relative to thermoset-based, is increasing: from 33% in 2012 to nearly 50% in 2017 [7,26]. Reinforcements come in the form of particles and fibres, ranging from short and randomly ordered to continuous and unidirectional aligned [25,27]. Glass fibres dominate the market with 99% in volume versus 1% for carbon fibres [28]. The final material properties can be tuned by many factors, of which the most important are the selection of matrix and reinforcements, mixture ratio, and reinforcement structure (orientations and dimensions) [25].

Opportunities for reuse and recycling of composites will increase if they are addressed in the design stage [7,8,29]. End-of-life processing can be anticipated in the design stage by starting from the process needs, followed by analysis of the product structure [30,31]. This approach requires intricate knowledge of the product use, to be able to evaluate its residual quality and the intended recovery process. However, information about the product life and end-of-life is only available to a limited extent in the design stage, which limits such approaches [32]. Thus, designing composite products for recovery means the designer has to integrate additional, but uncertain, requirements into an already complex design process; designers often require additional support for this task [29,33]. However, despite the growing attention towards end-of-life processing, design for the recovery of composite products remains largely unexplored [29,34,35].

To make the circular economy concept more actionable in design practice, Den Hollander proposed the Circular Product Design framework which connects circular strategies to design aspects [36]. Circular strategies describe measures to preserve product or material integrity, i.e., remanufacturing or recycling, and have a strong connection to business models [1]. Design aspects relate to product realisation and provide insights as to how recovery can be anticipated by design intent, such as choices with respect to materials and connections [3]. Combined in a framework, these strategies and design aspects provide designers with a starting point for new circular product development.

We aim to identify circular strategies and determine related design aspects for products containing fibre-reinforced polymers, and to make these accessible for use in both research and design practice. We performed a systematic literature review and consulted experts to identify the relevant strategies and design aspects for these composite products. We then clustered and connected these strategies and design aspects in a framework to create an overview of their relations and facilitate implementation.

2. Methods

The circular strategies and design aspects were collected through an expanded systematic literature review and by consulting experts on design of composite products for a circular economy. The literature review was combined with expert interviews to collect current knowledge from both scientific publications and industry practice. Through this approach, the existing knowledge gap considering designing composite products for a circular economy was addressed by integrating insights from academia and professional expertise. The Circular Product Design framework [36] was used as the basis for the analysis.

2.1. Literature Review

In July 2020, we reviewed literature with the objective to identify circular strategies and design aspects for products containing composites in a circular economy (Figure 1). The data collection was set up as a systematic literature review, which was expanded through snowballing. An initial search revealed that no literature was available on the main topic, therefore, we separated the main topic into three key concepts: circular economy, design, and composite materials. Literature was sought in pairs of these key concepts to cover the search fields (Figure 2): (1) circular economy and design, (2) circular economy and composite materials, and (3) composite materials and design.

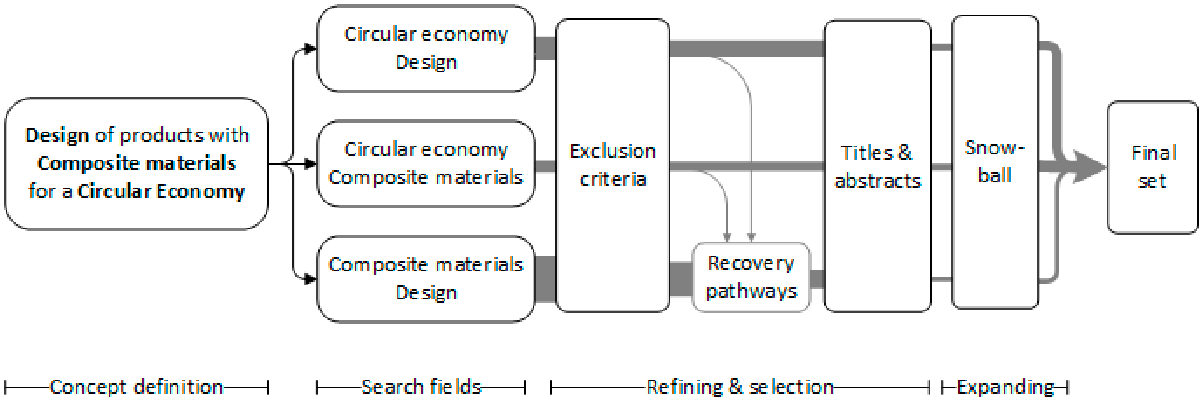

Figure 1. Schematic of the literature collection and selection procedure.

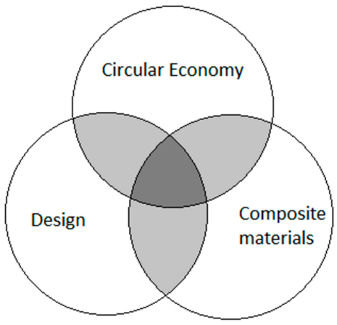

Figure 2. Venn diagram of key concepts, paired into three search fields (light grey) to cover the main topic (dark grey).

The initial literature set was composed using search queries (in Appendix A) in Scopus and Web of Science [37,38]. The queries were formulated using synonyms of each key concept and wildcards to ensure full coverage [39]. This resulted in 449 articles on circular economy and design, 113 on circular economy and composite materials, and 6157 on composite materials and design.

The results were refined in three steps. First, we excluded publications focusing on out-of-scope topics: bio-based polymers, additive manufacturing, and consumer perception. Given the technological and functional nature of composite material applications, circular strategies related to emotional attachment were also excluded. Then, to select relevant papers from the large set of articles on composite materials and design, the search results were narrowed down by searching for articles addressing design in relation to recovery. For this, the recovery pathways identified in the first two sets were used. Wildcards were used to ensure full coverage. In this way, the composites and design set delivered 31 results on long life, 14 on maintenance, 39 on repair, 1 on adapting, 13 on upgrading, and 6 on recycling. No articles were found in the composite materials and design set addressing design for refurbishment, remanufacturing, parts harvesting, or structural reuse. Finally, the results from all three search fields were evaluated by reading titles and abstracts, selecting those that contributed to identifying circular strategies and design aspects for fibre-reinforced polymers.

The selection was then expanded through snowballing and citation searching to include related relevant publications [39]. After refining and selection, the literature set consisted of 29 articles covering design, circular economy, and composite materials. Another 8 publications were added through snowballing. The final selection consisted of 12 publications on design and circular economy, 18 on circular economy and composite materials, and 7 on composite materials and design for recovery.

2.2. Expert Opinions

To explore circular strategies and design aspects for products containing composites, focus-group sessions were performed with experts from the field. Focus groups are useful in exploratory research as they create rich and easily understandable data, they are undirected by predefined responses, and they benefit from group synergy [40]. This approach fits the research context, as design is typically a creative and collaborative act which integrates knowledge and requirements from various disciplines and product stakeholders [41].

The focus group sessions were organised as workshops in the context of a project aiming to demonstrate closing the loop for composite-containing products from the automotive, construction and furniture industries [22]. The sessions were held in June 2018 during a general assembly in Koblenz, Germany. The participants were selected to represent stakeholders from the respective product value chains and to have expertise in the relevant stakeholder activities and processes concerning the case product. The participants included material suppliers, designers, manufacturers, and recyclers. In total, 47 experts participated in the focus group sessions. Based on their expertise, some were invited to multiple sessions. During the session, 10 groups of 6 to 8 participants were asked to explore opportunities for the circular redesign of the following products: a car interior part, a bookcase or bed, and an outdoor panel or bar construction materials. The sessions started with a plenary introduction of the session setup and introduction of the product at hand. Each group session was guided by a moderator with expertise in circular product design, using shared worksheets as a discussion guide (in Appendix B).

Two worksheets were developed based on a preliminary literature study (in Appendix B). The first worksheet depicts a generic product lifecycle, to which the participants could add stakeholders, resources, and recovery actions. This was used to map out the current value chain of the product, the stakeholders involved, and to explore potential circular strategies. The moderator used the worksheet to guide the discussion, by asking questions on which products, parts or materials would be recovered, and which stakeholders would be involved. The second worksheet depicted the circular strategies and served to identify the intended recovery actions and processes, which led to finding challenges for recovery of the case product. The moderator asked questions to clarify the recovery case and intervened when the discussion went off-topic. Finally, the layout guided the discussion towards generating design solutions that would facilitate recovery.

Group members added notes to the worksheets during the sessions. After the session, the worksheets were collected and the notes transcribed. Preliminary findings were reported and discussed with the focus group members.

2.3. Analysis and Clustering of Quotations from Literature and Experts

Literature and focus group responses were annotated in Atlas.ti [42] using a provisional coding approach [43]. The provisional coding set was based on the Circular Product Design framework [36]. The set was expanded with additional codes which emerged while coding. The final code set was used to adapt the Circular Product Design framework to include the design of products containing composites in a circular economy.

In the analysis, it was observed that literature, as well as experts, often discussed design aspects in conjunction, indicating implicit relations. To elicit these relations and create an overview that would facilitate implementation, the design aspects were clustered in two steps. First, we counted the number of times two design aspects were discussed in conjunction using a code co-occurrence table in Atlas.ti (in Appendix C). With this table, we generated a network map in VOSviewer [44] to create an initial clustering based on link strength. Second, the clustering was refined based on the stages in the design process as defined by Pahl et. al. [31]: concept, embodiment and detail design. This clustering enabled relating the design aspects to the design process at large, and thereby facilitate implementation in design practice.

3. Results

From the literature search, we observed notable differences in the number of retrieved search results. The search field of circular economy and design delivered a number of literature reviews [45–47], and a recent increase in publications, indicating this is an emerging field. The circular economy in relation to composite materials has also received increasing attention in recent years. While initially focused on recycling technology, more recent publications explore alternative recovery pathways for composite materials, most notably for wind turbine blades [8,9]. The search field of composite materials and design delivered a wide range of results, including many engineering approaches to optimising mechanical performance. This large set was further refined by using the recovery pathways identified in the first two sets. Together, these three sets provided a comprehensive overview of strategies and design aspects for composite products in a circular economy.

The following sections elaborate on the design of products containing composite materials. Section 3.1 describes circular strategies identified from the literature and expert consultations. Section 3.2 presents the identified design aspects.

3.1. Circular Strategies for Composites

In Table 1, we list the circular strategies with references to the literature and example quotes from the expert consultation. We then used these to formulate brief descriptions of each strategy.

Table 1. Circular economy strategies for products containing composite materials.

Circular Strategies [References]	Description from the Literature	Quotes from Expert Consultation
Long life [3–5,8,9,31,36,46–54]	Ensuring long product lifetime by promoting long use and reuse of the product as a whole, through manufacturing physically durable products, resisting ageing, fatigue and corrosion, able to sustain wear and tear without failure.	"[incorporating] additives [in the material] to make the panel more scratch resistant"
Lifetime extension [3–5,7–9,12,31,32,34,36,45–47,50–52,55–59]	Extending the time in use through maintenance, repair, technical upgrading or adapting, by users or service personnel. This can be promoted by facilitating handling of the product and subsequent rework tasks.	"Repairing strategies favouring parts replacement and upgrades" "Design for disassembly (screws, reversible snapfits)"
Product recovery [3–5,7,9,31,32,34,36,45–47,50–52,56,60]	Returning products or parts to working condition, thereby increasing the number of use cycles.	"[Keep product parts] fixed so they don't drop off during use but come off easily and quickly during reman/refurbish"
Structural reuse [8,9,31,32,34,61–63]	Retrieving structural elements, preserving the material composition, through repurposing, resizing or reshaping product parts for reuse in another context or construction.	"Remove panel elements for another furniture" "Structure made of linear components like truss structures so components could be re-used in other products"
Recycling [3–5,7–9,12,16,29,31,32,45,47–52,55–57,60,61,64–66]	Recovery of materials through thermal, chemical, or mechanical processes, resulting in raw materials ("recyclate"), aiming to close the materials loop.	"use of compatible materials [compatible with process and other materials in the product to warrant a good recyclate grade]" "[facilitate composite material] recovery from bulky waste"

3.1.1. Long Life

Long life slows the flow of resources through the economic system by extending the utilization period of a product [5]. Therefore, products have to be durable and reliable in use [3]. The goal is to keep the product close to its original state at relatively little cost, thus preserving resources as well as design and manufacturing efforts. Both the experts and the literature emphasize the good fatigue and corrosion resistance properties of composite materials, enabling long product life spans [8,49]. Building on these beneficial characteristics, composite materials are often employed in mechanically optimised structures exposed to cyclic loads, where long operational lifetime and reliability are important [53].

To ensure a long life, products need to be protected against degradation. Load conditions and ageing affect product lifetime. Cyclic loads cause structural fatigue which can lead to a reduction in strength [53]. The fatigue behaviour of composite materials differs from that of metals, and is more difficult to predict and inspect. Understanding strength reduction in relation to time, loads and environmental conditions, as well as that resulting from impact damage, continues to be an important research topic [53]. Ageing, caused by environmental exposure, can lead to deterioration of the materials [8,9,48]; experts suggested countering such deterioration by applying a protective coating. Thus, degradation mechanisms need to be considered in the design of long-living composite parts.

A long lifespan combined with use in mechanically optimised parts introduces additional demands on reliability and safe operation. These factors can be addressed by design. Design strategies for safe life, fail-safe and damage tolerance ensure reliable performance, but come at the cost of lifespan (replacement at fixed time intervals), inefficient structural design (redundant load paths) or increased material use (by high safety margins), respectively [54]. Developments in design, engineering, and computation have reduced these safety margins, but especially older products may be over-dimensioned and still be in sound physical condition when rendered obsolete [9]. Thus, these design approaches ensure safe operation of the product, but may conflict with prolonging lifetime or minimising material usage. The gains of incorporating these strategies need to be carefully weighed in the design.

The physical condition of a product is not necessarily the driver for ending operational life. There are factors of a more contextual nature such as legislation or technological obsolescence that can end product use. Keeping the product in operations after its intended design lifetime requires additional certification and maintenance [8,55]. Technological obsolescence may challenge spare parts provision. Together, these factors decrease the economic incentive for continued operation [34].

Lifetime extension concerns all interventions taken during the product lifetime to prolong its use phase, for example through maintenance, repair, upgrades and adaptations [47]. Maintenance and repair depend on the type of damage and its occurrence, as well as damage growth in the material. Literature and experts noted opportunities for both thermosets as well as thermoplastic composites to be repaired on-site [9,59]. Many repair techniques and bond patches are available; application depends on considerations like time constraints, aesthetic and aerodynamic quality, as well as residual strength and restoration [58].

3.1.2. Lifetime Extension

The opportunities for lifetime extension depend on the product design as well as its operational context. Upgrades and adaptations can answer to changes in, e.g., user desires and legislation, which means time becomes an explicit factor in design [51]. Therefore, the use of roadmaps is recommended [3]. Use scenarios that are predefined in the design stage may also serve to estimate degradation and residual quality, and thereby lifetime extension potential at end-of-use [32]. In practice, lifetime extension is considered feasible for composite products, depending on the product state [34].

Product recovery aims to increase the number of use cycles through refurbishment and remanufacturing of products [5,51]. It also includes harvesting parts to reuse them as spares for lifetime extension measures [3]. Experts pointed out that these strategies are already applied to various composite products including car and aircraft parts, for example [7,9], but also to larger structures like wind turbine blades. For the latter, refurbished blades offer short lead times and choice from a range of models at a reduced cost compared to new models [9]. As with long life and lifetime extension strategies, assessment of the structural state of the material is crucial, yet challenging for composite materials [58].

3.1.3. Structural Reuse

Structural reuse was identified as a strategy to preserve material integrity. Structural reuse takes place through repurposing, resizing, or reshaping the product. These actions discard the original product function, but maintain the unique structural properties, determined by the combination of material composition and structural design [8]. Experts and the literature both note that the approach preserves material quality and value with a relatively small investment of energy and resources [8,9,61].

Applications of structural reuse were explored in occasional projects [8,9]. Large parts of wind turbine blades have been used to construct outdoor furniture and a playground. The building and construction industry could also reuse these recovered elements, but scalable applications have thus far been challenged by design and materials complexity [63]. It is expected that segmenting large parts into (standardised) construction elements like panels and beams will result in more diverse reuse opportunities [9].

3.1.4. Material Recycling

Material recycling options for composites are determined by the matrix material, while most value is found in retrieved fibres [64]. Thermoplastic matrix composites can be remoulded into new products, while thermoset reprocessing is usually based on polymer degradation and aimed at fibre recovery [57,64]. The experts stressed the inherent complexity of the materials: there are few standardised composite formulations, and often additional materials are used like core materials, adhesives, and metal inserts. Generic recycling problems apply for collection, identification, separation, and sorting of the material and contamination in the reprocessing stage [66].

Table 2 shows the framework of design aims, circular economy strategies and associated actions or processes. The design aims distinguish between preserving product and material integrity [4], and the strategies show the effect on the product or material lifetime. The actions and processes show which activities are involved. Adaptations to the initial Circular Product Design framework [36] are printed in bold. These changes pertain to the design aim of preserving material integrity. Structural reuse was added as additional strategy, positioned between product recovery and material recycling. In addition, the applicable processes for composite materials were added for both structural reuse and material recycling.

Table 2. Circular design strategies for composite products, additions for composite materials in bold.

Design Aim	Preserving Product Integrity			Preserving Material Integrity	
Circular Economy Strategies	Long Life	Lifetime Extension	Product Recovery	**Structural Reuse**	Material Recycling
Actions/Processes	Physical-durability Long use Reuse	Repair Maintenance Adapt Upgrade	Refurbishment Remanufacture Parts-harvesting	**Repurpose** **Resize** **Reshape**	**Remould** **Mechanical** **Thermal** **Chemical**

3.2. *Design Aspects Applicable to Composite Materials*

We identified 24 design aspects for products containing composite materials. To further structure the design aspects, we looked for patterns in the coded data. As evident in the co-occurrence analysis, the design aspects were strongly interconnected (in Appendix C); all design aspects related to one or more of the others and the number of connections varied per aspect. Mapping out the co-occurrences provided an initial clustering of four clusters.

We identified four themes: (cluster i) handling and rework, (cluster ii) product architecture, (cluster iii) product specifications and (cluster iv) product traceability. In Tables 3–6, the design aspects are listed per cluster with references to and a description from the literature, and the associated design guidelines for each aspect.

To support implementation in design practice, the four initial clusters were related to the design process at large. Table 7 shows the design aspects related to the stages of conceptual, embodiment and detail design, as described by Pahl et.al. [31]. This positioning makes the design aspects more accessible to design engineers by providing a starting point and a structure for applying them in the product development process.

3.2.1. Concept Design

Concept design is about exploring solutions in the first stages of the product development process. The related design aspects are further elaborated in cluster i, and mostly aim to facilitate handling and rework actions, such as "Design for Accessibility". Adaptability was mostly recognised by the experts as a way to make a product "suitable for different uses" by making multifunctional or evolving structures. Most rework includes some form of cleaning, gaining access (opening) to the product, and inspecting imminent malfunctions or already occurred faults, followed by interchanging parts. The users and service personnel involved benefit from a simple and ergonomic product design where ease of disassembly and reassembly is important. These conceptual design solutions set the stage for a further embodiment of the product.

3.2.2. Embodiment Design

Embodiment design entails engineering these initial solutions into the product architecture in cluster ii. Here, the designer constructs the product layout, how the product and its subassemblies are built and interconnected. The literature and experts often referred to modular approaches and careful selection of connections and keying features. Integrating functions and multiple components into a single optimised part is one of the main potential benefits of using composite materials. Experts recognised this as an opportunity to accumulate functions, and thereby mass into a single component, increasing its potential value for recycling. The level of integration has to be carefully considered based on the prospective product use cycles. Redundancy relates to the design strategies of "Safe life", "Fail safe" and "Damage tolerant". These design aspects construct a product architecture of which the part properties need to be further specified.

Embodiment design also includes defining the product specifications in cluster iii. This requires selection of the manufacturing process, surface treatments and materials, as well as structural design. Some products may require built-in redundancy or (additional) sacrificial elements. The experts mostly regarded material selection as a means to make the product more recyclable. For example, experts suggested "Creating materials with inherent aesthetic properties", to avoid coatings and thereby material contamination in the recycling process. With the specifications known, the design is ready to proceed to the final stage: detailing.

Table 3. Design aspects to facilitate handling and rework of products containing composites in a circular economy (cluster i).

Design Aspects [References]	Description from the Literature	Design Guidelines
Accessibility [3,31,36,45,51,52,56,60]	Ensuring (internal) parts and materials as well as their connections can be reached and/or removed easily, keeping them at maximum utility level, and facilitating separation and sorting.	Platform design Using a disassembly map Grouping parts and/or materials in modules Access from one side, using a single tool Connections/fasteners that are easily identifiable and removable
Adaptability [4,36,50,51,63]	Anticipating and enabling changes and adjustments to be made to the product during its (successive) use cycle(s).	Multifunctional design Facilitate DIY solutions/adaptations Versatile, customisable layout of the components; adaptable/changing the (surface) colour Transformable system, and reversible assembly
Cleanability [31,45,47,51,52]	Making products, parts, and surfaces so that they can be cleaned or prevent accumulation of dirt.	Smooth surfaces Accessible and demountable parts and modules, especially where dirt accumulates Use of the same cleaning method, and materials and surfaces withstanding the same chemicals
Ergonomics [29,31,36]	Ensuring the product can be used, maintained, reworked, and reprocessed in a safe and efficient way.	Dis- and reassembly as needed, with accessible component and connections
Fault isolation [3,29,31,36,45,52]	Enabling tracking an occurring fault to its cause, e.g., a worn component, for quick and easy repair.	Develop and promote repair diagnostics Making (approaching) failure noticeable for users or service inspections
Functional packaging [31,36,45,50,51]	Choosing packaging for the product and/or components to optimise transport and distribution.	Reducing packaging weight and volume, Improving stackability and handling Ensuring product/component protection
Interchangeability [3,36,45,52,63]	Making parts or subassemblies of the product readily replaceable or exchangeable.	Interfaces that allow exchange of parts Matching dimensions and functions of parts and replacements Standard, accessible and dismountable parts, modules, and connections
Malfunction signalling [36,45,52]	Indicating (imminent) product failure to facilitate inspection and subsequent actions.	Accessible parts Indicating elements, e.g., wearing strips Monitoring of components
Simplification [31,36,45,51]	Minimising the complexity of the product in terms of functionality, assembly, appearance, and materials composition.	Select the simplest design option available Reduce the number of material types, components, and assembly steps

Table 4. Design aspects to construct the product architecture of products containing composites in a circular economy (cluster ii).

Design Aspects [References]	Description from the Literature	Design Guidelines
Connection selection [3,7,8,45,48,50–52,60,63]	Selecting connections that can be accessed, opened, and reused where appropriate to facilitate use, rework, and recovery actions during product life.	Reversibility; e.g., screws, clips and several types of snapfits Recovery action, operator (e.g., user or service personnel), tool types (that need to be) available, Material compatibility and use resistance (e.g., wear and ageing)
Dis- and reassembly [3,5,7,29,31,36,45,50,51,56,60]	Facilitating manual or mechanical disassembly and reassembly of the product to enable reuse of parts to improve the recovery rate.	Using reversible connections (e.g., screws), and avoiding in-moulded inserts Mechanical assembly systems (e.g., form fits) Optimised and short component disassembly paths Use commonly available, standard, accessible tools, and connections.
Function integration [50]	Combining multiple functions and (sub)components into one part.	Integration of connectors with parts Combine structural design and other functions, e.g., aesthetic or aerodynamic
Keying [36,45]	Using product shape to facilitate alignment, e.g., holes and pins	Using pins, grooves, and other mating shapes for alignment and placing components
Modularity [3,4,7,8,29,36,45,50–52,60,63]	Grouping features within the product to create sub-assemblies that are accessible, removable, and interchangeable.	Match lifetime or maintenance intervals of components, Sort chemically similar materials, or isolate hazardous substances, Allow for (functional) customisation and adaptation
Redundancy [31,36,51]	Adding additional materials or functionality to ensure continued operation and safety, even when parts degrade or are (partially) removed.	Add materials on wearing areas Integrate multiple, redundant, load paths Add excess functionality
Sacrificial elements [36,50]	Defining replaceable components and surface treatments to take up wear and damage, thus protecting other parts.	Identify the areas subject to degradation Apply protective surface treatments Apply protective elements, e.g., covers

Table 5. Design aspects concerning product specifications of products containing composites in a circular economy (cluster iii).

Design Aspects [References]	Description from the Literature	Design Guidelines
Material selection [5,7,8,16,29,36,45,48,50–52,55–57,60]	Selecting matrix, reinforcement, connections, and other materials to perform optimally for the use phase, as well as recovery stage of the product. For composites, this includes the type and orientation of reinforcements.	Consider reprocessing compatibility, by, e.g., using chemically similar matrix and reinforcement (self-reinforced composites), avoiding mix of biological and technological materials Using recycled and recyclable materials, thermoplastic or reversible thermoset matrices and short fibres, and limit the number of materials used within an assembly to promote recyclability Reconsider hazardous chemicals, effect of ageing (e.g., discolouring and loss of quality) Selection to cope with hostile conditions, to prolong lifetime
Manufacturing process selection [7,8,48,50,52,55]	Selecting and optimising the process to minimise emissions and meet the material, functional, shape and recovery criteria.	Optimise fibre architecture. Automate manufacturing for consistency Reduce waste and emissions of manufacturing process; consumables (foils, tapes, etc.) and material offcuts, especially when impregnated with resin Allow recycled content uptake
Structural design [7,8,29,31,51]	Optimising the material structure, shape, and product architecture to achieve the desired structural performance.	Use form stiffness and load bearing shapes Integrate form and material placement to meet load cases Consider reusable structural elements
Surface treatments [3,7–9,16,31,36,48,51,60]	Selecting coatings and other surface treatments appropriate for the use, reuse and reprocessing of the product and its materials.	Protective gelcoats, paints, tapes, foils, or other treatments to prevent material degradation by UV radiation, moisture, or erosion Use non-hazardous substances to support rework and reprocessing Ensure materials including surface treatments compatibility in the recycling process

Table 6. Design aspects to facilitate traceability of products containing composites in a circular economy (cluster iv).

Design Aspects [References]	Description from the Literature	Design Guidelines
Documentation [7–9,29,31,50,52,56,62,63]	Providing information about the product, components, and functions to stakeholders in the value chain and actors in the product and component lifecycle.	Identify which information the actors need, and how, e.g., Design specifications, e.g., dimensions, assembly, part id's, material composition Service manuals and repair tutorials Certification and standards Material passports
Identification [7–9,29,31,36,45,52]	Using labels, tags etc. to facilitate recognition of the product, parts, materials and/or its specifications.	Labelling products and components Defining material characteristics for separation processes (i.e., IR scanning, density) Placing material markings on parts Mixing in markers into the materials
Monitoring [8,51,52]	Determining and logging of product properties and use conditions over the product lifetime.	Regular inspection intervals Embedded monitoring devices Sample or coupon testing (e.g., fatigue, strength) of used components Internet of Things solutions Digital measurement and identification systems
Standardisation [3,5,8,9,29,31,36,45,50–52,56,62,63]	Using well-known, defined, and widely used components, processes, dimensions, materials, etc., in the product design, or developing a standard layout for the product(range). This design aspect relates, but is not restricted to, industry standardisation.	Standardisation comes in many forms, e.g., Components (connections, bearings, etc.) Construction codes Dimensional tolerances Certification and inspection procedures Standard layout across product (range) Basic or standard available tools

Table 7. Design aspects for products containing composite materials in a circular economy, clustered and related to the stages in the product development process [31].

Concept Design	Embodiment Design		Detail Design
Cluster i: Handling and Rework	**Cluster ii: Product Architecture**	**Cluster iii: Product Specifications**	**Cluster iv: Traceability**
Accessibility Adaptability Cleanability Ergonomics Fault isolation Functional packaging Interchangeability Malfunction signalling Simplification	Connection selection Dis- and reassembly Modularity Keying Function Integration Redundancy Sacrificial elements	Material selection Structural design Manufacturing process Surface treatments	Documentation Identification Monitoring Standardisation

3.2.3. Detail Design

The detail design stage includes design aspects that facilitate tracing back product information in cluster iv. To facilitate recovery, the product has to be identifiable, and its initial specifications should be laid down in appropriate documentation. Documentation of the product specifications and instructions—and making these available to the designated stakeholders—serves to solve the information gap that hampers many actual recovery processes. For example, experts also suggested "attaching information to the product" to inform the user on return options, stimulating and supporting collection at end of use. Literature and experts both proposed standardisation of components, materials, and assembly systems to facilitate processing. Standardisation of tests and certification procedures, as well as monitoring actions also support assessing the current product state. Monitoring can serve to extend knowledge on the original product characteristics to the state at end-of-use. These design aspects support the availability of product information, which is key for efficient recovery actions and effective value retrieval.

4. Discussion

4.1. Circular Product Design Framework for Composites

Both the circular strategies and design aspects showed distinct features for composites. To arrive at a framework suitable for products containing composite materials, we adapted Den Hollander's Circular Product Design framework [36]. Table 8 shows the Circular Product Design framework connecting circular economy strategies to design aspects. Compared to the original Circular Product Design framework, the following adaptions were made:

- Structural recycling is added as an intermediate strategy between product recovery and material recycling, preserving part of a product's functional value [8,9,34,61–63].
- Seven design aspects were added, notably (1) Manufacturing process selection, (2) Structural design, (3) Connection selection (4) Documentation, (5) Monitoring, (6) Cleanability and (7) Function integration.
- One design aspect was omitted: Animacy, as the functional applications do not call for making the product behave as if it were alive.

The study collected perspectives from industry and academia through respectively focus group sessions and a literature review. The Circular Product Design framework brings these perspectives together and shows, as can be expected, considerable overlap in the findings from the literature and expert consultations, although we found more conceptual solutions in the literature. This may indicate that the focus of experts primarily lies on the technological aspects of embodiment and detail design, whereas the literature tends to explore new directions.

Table 8. Circular Product Design framework for composites in a circular economy, connections between circular strategies and design aspects indicated with filled cells.

Design Aim	**Product Integrity**			**Material Integrity**	
Circular Strategy	**Long Life**	**Lifetime Extension**	**Product Recovery**	**Structural Reuse**	**Material Recycling**
Design aspects					
Concept design					
Accessibility		■	■		■
Adaptability	■	■	■	■	
Cleanability		■	■		■
Dis- and reassembly	■	■	■	■	■
Ergonomics		■	■		
Fault isolation		■	■		■
Functional packaging		■	■		■
Interchangeability		■	■	■	■
Malfunction signaling	■	■	■		
Simplification	■	■	■		■
Embodiment					
Connection selection	■	■	■	■	■
Function integration	■	■			■
Keying		■	■		
Material selection	■	■	■	■	■
Manufacturing		■	■		■
Modularity		■	■	■	■
Redundancy	■	■	■		
Sacrificial elements		■	■		
Structural design	■	■	■	■	■
Surface treatment selection	■	■	■		■
Detail design					
Documentation		■	■	■	■
Identification		■	■	■	■
Monitoring	■	■	■		
Standardisation		■	■	■	■

Concerning the strategies, most design aspects were identified for lifetime extension and product recovery. Fewer design aspects were found for material recycling, while structural reuse was only encountered incidentally. Structural reuse as a recovery pathway has been a topic of discussion in the field of composite materials, but is generally not addressed in circular product design literature.

Seven design aspects were added to address the specific characteristics of composite materials. Composites clearly distinguish themselves from other bulk processing materials in the way they integrate internal and external product properties. Internal properties such as material selection are defined by the designer, to create external properties that the user observes, such as product function and performance [41,67]. Composite material properties can be tailored, even locally, to achieve the desired external properties, which provides opportunities for function integration within a single component. Moreover, the material, and thereby its exact properties, is created at the same time as the product itself, and as such is highly subject to manufacturing process conditions. Thus, the material formulation is an integral part of the design and production process. Therefore, function integration, structural design, and manufacturing process selection were added to the framework.

Determining the residual quality of composite materials can be challenging as defects are not always observable from the product's surface. To support quality assessments and reprocessing, documentation and monitoring were added to the Circular Product Design framework. Documentation, such as product or material passports, is often seen as enabler for many recovery pathways and servicing activities [38]. A greater understanding of material behaviour over time, in relation to factors like load history, environmental exposure and impact damage remains a topic of ongoing research [68,69].

4.2. Connections within the Circular Product Design Framework

The Circular Product Design framework shows that many design aspects are related to multiple strategies, and that the circular strategies have many design aspects in common. For implementation, this has several consequences which have also been observed in other design frameworks [36,52,54]. The circular strategies of lifetime extension and product recovery largely connect to the same aspects, indicating that these strategies are, to a large extent, similar from a design perspective. Long life and recycling, however, pose very different demands, which is reflected in the more distinct set of design aspects they connect to.

The design aspects themselves cannot be regarded as stand-alone factors in product design. Addressing a particular design aspect is likely to affect multiple strategies. This might lead to tensions regarding the appropriate design intervention, as a specific embodiment of a design aspect might be simultaneously positive for one strategy but negative for another. For example, surface treatments may enable a long product life, but they may contaminate a recycling process. The Circular Product Design framework (Table 8) provides an overview of potential tensions, and thus raises awareness concerning the effect of design decisions on their realisation of circular strategies that can be taken into account during the early stages of product development. In addition to the tensions between strategies, there are various connections and interdependencies between design aspects.

The design aspects were strongly interconnected. There are different reasons for these connections, which have also been encountered in earlier studies [36,52]. First, some design aspects are obvious and therefore often-mentioned when discussing product design or recovery aims. For example, material selection is often connected to identification and standardisation to improve recyclate quality. Second, both the literature and experts build on each others' insights, resulting in a subset of design aspects often noted in conjunction. Third, there are many well-known relations and interdependencies between design aspects which makes it logical to discuss them together. For example, modularity is often discussed in relation to dis- and reassembly [7,29,31]. These connections need to be addressed in the product design process. Thus, the designer has to account for connections and interdependencies between design aspects which are made explicit in the Circular Product Design framework (Table 8) and co-occurrence mapping (in Appendix C).

4.3. Limitations and Recommendations

The aim of this study was to provide an overview of circular strategies and design aspects for composite products in a Circular Economy. The results of this study are quite generic due to the width of the initial scope. However, the constructed framework has demonstrated its use in practice. A preliminary version of the framework [6] has successfully been used in product development [22], analysis of design case studies [70] and for standard development through a CEN Workshop Agreement [71]. Thus, the Circular Product Design framework for composite products is a first step in designing products containing composite materials for a circular economy. However, the framework could be further refined and expanded. The strategy of structural reuse should be further investigated, exploring its potential across different industry sectors and product types. The set of design aspects should be further expanded by investigating additional case studies. Building on this, the collected design aspects and design guidelines could then form the foundation of a design catalogue. Implementation of the framework in the product development process has to be further detailed. Further research, building on design studies with composite products, will be carried out to validate and build the framework.

The presented strategies focus on prolonging product lifetime and preserving resources, but do not explicitly account for safety issues involved with composite materials. Risks are found across the composite product life and include the release of volatile organic compounds, fibres and particles and dust [72,73]. All of these pose a threat to human health and the environment. Zappeloni [73] discusses best practices to minimise such emissions in the manufacturing stage, and Medici expressed concerns over long-term outdoor exposure [74]. Additionally, (re)processing, which aims to separate, or at least downsize the materials, risks hazardous emissions [7,72,75]. Thus, next to preserving resources, additional measures are needed to address human, environmental and ecological impacts of manufacturing, using and reprocessing composite materials.

Contamination of the materials in the recycling stage remains a challenge. Undesired mixing hampers reprocessing as most processes benefit from or even rely on a well-defined material input in order to deliver a good quality recyclate. For reuse, mixing of different material types should be avoided to prevent further complicating the material composition for future recovery. Solutions to prevent or cope with material contamination are developed in materials [7,76,77] and reprocessing technology [11] and should be addressed in the product design [7,29]. All of these relate to the development of a market for recycled composite materials. Appropriate and scalable reuse applications are needed to assign value to the recyclate and as such provide an economic rationale for recovery [66,76].

5. Conclusions

Composite materials offer great opportunities for product development and high performance in use, but their position in a circular economy system remains challenging. The increased use and proportional increasing volume of end-of-life material have led to increased attention from governments, industry and academia.

This paper set out to explore how products containing composite materials can be designed to close resource loops in a circular economy. An initial literature exploration showed that limited information was available, therefore we conducted a literature review and consulted experts to collect insights on the design and recovery of composite products. Experts were involved, as the industry perspective is vital to identify challenges and solutions that are feasible in design practice. These insights are brought together in an adapted Circular Product Design framework for Composites. The circular economy strategies are largely similar to reported strategies as far as product integrity is involved. However, recovery pathways focusing on material integrity show some distinct opportunities for composite reuse, in particular, structural reuse. The strategy, positioned between product recovery and material recycling, has the potential to preserve composite material value at a relatively low cost. Moreover, the characteristics of composite materials cannot be regarded without reference to their structural shape. Structural reuse retains the material composition and structure, yet relieves it from its initial function, making the material available for reuse and repurposing in other applications.

We identified 24 design aspects for products containing composites the majority of which aligned with earlier Circular Product Design frameworks. Because composite materials differ from bulk materials in the way they are processed and created, seven additional design aspects were added to the framework. Most notable of these are structural design and function integration. Both these design aspects build on the potential of composite materials to integrate form and functionality to achieve optimal performance, in the first, as well as in subsequent use phases.

The identified strategies and design aspects are highly interconnected, which signals that designers need a clear overview of the product design as well as its planned use cycles, and the stakeholders involved. Circularity adds requirements to an already complex task of composite product design and material engineering. The Circular Product Design framework for composites aims to support designers and researchers to create an overview and to integrate circular design measures into products containing composite materials. Further studies could expand on and detail the framework by analysing cases, and through implementation in new product development. As such, the framework is considered a first step towards providing insights into available circular strategies and design aspects and their interrelations, to support designers developing new composite products for a circular economy.

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Institutional Review Board Statement: Ethical review and approval were waived for this study, as all activities in the Ecobulk project comply to ethical and research integrity principles, stated and undersigned by all participants in the Ecobulk grant agreement.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

The main topic was divided into three key concepts: circular economy, design, and composite materials. Literature was sought in pairs of these key concepts in Web of Science and Scopus. To ensure full coverage we used wildcards (*), and a proximity criterion of 5 words (W/5) to account for co-occurrence of search terms in a single sentence. The set was refined by excluding out of scope topics and narrowing down the composites and design set using recovery pathways in relation to design. The selection was expanded by snowballing.

Table A1. Literature search, refining and selection for first search field.

Circular Economy and Design	
Query	(TITLE-ABS-KEY (*"circular economy"* OR *"circular product design"*) AND TITLE-ABS-KEY((*design* W/5 (*method* OR *guideline* OR *strategy* OR *principle*)))
Refine	AND NOT TITLE-ABS-KEY (*"additive manufacturing"*) AND NOT TITLE-ABS-KEY (*biobased*) AND NOT TITLE-ABS-KEY (*"consumer perception"*))
Select	Read titles & abstracts
Result	[5,45–47,50,52,56,60,63]

Table A2. Literature search, refining and selection for second search field.

Circular economy and Composite Materials	
Query	(TITLE-ABS-KEY (*"circular economy"* OR *"circular product design"*) AND TITLE-ABS-KEY (*"composite material*"* OR ((*"fibre reinforced"* OR *"fiber reinforced"*) AND (*polymer* OR *plastic*)))
Refine	AND NOT TITLE-ABS-KEY (*"additive manufacturing"*) AND NOT TITLE-ABS-KEY (*biobased*) AND NOT TITLE-ABS-KEY (*"consumer perception"*))
Select	Read titles & abstracts
Result	[7,8,12,13,16,29,32,48,49,57,62,65,67,78]

Table A3. Literature search, refining and selection for third search field.

	Composite Materials and Design
Query	TITLE-ABS-KEY (*"composite material*"* OR ((*"fibre reinforced"* OR *"fiber reinforced"*) AND (*polymer* OR *plastic*))) AND TITLE-ABS-KEY ((*design* W/5 (*method* OR *guideline* OR *strategy* OR *principle*)))
Refine	AND NOT TITLE-ABS-KEY (*"additive manufacturing"*) AND NOT TITLE-ABS-KEY (*biobased* OR biopolymer) AND NOT TITLE-ABS-KEY (*"consumer perception"*))
Select	Design W/5 recycling
	design W/5 "structur* reuse"
	design W/5 (*"product recovery"* OR *remanufactur** OR *refurbish** OR *"parts harvest*"*))
	design W/5 repair*
	design W/5 upgrade
	design W/5 *maintenance*
	design W/5 adapt
	design W/5 (*durability* OR *durable* OR *"long use"* OR *"long life"* OR *reuse*)))
Select	Read titles & abstracts
Result	[29,32,54,58,79,80]

Table A4. Expanding literature set through snowballing; resulting publications.

Sources	Refer to
[3,8,12,29,45,46,65]	[4,9,34,36,51,61,64,81]

Appendix B

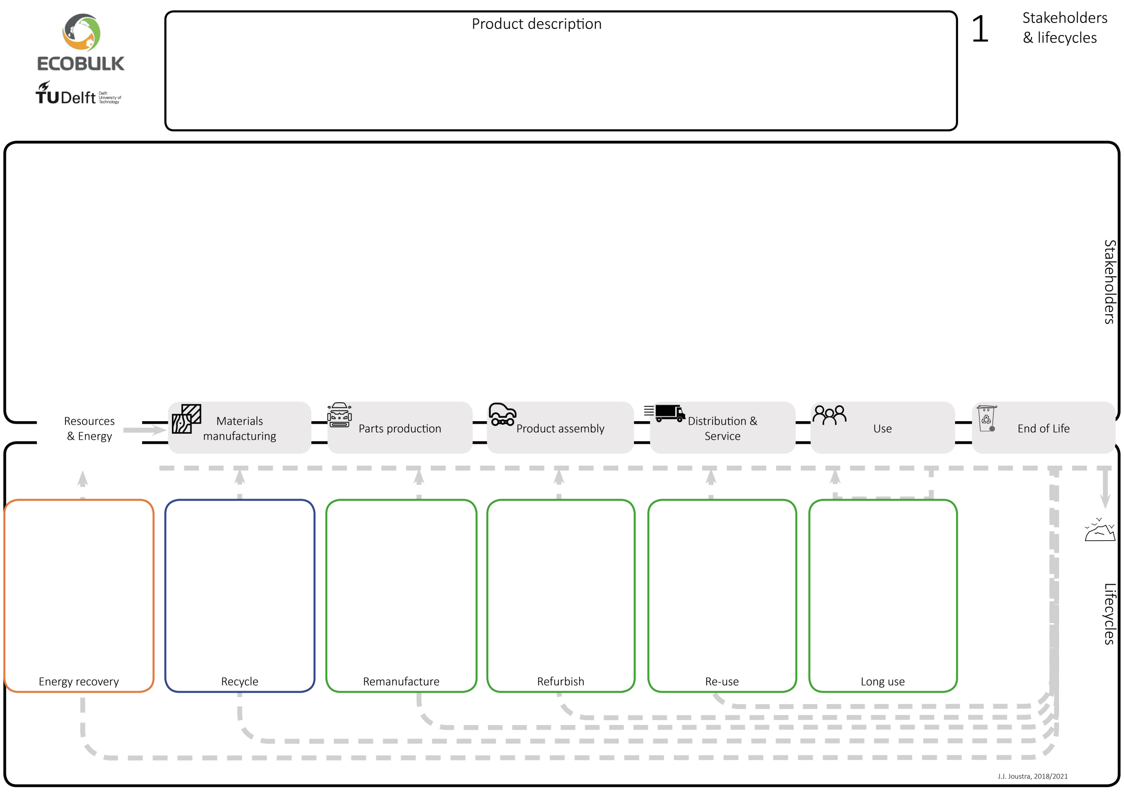

Figure A1. Lifecycle worksheet used during the focus group sessions. The participants added stakeholders, resources, and recovery actions The moderator used the worksheet to guide the discussion, by asking questions on which products, parts or materials would be recovered, and which stakeholders would be involved.

Figure A2. Design for recovery exploration worksheet used in the focus group sessions. The participants added intended recovery actions and processes, which led to finding challenges for recovery of the case product. The moderator asked questions to clarify the recovery case and intervened when the discussion went off-topic. Finally, the layout guided the discussion towards generating design solutions that would facilitate recovery.

Appendix C

Table A5. Co-occurrence table of coded design aspects for products containing composites in a circular economy.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	Accessibility	0	6	2	4	26	0	7	9	0	8	9	11	7	8	0	13	13	0	6	3	10	10	0	6
2	Adaptability	6	0	0	0	7	0	6	6	1	6	6	7	6	6	0	6	9	0	6	3	6	8	0	7
3	Cleanability	2	0	0	2	5	0	0	1	0	2	3	0	1	1	0	3	1	0	0	0	0	0	0	0
4	Connection selection	4	0	2	0	34	2	1	2	0	2	2	0	0	0	0	13	5	1	0	0	2	6	2	1
5	Dis & reassembly	26	7	5	34	0	2	9	9	0	8	12	9	7	6	0	21	22	0	6	3	9	12	4	7
6	Documentation	0	0	0	2	2	0	0	1	0	1	5	0	0	1	0	7	3	0	0	0	1	6	3	0
7	Ergonomics	7	6	0	1	9	0	0	7	0	6	7	6	6	7	0	7	6	0	6	3	6	6	0	6
8	Fault isolation	9	6	1	2	9	1	7	0	0	8	8	8	6	8	0	7	9	1	7	3	7	9	1	6
9	Function integration	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
10	Functional packaging	8	6	2	2	8	1	6	8	0	0	10	7	7	8	0	8	8	0	6	3	7	8	1	6
11	Identification	9	6	3	2	12	5	7	8	0	10	0	7	7	8	0	19	10	1	6	4	7	9	2	6
12	Interchangeability	11	7	0	0	9	0	6	8	0	7	7	0	6	7	0	7	12	0	6	3	8	10	0	6
13	Keying	7	6	1	0	7	0	6	6	0	7	7	6	0	7	0	7	7	0	6	3	6	6	0	6
14	Malfunction signalling	8	6	1	0	6	1	7	8	0	8	8	7	7	0	0	7	7	0	6	3	6	7	0	6
15	Manufacturing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	2	1
16	Material selection	13	6	3	13	21	7	7	7	2	8	19	7	7	7	5	0	15	0	7	3	9	13	8	15
17	Modularity	13	9	1	5	22	3	6	9	0	8	10	12	7	7	0	15	0	1	6	3	8	15	3	6
18	Monitoring	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0
19	Redundancy	6	6	0	0	6	0	6	7	0	6	6	6	6	6	0	7	6	1	0	3	7	6	1	7
20	Sacrificial elements	3	3	0	0	3	0	3	3	0	3	4	3	3	3	0	3	3	0	3	0	3	3	1	3
21	Simplification	10	6	0	2	9	1	6	7	0	7	7	8	6	6	0	9	8	0	7	3	0	10	1	7
22	Standardisation	10	8	0	6	12	6	6	9	0	8	9	10	6	7	0	13	15	0	6	3	10	0	2	7
23	Structural design	0	0	0	2	4	3	0	1	0	1	2	0	0	0	2	8	3	0	1	1	1	2	0	1
24	Surface treatment selection	6	7	0	1	7	0	6	6	0	6	6	6	6	6	1	15	6	0	7	3	7	7	1	0

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