Circular Composites

Design strategies for products containing composite materials in a circular economy

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DOI
10.4233/uuid:ab19c21b-692a-4dd2-9d78-d62ce447cb4f

Publication date
2022

Document Version
Final published version

Citation (APA)
Joustra, J. J. (2022). *Circular Composites: Design strategies for products containing composite materials in a circular economy*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:ab19c21b-692a-4dd2-9d78-d62ce447cb4f

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TU Delft

Circular composites

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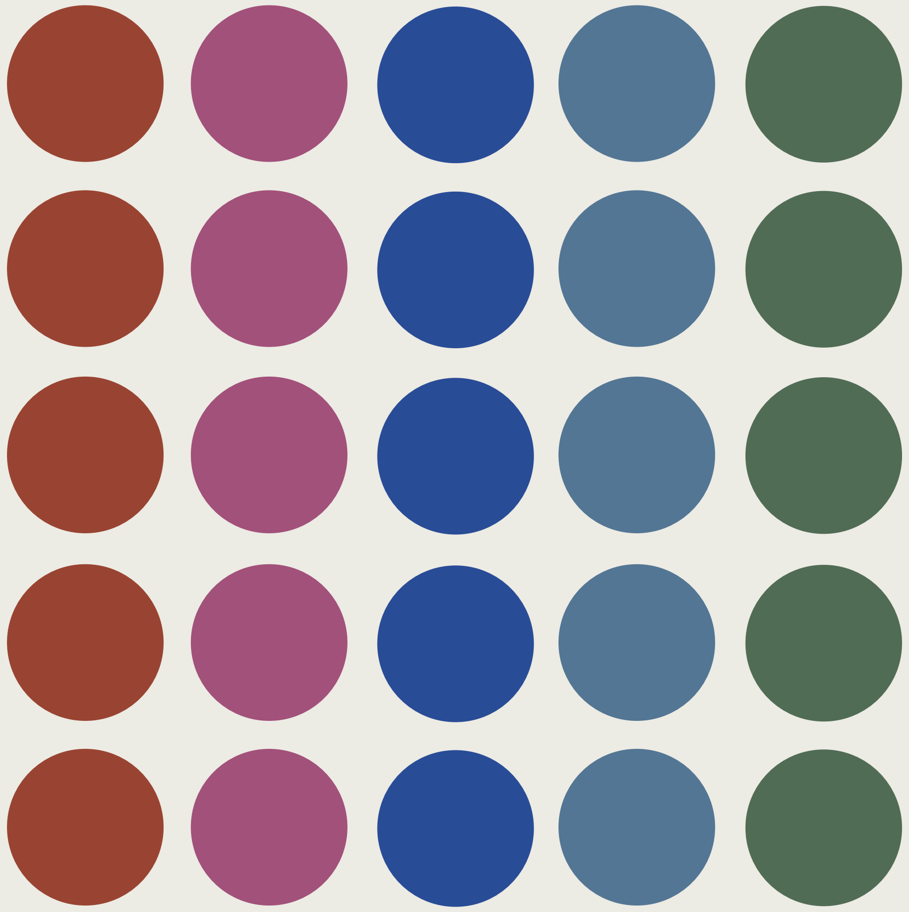

Jelle Joustra

Uitnodiging

Voor het bijwonen van de
openbare verdediging van
mijn proefschrift

Circular composites

Design strategies for products
containing composite materials
in a circular economy

Op maandag 31 oktober 2022
Inleidende presentatie
om 14:30

Verdediging om 15:00
In de Senaatszaal van
de Aula van de Technische
Universiteit Delft

Aansluitend een receptie
ter plaatse

Jelle Joustra

Paranimfen:
Nynke Joustra
Nina Boorsma

CIRCULAR COMPOSITES

Design strategies for products containing composite materials in a circular economy

Dissertation

For the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the rector magnificus Prof. dr. ir. T.H.J.J. van der Hagen
chair of the board for doctorates
To be defended publicly on
Monday 31 October 2022 at 15:00 o'clock

by

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The research was carried out as part of project Ecobulk, a large scale demonstration effort for composite products in a Circular Economy. This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 730456.

ISBN: 978-94-6384-373-7
Cover and Layout: Jelle Joustra, Riel Bessai, Gildeprint
Published by: TU Delft

To Sverre Teije

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Samenvatting / Summary

Samenvatting

In dit proefschrift onderzoek ik hoe producten met composietmaterialen te ontwerpen voor een circulaire economie. De circulaire economie is een mogelijke oplossing om duurzaam gebruik van grondstoffen te realiseren. Hergebruik van producten en materialen verlaagt de druk op grondstofvoorraden, bespaart energie en vermindert de opeenstapeling van afval. Dit vraagt een nieuwe kijk op productontwerpen. Producten moeten worden ontworpen worden voor lange levensduur, hergebruik en recycling. Composietmaterialen komen deels tegemoet aan deze vereisten; ze bieden de mogelijkheden voor efficiënt materiaalgebruik en een lange levensduur. Maar aan de andere kant zijn er nog uitdagingen rondom hergebruik en recycling.

Het hoofddoel van dit proefschrift is daarom om een methode te ontwikkelen en te demonstreren om te ontwerpen voor hergebruik en recycling van producten met composietmaterialen in een circulaire economie. In het kort: ontwikkeling van een “Circulaire Composieten ontwerpmethode”. Daarvoor heb ik gebruik gemaakt van literatuur, interviews en design case studies. De eerste twee hoofdstukken van dit proefschrift behandelen de ontwikkeling en validatie van de Circulaire Composieten ontwerpmethode, de volgende twee hoofdstukken betreffen “structureel hergebruik”, een circulaire strategie die met name interessant is voor composietproducten.

Binnen circulair productontwerpen onderscheiden we circulaire strategieën en ontwerpaspecten. De circulaire strategieën beschrijven hergebruikactiviteiten, bijvoorbeeld door onderdelen terug te nemen of materialen te recyclen, en relateren aan businessmodellen. De ontwerpaspecten bieden de ontwerper handvatten om deze strategieën te realiseren door middel van productontwerp. Zo kan recycling bijvoorbeeld worden gefaciliteerd door bepaalde keuzes op het gebied van materialen en verbindingen. Literatuur en interviews met experts uit de composietenindustrie leverden een eerste selectie van circulaire strategieën en ontwerpaspecten welke toepasbaar zijn op producten met composietmaterialen. Deze zijn verder aangevuld met inzichten uit ontwerp casestudies.

In totaal identificeerden we 5 circulaire strategieën en 26 ontwerp aspecten. Daarvan zijn er 1 strategie en 9 ontwerp aspecten nieuw en in het bijzonder relevant voor producten met composietmaterialen. De strategie van structureel hergebruik richt zich op behoud van de structurele integriteit, een bepalende factor in de materiaaleigenschappen van een composiet.

De ontwerpaspecten richtten zich met name op de materialisatie en integratie mogelijkheden die (productie met) composietmateriaal te bieden heeft. Zo bieden bijvoorbeeld functie-integratie en ingebedde markeringen kansen voor effectief hergebruik. De strategieën en aspecten zijn met elkaar verbonden in een kader zodat in een oogopslag duidelijk wordt welke aspecten relevant zijn voor een bepaalde strategie. Dit kader vormt een belangrijk onderdeel van de ontwerpmethode welke we toetsen in hoofdstuk 3.

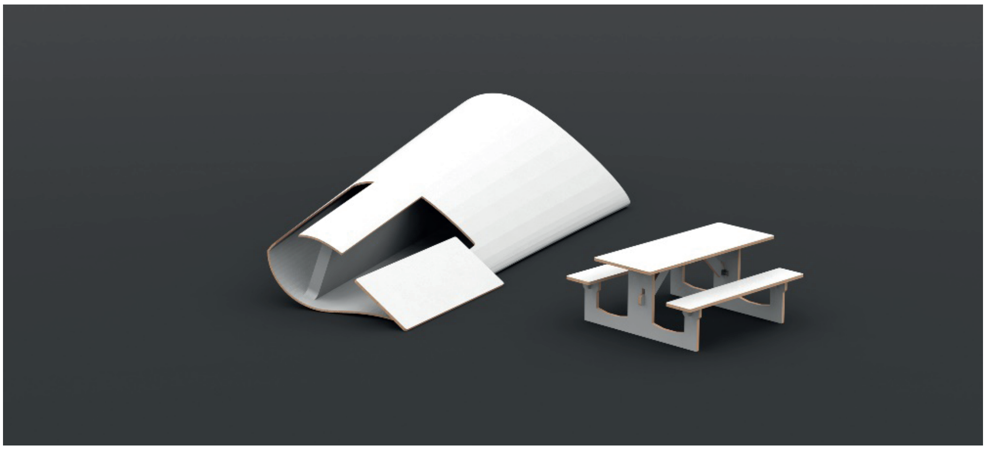
De Circulaire Composieten ontwerp methode ondersteunt ontwerpers in het verkennen, genereren en communiceren van ontwerpoplossingen. De methode bouwt voort op de literatuur, aangevuld met ervaring uit de ontwerppraktijk. De methode bestaat uit een product levenscyclusanalyse en het circulair ontwerp kader. Met een levenscyclusanalysewerkblad wordt de levensloop van het product uitgetekend, bij voorkeur betrekt de ontwerper andere betrokken partijen uit de waardeketen hierbij. Tezamen verkent men de mogelijkheden voor hergebruik van producten, onderdelen en materialen. Aan de hand van dit overzicht worden circulaire strategie(-ën) gekozen. Het kader geeft vervolgens aanwijzingen voor realisatie in het ontwerp. De methode is effectief, toegankelijk en goed bruikbaar bevonden na validatie in vijf ontwerp casestudies in de composietenindustrie.

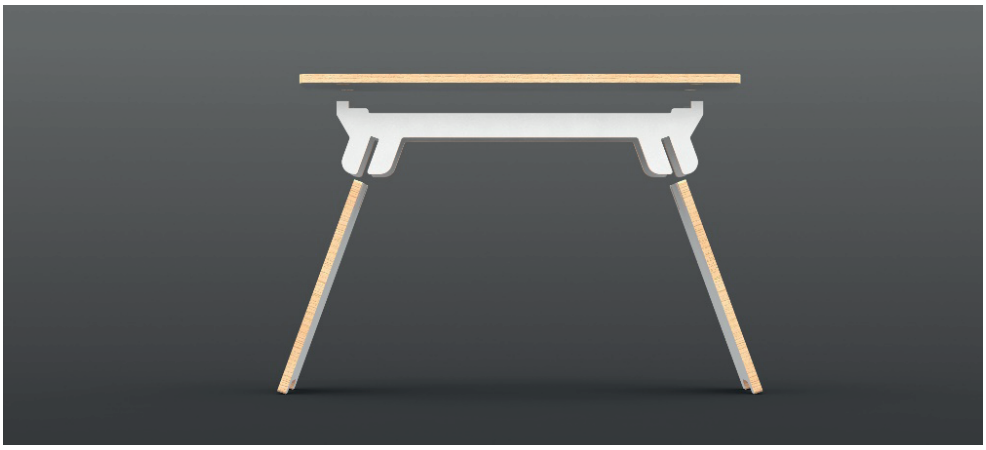
De circulaire strategie structureel hergebruik biedt extra kansen voor producten met composietmaterialen. Met deze strategie wordt een composietproduct in herbruikbare segmenten opgedeeld. Hiermee blijft de structurele integriteit behouden, terwijl het mogelijkheden opent voor hergebruik in uiteenlopende toepassingen. We hebben de haalbaarheid aangetoond met een ontwerp case studie op een windturbineblad. Met de ontwikkelde segmentatiemethode is circa 55% (in gewicht) van een blad herbruikbaar als paneel of balksegment. Die segmenten presteren beter op sterkte en stijfheid per gewicht dan conventionele bouwmaterialen en bovendien zijn er slechts kleine ontwerpaanpassingen nodig om het hergebruik in praktijk te optimaliseren. Daarom is structureel hergebruik een uitgelezen kans om deze hoogwaardige composietmaterialen in gebruik te houden in plaats van ze te vernietigen in laagwaardige verwerkingsprocessen.

De ontwerpmethode en circulaire strategie dragen bij aan zowel de kennisontwikkeling als de ontwerppraktijk in het gebied van circulaire economie, composietmaterialen en productontwerp. De wetenschappelijke bijdrage van dit proefschrift kenmerkt zich met name door overwegingen inzake circulaire economie te verbinden aan ontwerpen met composieten. Dit is gedaan door ontwikkeling van een typologie van strategieën waarin structureel hergebruik is toegevoegd aan het discours over hergebruik van deze materialen en producten. De fundering van circulaire productontwerpkennis is versterkt door verbindingen te leggen tussen ontwerp-aspecten en circulaire strategieën. Het resulterende kader kan bovendien worden gebruikt voor verdere analyse van ontwerp casestudies.

De bijdrage aan en implicaties voor de ontwerppraktijk betreffen met name de positionering van structureel hergebruik als ontwerpstrategie en ondersteuning voor ontwerpers. Met structureel hergebruik als ontwerpstrategie verbreden we de toepassing van incidenteel naar seriematig hergebruik en waarde behoud. De ontwikkelde Circulaire Composieten ontwerpmethode ondersteunt ontwerpers in het ontwikkelen van producten met composietmaterialen voor een circulaire economie. De methode is gebundeld in de Circular Composites Design Guide. Dit boek, gepubliceerd en vrij toegankelijk, beschrijft de Circulaire Composieten ontwerpmethode en geeft voorbeelden aan de hand van de ontwikkelde case studies. Daarnaast heb ik met dit onderzoek bewustzijn gecreëerd via academische, professionele en publieke kanalen. Dit leidde tot vele reacties en erkenning van de mogelijkheden en uitdagingen die deze materialen bieden om producten te ontwerpen voor een circulaire economie.

Selection of developed prototypes





Summary

In this dissertation, I investigate how to design products for a circular economy using composite materials. The circular economy is a potential solution to achieving a sustainable use of resources. Reuse of products and recycling materials lowers pressure on resource stocks, saves energy, and reduces the accumulation of waste. This requires a new approach to product design. Products have to be designed for long life, reuse and recycling. Composite materials partly meet these requirements; they offer the potential for efficient material use and have a long product lifespan. However, there are still challenges considering their reuse and recycling.

The main objective of this dissertation is therefore to develop and demonstrate a method to design for reuse and recycling of products containing composite materials in a circular economy. In short: the development of a 'Circular Composites design method'. For this I reviewed the literature, held interviews and developed design case studies. The first two chapters deal with the development and validation of the Circular Composites design method, the following two are about “Structural reuse”, a circular strategy specifically interesting for products containing composite materials.

In circular product design we distinguish between circular strategies and design aspects. The circular strategies describe reuse activities, for instance product recovery or recycling materials, and relate them to business models. The design aspects offer the designer handles to realise these strategies through product design. For example, recycling can be facilitated by certain choices in materials and connections. The literature review and interviews with experts from the composites industry provided an initial selection of circular strategies and design aspects applicable to products with composite materials. These were further supplemented with insights from design case studies.

In total we identified 5 circular strategies and 26 design aspects. Of these, 1 strategy and 9 design aspects are new and particularly relevant to products with composite materials. The strategy of structural reuse focuses on maintaining structural integrity, a determining factor in the material properties of a composite. The design aspects focus mainly on the materialisation and integration possibilities that (production with) composite material can offer. For example, function integration and embedded markings offer opportunities for effective reuse. The strategies and

aspects are linked in a framework, showing which aspects are relevant to a particular strategy. This framework is an important part of the design method and is presented and reviewed in Chapter 3.

The Circular Composites design method supports designers in exploring, generating, and communicating design solutions. The method builds on the literature, supplemented with experience from design practice. The method consists of a product life cycle analysis and the circular product design framework. The designer uses a product lifecycle analysis worksheet to map material flows, stakeholders, and activities, preferably involving other parties in the value chain. Together they explore the possibilities for reuse of products, parts and materials. On the basis of this overview circular strategy(s) are chosen. The framework then provides suggestions for implementing these strategies in the design. The method was considered effective, accessible, and usable after validation in five design case studies in the composites industry.

The circular strategy of structural reuse offers additional opportunities for products with composite materials. Using this strategy, the product can be divided into reusable segments. This preserves the structural integrity, while opening up opportunities for reuse in various applications. We demonstrate the feasibility with a design case study on a wind turbine blade in Chapter 4. With the segmentation method developed in Chapter 5, approximately 55% (by weight) of a blade is reusable as panel or beam segments. These segments perform better on strength and stiffness per weight than conventional building materials and, moreover, only need small design adjustments to optimise reuse in practice. Therefore, structural reuse is an excellent opportunity to keep these high-quality composite materials in use instead of destroying them in low-grade reprocessing.

The Circular Composites design method and structural reuse strategy contribute to both knowledge development and design practice in the field of circular economy, composite materials and product design. This thesis's scientific contribution is characterised in particular by linking considerations of circular economy to designing with composites. This was achieved by developing a typology of strategies in which structural reuse was added to the discourse on reuse of these materials and products. The grounding of circular product design knowledge has been strengthened by identifying connections between design aspects and circular strategies. Moreover, the resulting framework can be used for further analysis of design case studies.

The contribution to and implications for design practice concern in particular the positioning of structural reuse as a design strategy and support for designers. With structural reuse as a design strategy, we broaden the application from incidental to serial reuse and value retention. The Circular Composites design method supports designers when using composite materials to create products for a circular economy. The method is bundled in the Circular Composites Design Guide. This book has been published and is freely available. It describes the Circular Composites design method and gives examples based on the case studies. In addition, I have created awareness through academic, professional and public channels. This has led to many responses and recognition of the opportunities and challenges composite materials offer when designing products for a circular economy.

Chapter 1

Introduction

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1. Introduction

Composites are fascinating materials. They combine two or more materials to attain properties that cannot be achieved by any of the constituents alone [1]. The material combinations can be tailored, which leads to unprecedented properties and opens new perspectives on product design [2]. Most notably, composites enable efficient material use for creating lightweight and long-lasting products. These materials currently are used extensively in numerous fields and their annual market volumes keep increasing [3]. Within the extensive realm of possible material combinations, I focus on fibre reinforced polymers (materials and applications are further elaborated in section 2).

Increasing use, however, comes with an equivalently increasing volume of end-of-use products. Composite materials are notoriously difficult to recycle. Recycling is hampered by the heterogeneous material composition and lack of appropriate, scalable, recycling technologies [4]. Furthermore, regular challenges apply to collection and sorting, exacerbated by the long materials lifespan, which in turn complicates return flow planning [5]. Consequently, large volumes of end of use composite materials are currently sent for incineration or landfill [4]. These treatments are unsustainable as they eliminate reuse, incur loss of the materials, and void the opportunity for recapturing value [6]. Moreover, when disposed of in the environment, decaying composites can harm the ecosystem by expelling fine polymer particles and fibres [7]. Thus, when the complete lifecycle is taken into account, the environmental advantage of using composite materials becomes less evident [8].

From a circular economy perspective, this take-make-use-dispose scenario for composite materials does not suffice. The circular economy opposes the “linear” economic system and aims to make better use of resources [9]. Instead of wasting materials, resource loops should be closed through recovering products and materials. The recovery strategies follow a hierarchy. Preventing waste by prolonging product lifetimes through e.g., reuse, repair or remanufacturing, is preferred over recycling [10,11]. Keeping products in use preserves most of the embedded value for a relatively limited investment of time, energy and resources [12]. But, materials recycling remains necessary to close the resource loop, prevent loss, and reduce the need for primary raw materials. Circular economy strategies, both at product and materials level, are most effective when addressed at the initial design stage of a product [13,14].

Designers can anticipate for intended recovery processes at the end of product use [15,16]. However, the design process of products containing composite materials is more complex than that of those containing conventional mono-materials [17]. The performance of a composite part depends on the interplay between design, materials selection, and manufacturing process [2]. Addressing recovery operations in the design process increases the number of constraints, interdependencies and thereby complexity. Designers have signalled the need for support on this issue, because even though the attention paid to reprocessing technologies for composite materials has increased in recent years, associated design strategies remain largely unexplored [18–20]. Therefore, there is a need for validated approaches to support designers developing composite-containing products for a circular economy.

2. Composite materials and applications

In this dissertation I focus on a specific subset of composite materials: fibre reinforced polymers. Composites have been known and used for many centuries, the concept is not new. Examples include straw-reinforced clay bricks used in ancient Egypt, moulded plywood furniture since the industrial revolution, and fibreglass radar domes in the Second World War [2,21,22]. While the constituting materials changed, the concept remained the same. Fibres carry the loads, while a matrix (resin) keeps them in place, transfers loads, and protects the reinforcements from environmental exposure [17].

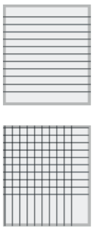
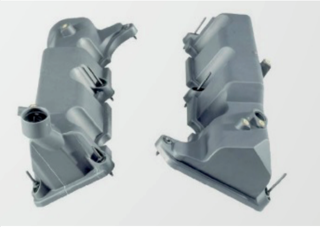
The most important variables in creating a composite are the selection of matrix and reinforcement materials, their mixture ratio, and reinforcement structure [23]. Of all available matrices, polymers are by far the largest group [20] and thus form the focus of this study. Polymer matrices include thermosets (mainly epoxides and polyesters) and thermoplastics. Reinforcements come in the form of fibres, most commonly glass-based (99% market share in 2018 [24]) while other options include carbon, aramid and natural fibres. The reinforcement structure plays a crucial role in determining the final material properties.

Reinforcement structure encompasses the orientations and dimensions of the reinforcements in the composite [23]. These range from short and randomly ordered to continuous and unidirectional aligned fibres [1]. Generally, mechanical properties improve with increasing fibre length and alignment, emphasizing the importance of these characteristics in design as well as in composite materials recovery. Within the reinforcement structures we distinguish two main classes: laminated composites and fibre-reinforced moulding compounds. Laminates are made by stacking plies of e.g., woven, unidirectional or randomly oriented fibres. Fibre-reinforced moulding compounds consist of fibres dispersed within a matrix.

Table 1 shows an overview of typical applications classified by matrix type and reinforcement structure. In this dissertation I focus on thermoset-based laminates and thermoplastic fibre-reinforced moulding compounds. Thermoset laminates are often used to reduce weight and hence fuel consumption of vehicles and aircraft. Moreover, their resistance to corrosion reduces maintenance (e.g., in boats), and their resistance to fatigue enables large scale harnessing of wind energy [25,26]. Fibre-reinforced thermoplastic moulding compounds are often used to increase impact strength of product housings and improve stiffness of mass-produced automotive components [3].

I focus on laminated thermosets because these are the classic examples of composite materials; they use advanced material combinations and structures to tailor mechanical properties. Such optimised use however complicates reuse. Fibre-reinforced thermoplastic moulding compounds have a large market volume compared to thermosets [3] and their widespread use challenges recollection and reprocessing. These thermoplastic moulding compounds were investigated in the Ecobulk project, which ran between 2017 and 2022. In the project, thirty partners from industry, academia and research institutes collaborated to demonstrate a closed loop for composite products in a circular economy. The project provided an industrial context for this research and mainly focused on moulded thermoplastics. As this did not include the important class of laminated composites, we also addressed wind turbine blades as archetypical laminated composite product.

Table 1 Typical applications of composite materials, classified by matrix type and reinforcement structure. Images by [27–30].

		Thermoset	Thermoplastic
Laminated			
Moulding compounds			

3. Gaps and research questions

We addressed two knowledge gaps. First, the design of composite-containing products for a circular economy is a new and unexplored field. In 2017, when this project started, no articles had yet been published on this topic. An initial literature study revealed that composite product design mostly focused on optimization of products, parts and structures for a single use phase [31]. Studies on composite materials in a circular economy predominantly described development of processes and materials to improve materials recycling, without linking back to initial design. In the field of circular product design, we found circular economy strategies, design aspects, and design approaches in general (for example by Den Hollander (2018), Mestre & Cooper (2017) and Moreno et.al. (2016) [32–34]). However, these studies did not target composite materials and their specific challenges. Overall we observed that composite materials, the circular economy, and product design were well-developed fields in their own right, but little cross-sectional knowledge was available.

Secondly, we observed a gap between circular economy theory and composites recovery in practice. In an initial study we found that general circular economy strategies can largely be followed as far as product integrity is involved [31]. However, recycling routes for composite materials show some distinct aspects. Composite materials can only be recycled to a limited extent by mechanical (shredding), thermal, and chemical processing. In all cases the loss of material functionality and the deterioration of material properties is considerable [4,20]. More interesting, and specific to composites, is structural reuse: large parts can be repurposed as a whole or cut into reusable construction elements, preserving the materials' structural quality while diversifying reuse options [35,36]. This strategy has occasionally been demonstrated as a solution, but was not yet related to the initial product design.

At the onset of this study, knowledge was spread across various disciplines and remained largely unconnected. This makes it difficult for designers in practice to get an overview and generate design solutions for products containing composite materials in a circular economy. These observations led to the main research question:

How to design products containing composite materials for a circular economy?

With this dissertation I aimed to develop and demonstrate a methodology to design for reuse and recycling of composite-containing products in a circular economy. This was achieved through the development of validated strategies for the initial design stage.

To address the first gap, circular design strategies specifically dealing with composite materials, we combined insights from the fields of circular economy, product design and composite materials. This led to the following sub-research question:

1. Which circular strategies and related design aspects can be identified for products containing fibre reinforced polymers?

Based on the results of the first study, we developed a design method for composite-containing products in a circular economy. However, it is not uncommon for newly developed methods to find poor uptake in design practice. This lack of acceptance is often caused by poor accessibility, usability, and unproven performance. To increase the chances of acceptance and to identify improvements where needed, we needed to test the method in context. Thus, to validate the method in design practice, we formulated the following research question.

2. How effective, accessible and usable is the circular composites design method in design practice?

To address the second gap, retaining material integrity with composites at end-of-use, we explored the strategy of structural reuse. This strategy preserves material quality with relatively little effort [35], for example by resizing and repurposing composite parts in such a way that their unique properties as determined by the combination of material composition and structural design is maintained [39]. This is considered a promising approach to preserve value with relatively little investment of energy and resources, and has been demonstrated on a small scale [36,39]. However, how to anticipate for structural reuse by design and achieve large-scale reuse had not been investigated, which led to the following research question:

3. How to design composite products for structural reuse in a circular economy?

Most of the structural reuse cases to date focus on repurposing large sections of the original product [37,38]. While this approach can lead to aesthetically attractive demonstrators, their scope in terms of materials volume is often limited to a single or small number of installations [36]. The sheer size, complex geometry, and integrated material structures challenge upscaling. Reusing these structures in the form of standardised panels and beams however seems a promising approach to diversify the number of potential applications [35,39]. But this approach to structural reuse and its ramifications on design remain under-exposed. This led to the final research question:

4. How to segment complex composite products into reusable construction elements?

4. Outline

The dissertation's chapters are based on separate articles published in scientific journals and can be read independently. As such, the chapters follow the format of the publications and all have an introduction, body and conclusion. The chapters are ordered to follow the narrative presented in the research aims. While this introduces some repetition across chapters, the original article structure has been retained. The full list of publications and author contributions is given at the end of the dissertation.

In the rest of this dissertation. I use the “we” form to describe research activities. While this dissertation primarily resulted from my own work, as reflected by lead authorship on the individual chapters, research of this scope is never performed in solitude. The studies were performed in collaboration with my supervisors, Ecobulk project partners, design engineering students, and many others. Thus, “we” refers to the research team. Specific contributions and acknowledgements are given in the latter chapters of this dissertation.

Table 2 outlines the chapters with respect to the research questions and methods. A literature review, interviews and Research-through-Design (RtD) cases were applied at different stages in the research.

Table 2 Outline of chapters, research questions and methods used in this dissertation

Ch.	Research question	Methods
2	Which circular strategies and related design aspects can be identified for products containing fibre-reinforced polymers? (RQ1)	Systematic literature review Focus group interviews
3	How effective, accessible and usable is the circular composites design method in design practice? (RQ2)	Design case studies Semi-structured interviews
4	How to design composite products for structural reuse in a circular economy? (RQ3)	Research through Design Semi-structured interviews
5	How to segment complex composite products into reusable construction elements? (RQ4)	Modelling Material property charts

Chapter 2: Circular Design of Composite Products: A Framework Based on Insights from Literature and Industry [40]

In chapter 2 we identify circular strategies and determine related design aspects for products containing fibre-reinforced polymers, and make these accessible for use in both research and design practice. To collect insights from both theory and design practice, we combined insights from the literature with focus group interviews. Focus groups are valuable in exploratory research as they create rich and easily understandable data, they are undirected by predefined responses, and they benefit from group synergy [41].

Chapter 3: Circular composites by design: testing a design method in industry [42]

In Chapter 3 we present a design method based on the knowledge from Chapter 2. The method is validated by investigating design cases in the composites industry. After completing their design case, the participating designers reflected on their design process in a semi-structured interview. The semi-structured interview enabled capture of both the specific implementations of circular strategies and the design aspects, as well as providing in-depth insights on underlying design considerations. The responses and design results were analysed to evaluate the method's effectiveness, accessibility, and usability in design practice.

Chapter 4: Structural Reuse of High-End Composite Products: a Design Case Study on Wind Turbine Blades [43]

Chapter 4 presents a design case study regarding the structural reuse of a wind turbine blade. In a Research-through-Design study, we cut construction elements from a decommissioned wind turbine blade and reused them in a furniture piece. The case was carried out by the researcher and provided first-hand observations on the recovery process, material characteristics, and the associated design aspects. Physical prototype development played an important role, but was not a goal in itself. While it can lead to interesting spin-offs, the prototype is an object of study. It was used to integrate knowledge from various fields and make a future situation observable [44]. We evaluated the prototype with experts from the field to elicit design aspects and current challenges for structural reuse.

Chapter 5: Structural reuse of wind turbine blades through segmentation [45]

In Chapter 5 we considered a systematic segmentation approach to the strategy of structural reuse. Composite products like wind turbine blades are known for their complex combination of geometry and structure. The approach provides a segmentation pattern to recover standardized and reusable construction elements, while minimizing cutting losses. The structural quality of the resulting construction elements was then compared to conventional construction materials by plotting them on material property charts.

Chapter 6: Discussion and conclusion

Chapter 6 collects the insights on designing products containing composites for a circular economy. I discuss the design method and strategy of structural reuse. In this chapter, I also present the contributions to science, practice and education, as well as closing with recommendations for further research.

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Chapter 2

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

This chapter was published as Joustra, J., Flipsen, B., & Balkenende, R. (2021). Circular Design of Composite Products : A Framework Based on Insights from Literature and Industry. Sustainability, 13 (The Susainability Challenges in Polymer Composite Materials: Bio-Based Materials, Recycling, and Life Cycle), 7223. https://doi.org/10.3390/su13137223

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

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.

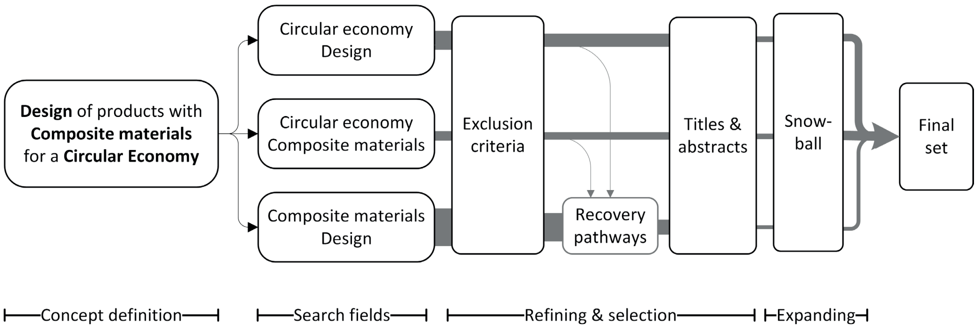

Figure 1. Schematic of the literature collection and selection procedure.

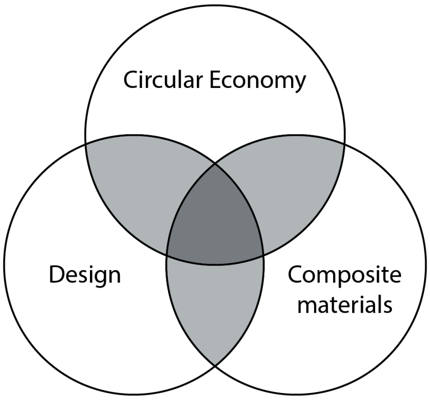

Figure 2. Venn diagram of key concepts, paired into three search fields (light grey) to cover the main topic (dark grey).

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 [3,4,5,7,9,31,32,34,36,45–47,50–52,56,60]	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 [3,4,5,7–9,12,16,29,31,32,45,47–52,55–57,60,61,64–66]	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.

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

Design Aspects [References]	**Description from the Literature**	**Design Guidelines**
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

Design Aspects [References]	Description from the Literature	Design Guidelines
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:	**Cluster ii:**	**Cluster iii:**	**Cluster iv:**
Handling and Rework	**Product Architecture**	**Product Specifications**	**Traceability**
Accessibility	Connection selection	Material selection	Documentation
Adaptability	Dis- and reassembly	Structural design	Identification
Cleanability	Modularity	Manufacturing process	Monitoring
Ergonomics	Keying	Surface treatments	Standardisation
Fault isolation	Function Integration		
Functional packaging	Redundancy		
Interchangeability	Sacrificial elements		
Malfunction signalling			
Simplification			

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.

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.

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.

\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		■	■	■	■

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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Chapter 3

Circular Composites by Design: Testing a Design Method in Industry

This chapter was published as Joustra, J., Bakker, C., Bessai, R., & Balkenende, R. (2022). Circular composites by design: testing a design method in industry. Sustainability, 14(13 (Product Eco-Design in the Era of Circular Economy)), 7993. Retrieved from https://doi.org/10.3390/su14137993

Abstract

Design of composite products for a circular economy is challenging. Materials such as glassfibre reinforced plastics have long product lifetimes but are hard to recycle. For effective reuse and recycling of products, parts, and materials, recovery strategies must be selected and implemented in the product design stage. This extends the scope and complexity of the design process and requires additional skills from designers. We developed a novel Circular Composites design method for products containing composite materials, to support designers and improve product circularity. This method, which is the first of its kind to address the circular design of composite products, helps designers explore recovery pathways and generate design solutions. In this study we evaluated the method's effectiveness, accessibility, and usability in design practice. We tested the method with five design case studies in the construction, furniture, and automotive industries. The method was used to generate, evaluate, communicate, and detail product designs. We found that two of the five cases used the method to develop circular product concepts. In the other three cases, recycling rather than product-level recovery strategies was the result, with a focus on improving material formulations instead of the overall product design. Although designers considered the method accessible and usable, its effectiveness was restricted by the existing business, logistics, reprocessing technology, and policy contexts. These factors are intertwined and partly dictate boundary conditions to design, which means that to successfully implement the proposed method, the transition to a circular economy needs a holistic approach to adjust the design process, organisations, and value chains.

Keywords: circular economy; product design; composite materials; design methodology

1. Introduction

A circular economy is an economic and industrial system which aims to eliminate waste through restorative use of resources [1]. Resources are retained in the system rather than being wasted by focusing on product, component, and material reuse [2,3]. The recovery strategies are prioritised according to their capacity to preserve embedded value, with product reuse being preferred over material recycling [4]. Product design is regarded as a powerful contributor to establish circular production and consumption [1,5], as design determines to a large extent how products are made, used, and processed at end of life.

Designing products for a circular economy can be challenging. Products need to be designed for multiple lifecycles [6], including the complete system in which the product operates as well as prospective recovery activities [7,8]. Thus, time becomes an explicit factor in design [9]. The design is accompanied by development of tailored circular business models to incentivise prolonged use and the return of products and to promote recovery [10,11]. These factors widen the scope of product development in terms of, for example, stakeholder interactions [12,13]. This requires additional and altered competencies from the designer, such as designing for multiple use and recovery cycles, working with circular business models, and collaborating and engaging with stakeholders [14,15]. Additional challenges are found in specific industry sectors, such as when dealing with high end, yet poorly recyclable materials such as composites [16–18]. To date, the advantages and challenges of the materials have been widely acknowledged [16,17,19], but the design of products using composite materials has not explicitly been considered in circular product design approaches.

To improve design of composite products for a circular economy, we developed a Circular Composites design method based on the study by Joustra et al. (2021) [16]. The design method consists of two parts: a product lifecycle exploration sheet and a product design framework. The product lifecycle exploration sheet is used to explore recovery loops, including stakeholders and their activities. The circular product design framework then relates the recovery strategies to design aspects that facilitate recovery. This novel method increases product circularity by identifying recovery pathways and generating design solutions. As such it supports designers when preparing products for reuse and recovery by design intent.

Industry insights were included when developing the Circular Composites design method, however its application has not yet been tested in practice. Such a test is essential, since many developed design methods find limited uptake in industry and their actual impact remains unclear [20,21]. This is caused by many of the methods being developed out of context and without having the user in mind [22,23]. Design methods do not merely provide a formal description of the design process, they are part of the interaction between the designer, context, and design goal [21,22]. Failing to take these factors into account during method development leads to design methods having limited usability, unknown performance and ensuing poor acceptance in industry practice [22,23].

In this study, we describe and evaluate the Circular Composites design method through design case studies performed by expert designers. This approach takes the design method, its users, the industrial context, and the design goal explicitly into account. We focus on circular design of products containing composite materials, most notably those containing fibre-reinforced thermoplastics. These materials represent the majority of composite materials in the market today [24], with the automotive industry being the largest consumer. The automotive sector is represented by three design cases, while the other cases in this study are taken from the construction and furniture industries to broaden the scope of potential applications of the design method. All three are considered priority sectors for accelerating the transition to a circular economy in the European Union [25]. As such, the evaluation of these cases provides an indication of the performance and demonstrates the use of the Circular Composites design method in realising a circular economy for composite products.

In this study, the designers learn about the Circular Composites design method and apply it in their respective cases. Afterwards, we reflect on the design case with the designers to evaluate the use of the method in the design process. In Section 2, we outline the Circular Composites design method. In Section 3, we introduce the design case studies in which it was used. This section also describes data collection and analysis of the cases. In Section 4, the design cases and the reflections of the designers on their method usage in the design process are described in detail. In Section 5, we evaluate the method's effectiveness, accessibility, and usability for composite product design for a circular economy. The main insights are then brought together in Section 6.

2. Circular Composites Design Method

We describe the Circular Composites design method's use in context by following method content theory [22]. The method's goal is to support designers of composite products when integrating circular economy strategies. As such, it facilitates product design *for* a circular economy *with* composite materials. The method includes an explorative lifecycle mapping worksheet and a circular product design framework. Figure 1 shows the method's consecutive steps.

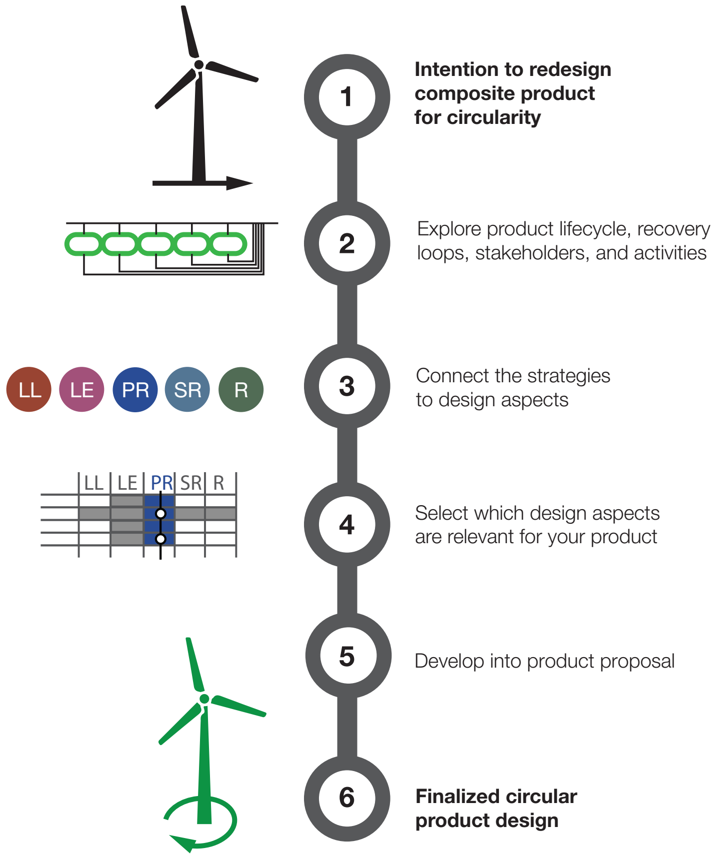


Figure 1. Procedure for using the Circular Composites design method.

The Circular Composites design method process follows the numbered steps depicted in Figure 1. The process starts with (1) the intent to (re)design a product containing composite materials for a circular economy. Then (2), the designer uses the lifecycle exploration sheet shown in Figure 2 to draw out and detail the product lifecycle. The mapping starts with a product description, followed by identifying stakeholders for each phase in the product value chain. Then, the recovery loops are explored, describing potential recovery actions to recover the product as an entity, parts, or materials at end of use. The sheet can be used in group sessions to stimulate discussion and create a shared understanding of the product lifecycle and circular opportunities. In the design cases in this study, the lifecycle exploration was done in stakeholder groups, facilitated by moderators.

The recovery loops relate to circular strategies such as long life, lifetime extension, or materials recycling. In the Circular Composites design method, the designer uses a circular product design framework to connect these strategies to design aspects (4). This framework, given in Appendix A, contains 5 circular strategies and relates these to 24 design aspects [16]. Three strategies aim to preserve the product integrity by ensuring long life, lifetime extension, and product recovery. The remaining two strategies aim to preserve the material integrity (maintaining material quality over time) via structural reuse and material recycling. While product integrity strategies are generally preferred to preserve performance and value, materials integrity remains necessary to reprocess products that have no next-use cycle [5]. The related design aspects support designers in anticipating for recovery by design intent. The designer can use a subset of design aspects to conceptualise, embody, and detail the design proposal (5). Finally, the process results in a circular product design proposal (6).

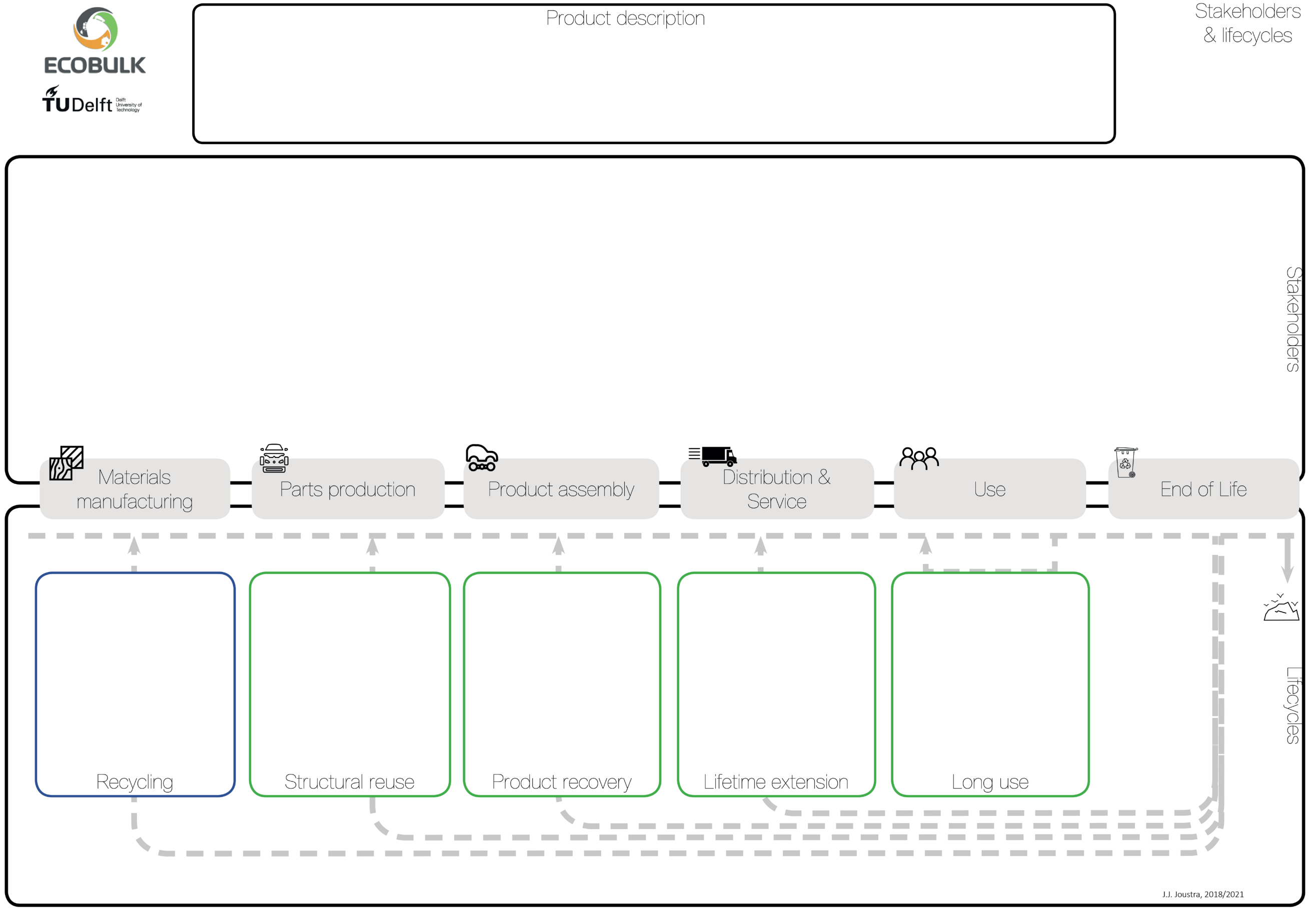


Figure 2. Product lifecycle exploration sheet.

3. Method

To evaluate the Circular Composites design method's effectiveness, accessibility and usability in the design process, we used a mixed methods approach to reflect on the design process with the designers. The approach consists of a questionnaire to elicit method use in the successive stages of the design process and a semi-structured interview to elaborate on the designers' reflections on the design process and the results achieved. These approaches were also used to evaluate method use in the design process [26,27] and to gain insight in how experts approach circular product design in practice [14]. The mixed methods approach allowed for systematic reflection, as well as elaborating on insights emerging in the design process.

The design case study and mixed methods reflection process were piloted in a student design course at Delft University of Technology. In the course, ten Industrial Design Engineering students used the Circular Composites design method to develop circular products for a fictional case in furniture industry. After completion of the course, the students reflected on their design process with the researcher. The interviews were subsequently transcribed and analysed together with the questionnaire responses. This pilot study showed the feasibility of using the questionnaire and semi-structured interview to evaluate effectiveness, accessibility, and usability of the design method.

3.1. Design Cases

Seven industry design experts used the Circular Composites design method to re-design a total of five case products. The designers developed their products in the context of a Horizon 2020 project on closing the loop of composite products in the automotive, furniture, and building sectors. The project ran from 2017 until 2021, of which three years were dedicated to product development [28]. The consortium included stakeholders from all stages of the product lifecycle for each of the product sectors, such as material suppliers, original equipment manufacturers (OEMs), and recycling companies. Knowledge generated by TU Delft on circular product design was shared with the industrial partners through regular project meetings and intermediate reports. Prototypes were developed by designers of the industrial partners to demonstrate a circular composite product, evaluate product performance in-use, and to simulate a closed loop recovery action.

Five case products were developed for three sectors (Table 1), namely the construction (*n* = 1), furniture (*n* = 1), and automotive (*n* = 3) industries. In one case (E4), we interviewed three designers, while other cases were represented by one designer, which brought the total number of participants to seven. For the construction sector, a small-to-medium enterprise (SME) company developed an outdoor pavilion using extruded pillars and beams. The extrusion agglomerate was based on recycled (shredded) glass fibre composite and polyethylene. For the furniture sector, a large manufacturer of interior furniture designed a modular bedroom set consisting of a bed, bookcase, chair, and desk, all made of particle board. For the automotive sector, three companies designed dashboard components using recycled or bio-based thermoplastic composite materials. The first company was a large manufacturer of automotive thermoplastics, the second was an SME developing hydrogen vehicles, and the third was a research and technology development (RTD) centre affiliated with a major car brand.

Table 1. The Ecobulk project—industry partner cases [28].

Sector	Company Focus	Company Type	Case
Construction	Extruded composite products	SME	Outdoor pavilion
Furniture	Interior furniture	Large	Bedroom set
Automotive	Automotive thermoplastics	Large	Dashboard fascia
Automotive	Hydrogen vehicle manufacturer	SME	Switchpack housing
Automotive	Brand research centre	RTD/Large	Dashboard component

3.2. Design Process and Data Acquisition

The designers were asked to use the Circular Composites design method to develop prototype products. Prototype products were produced and exhibited at locations across Europe. These were then used to demonstrate and evaluate the circular product proposals in the final stage of the Ecobulk project. All designers reflected on their design process through a questionnaire and a semi-structured interview.

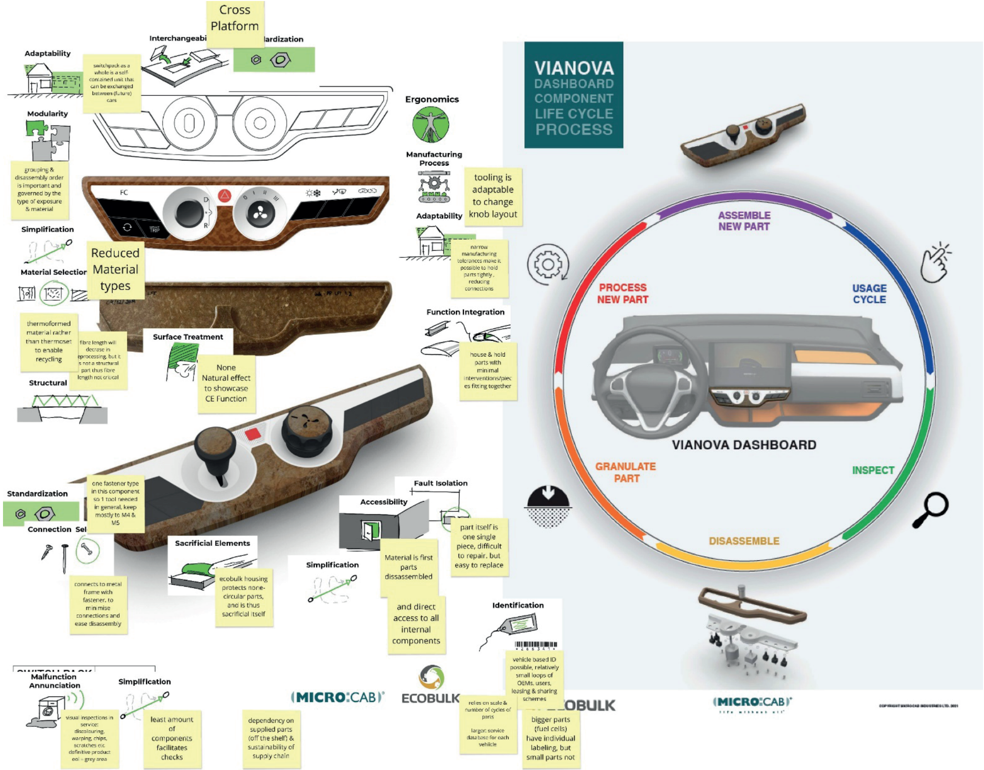
A baseline was established at the start of the design case study, for case products as well as circular design expertise [29]. The baseline consisted of a definition of the case product, the materials used, and the expected challenges to its uptake in a circular system. The current state of the art for the industry sectors was also established. The expertise of the designers in circular product design was evaluated by discussing to what extent recovery was already considered in the design stage and to what extent retrieved materials were used in ongoing product manufacturing.

At the end of the design process, we asked the designers to complete a questionnaire to reflect on their knowledge of the circular product design methods, and to identify how the Circular Composites design method was used in the design process. The questionnaire setup is provided in Appendix B. To assess prior knowledge, we offered several options such as “reading on the subject”, “courses” (including online open courseware), as well as options to add additional sources, or simply state “none”. The responses allowed us to identify the means and types of sources the designers used to become acquainted with the topic of circular product design.

To assess when the Circular Composites design method was used in the design process, we used a questionnaire setup developed by Person et al. (2013). This allowed us to relate the use of the design method to stages in the basic design cycle, which describes design as an iterative process of analysis, synthesis, simulation, evaluation, and decision making [30]. It must be noted that the intention was not to quantify the extent to which the proposed design method was used, but rather to qualitatively assess *when* and *how* the method was used in the design process.

We then conducted semi-structured interviews with the designers to reflect on their design process. The questionnaire answers were used as inputs for the interview, for example by questioning how the Circular Composites design method was used in the indicated design tasks. Reflecting on a design outcome can be difficult, and designers tend to prefer telling stories about the design process instead [31]. We, therefore, invited the participants to bring intermediate results such as reports, drawings, and the final prototype to help them describe their process. The interviewer then asked about the specifics of the design and the decisions that underpinned these. The interviews took 30–60 min each; see Appendix C for the interview template.

The designers were interviewed online as they worked at companies across Europe. For the online interviews we used videoconferencing software and a shared web-based “whiteboard”. This whiteboard was prepared with pictures of the case product and drawings of the circular strategies and design aspects. Both the researcher and the participant could move and add pictures and notes. In addition, hand-written notes were taken by the researcher during the interviews. The interview was audio-recorded and the virtual workspace was exported and saved to capture notes and the selection of strategies and design aspects (Figure 3).



switchpack as a whole is a self-contained unit that can be exchanged between (future) cars

grouping & disassembly order is important and governed by the type of exposure & material

thermoformed material rather than thermoset to enable recycling

fibre length will decrase in eprocessing, but it s not a structural part thus fibre length not critical

None Natural effect to showcase CE Function

tooling is adaptable to change knob layout

narrow manufacturing tolerances make it possible to hold parts tightly, reducing connections

house & hold parts with minimal interventions/pieces fitting together

one fastener type in this component so 1 tool needed in general, keep mostly to M4 & M5

connects to metal frame with fastener, to minimise connections and ease disassembly

ecobulk housing protects none-circular parts, and is thus sacrificial itself

Material is first parts dissassembled

and direct access to all internal components

part itself is one single piece, difficult to repair, but easy to replace

vehicle based ID possible, relatively small loops of OEMs, users, leasing & sharing schemes

relies on scale & number of cycles of parts

larger service database for each vehicle

bigger parts (fuel cells) have individual labeling, but small parts not

visual inspections in service: discolouring, warping, chips, scratches etc definitive product eol – grey area

least amount of components facilitates checks

dependency on supplied parts (off the shelf) & sustainability of supply chain

Figure 3. Example of product proposal annotated with circular strategies, design aspects, and notes. With permission from Microcab Industries, Ltd.

3.3. Analysis

To evaluate the effectiveness, accessibility and usability of the Circular Composites design method in practice, we analysed the questionnaire and interviews on their main aspects. In the questionnaire, the designers indicated the tasks for which the method had been used. The questionnaire setup was such, that these tasks related to stages in the design process [26]. Reviewing the questionnaire responses gave an immediate overview of when and how the designers used the design method in their design process.

Following, the recorded interviews were transcribed and reviewed. We analysed the responses using predefined codes drawn from [26] to identify tasks in the basic design cycle, from [5] to identify the type of recovery loop, and from [16] to identify the circular strategies and design aspects implemented in the product design. These were supplemented with codes that emerged from the interviews to capture additional method uses. The full list of codes is provided in Appendix D. After coding, the transcripts were reviewed again through the lens of the research questions to capture insights that may have been overlooked through the granularity of coding. The design method effectiveness, accessibility, and usability were analysed as follows.

Effectiveness relates to "*how well a method allows designers to achieve the desired effect in context*" [22]. In this design case study, we evaluated the extent to which the method invokes circularity in the design. We considered two aspects derived from [5]: the considered level of integrity strategies, and the nature of the circular system. First, we classified a design as being circular if both product integrity and material-level integrity strategies were considered and a substantiated selection of a specific circular strategy was made. Second, reprocessing is generally considered most effective when done in a closed system, where control over and responsibility for product recovery remains with the manufacturer.

Accessibility of a design method relates to "*the ease with which* [*the method*] *can be accessed by a designer. This can refer to the method description as a whole or elements of it.*" [23]. As learning builds on past knowledge and experience, we started by coding the questionnaire and project baseline report for prior knowledge on circular product design. We then coded the interview for prior experience and the means through which the designer learned and understood the method. Finally, we reviewed the interview for responses regarding the match of the method with their design practice.

Usability of a design method relates to "*the ease with which [the method] can be applied after it has been selected*" [23]. We therefore analysed when and how the method was used in various tasks of the individual design processes, referring to the basic design cycle. To evaluate method use, we reviewed the questionnaire responses and coded the interviews for references to typical design tasks and method manifestations. The majority of the codes were drawn from [26], supplemented by codes emerging from the interview. To evaluate the extent to which the design method could be used for each individual case, we mapped the product descriptions onto a template derived from the circular product design framework (Appendix A).

4. Results

4.1. Case Results

We analysed five design case studies based on their use of the Circular Composites design method. An overview of the five cases (E1 to E5) is given in Table 2.

We observed some notable similarities and differences in implementing circular strategies in the case designs. Table 3 shows the selection of design aspects and strategies used in the development of each case. The combinations of the circular economy strategies and design aspects that were used by the participants are labelled E1, E2, etc., with E1 representing the first case in Table 2. The green cells indicate design aspects that were identified in a previous study to be relevant to a particular design strategy [16].

Table 2. Cases developed in design case studies in the construction, furniture, and automotive industries.

Case	Picture	Description	Circular Composites Design Approach
E1		The construction case evolved around a previously used, mechanically reprocessed (shredded) thermoset composite obtained from wind turbine blades and polyethylene. Extruded into planks and pillars, these materials were used to design and build a water fountain shelter. The company developed a proprietary process for manufacturing and reprocessing composite profiles, which formed the basis of their business and operations.	Long life was enabled by formulating materials to resist degradation from UV radiation and cleaning (agents). Lifetime extension (repairs) and product recovery are facilitated by selecting reversible connections and adaptable construction methods. Recycling was enabled by substituting wood with extruded profiles based on an agglomerate of recycled polyethylene, glass-fibre-reinforced plastics, and wood.

Case	Picture	Description	Circular Composites Design Approach
E2		The furniture pieces were built using a set of basic elements: 2 differently sized cubes and 'L'-shaped elements. These can be reconfigured to make items for a bedroom and study area, including a desk, chair, bed, shelving units, and a bedside table. A new formulation of particle board was used, eliminating formaldehyde from its binder to prevent the accumulation of this substance in successive reprocessing cycles.	Lifetime extension (repairs) and product recovery (refurbishment and parts harvesting) were enabled by designing adaptable, interchangeable, modular subassemblies and parts. Lifetime extension and product recovery are facilitated by selecting reversible connections and providing documentation. The material formulation facilitates multiple loop recycling.
E3		The dashboard fascia is used to mount airducts and a multimedia display in the car dashboard. The component is produced by 2k injection moulding with a recycled composite material backing and an aesthetic front of primary plastic. In the structural design, fibre-reinforced recycled plastic was used to compensate for the lower strength of the recycled plastics.	The dashboard fascia was designed to increase the use of recycled materials and facilitate multiple-loop recycling. In the design, this was reflected by the materials, connections, and manufacturing process selection. The part is mounted using integrated snap-fits to allow for dis- and re-assembly, maintenance, and repairs.

Case	Picture	Description	Circular Composites Design Approach
E4		The switchpack housing is a central component of the car dashboard. The subassembly contains mechanical, electronic, structural, and aesthetic parts. The design paid attention to the lifespan and recovery pathways of the different materials and embedded parts.	The housing was designed to protect electronic elements, ensuring a long lifespan. The housing itself will be refurbished in planned intervals and recycled in a closed loop. This was achieved through design for dis- and reassembly, connection selection, and accessibility (of the assembly's internal components). Recycling is facilitated by preventing process contamination through material selection and by avoiding surface treatments.
E5		The dashboard component was manufactured using recycled and bio-based materials. The case envisions cascaded material use within the vehicle, subsequently as a visual dashboard part, an airduct, an under-the-hood part (e.g., wheel cover), and finally as carpet.	For the first use, the dashboard, the original component shape remained largely the same, using the same type of connections. These can be dis- and reassembled, allowing for maintenance and repairs. The manufacturing process was adapted to accept new material formulations. Recycling was enabled by selecting reprocessable thermoplastic matrix materials.

Mapping out the case results (Table 3) shows that the majority of the identified design aspect implementations align with those suggested by the framework. All circular strategies except structural reuse were used, and the designers selected the design aspects they found relevant to achieve circularity for their case product. This also meant that not all of the suggested design aspect implementations (indicated in green in the table) found recurrence in the cases. On the other hand, additional design aspects were identified for the long life strategy. The use of circular strategies and design aspects in the cases is discussed further in this section.

At the product integrity level, the designers most often selected lifetime extension strategies, while long life and product recovery were addressed to a lesser extent. Long life builds on the resilience of composite materials, which generally grant a long product life. The cases leveraged these materials' characteristics by facilitating lifetime extension.

At the material integrity level, none of the cases addressed structural reuse, but all addressed material recycling. The strategy of structural reuse aims to preserve the material integrity by repurposing parts or segments [32]. Structural reuse has specific relevance to large-sized high-performance composite products such as wind turbine blades, which were not amongst the design cases in this study. Material recycling was mostly achieved by selecting appropriate materials and manufacturing techniques. With the exception of the modified particle board (E2), all cases used thermoplastic matrices to warrant recyclability.

The automotive cases focused on the interior components, which are part of a larger vehicle assembly process. The vehicle lifetime, thus, formed a boundary condition for that of individual components. In addition, in the automotive industry, the governing recycling directive [33] has led to an industry model where vehicles are centrally reprocessed in bulk, for example by INDRA (France) and ARN (the Netherlands) [34,35]. E3 and E5, both of which are established players in the automotive sector, decided to focus on bulk recycling into plastic compounds. E4 on the other hand had the opportunity to design a complete vehicle, and planned for the maintenance and refurbishment of parts.

Several design aspects recurred across all projects. For example, dis- and reassembly, connection selection, standardisation, and material selection were used in all cases. The use of design aspects varied depending on the sector considered. For example, the automotive companies made extensive use of material selection, given their focus on recycling. They also all considered function integration through the inclusion of, among others, fasteners or keying during the injection moulding process. The furniture company considered modularity and fasteners as key design aspects. The construction company considered design aspects focused on materiality—namely material selection, cleanability, surface treatments, and manufacturing.

Table 3. Mapping of developed products on the framework, with design aspects identified as relevant for a particular circular strategy indicated in green [16] and the occurrence of design aspects in cases labelled E1 to E5.

			Circular Economy Strategies				
			Design for Preserving Product Integrity			Design for Preserving Materials Integrity	
			Long Life	Lifetime Extension	Product Recovery	Structural Reuse	Material Recycling
Design aspects	Concept design	Accessibility		🟩 E2, E3, E4, E5	🟩		🟩 E4
		Adaptability	🟩	🟩 E2	🟩 E1	🟩	
		Cleanability	E1, E5	🟩 E1, E3, E5	🟩		🟩
		Dis- and reassembly	🟩	🟩 E2, E3, E4, E5	🟩 E1, E4	🟩	🟩 E3, E4, E5
		Ergonomics	E2	🟩	🟩		
		Fault isolation	E2	🟩	🟩		🟩
		Functional packaging		🟩	🟩		🟩
		Interchangeability		🟩 E1, E2	🟩 E2, E4	🟩	🟩
		Malfunction signalling	🟩	🟩	🟩		
		Simplification	🟩 E2	🟩	🟩		🟩
	Embodiment design	Connection selection	🟩 E1	🟩 E2, E5	🟩 E1, E4	🟩	🟩 E1, E3, E4, E5
		Function integration	🟩	🟩			🟩 E3, E4, E5
		Keying		🟩 E5	🟩		
		Material selection	🟩 E1, E5	🟩 E5	🟩	🟩	🟩 E1, E2, E3, E4, E5
		Manufacturing		🟩	🟩 E2		🟩 E1, E3, E4, E5
		Modularity		🟩 E2	🟩 E4	🟩	🟩 E3
		Redundancy	🟩	🟩	🟩		
		Sacrificial elements	E2	🟩 E4, E5	🟩		
		Structural design	🟩 E1,	🟩	🟩 E2	🟩	🟩 E3, E4, E5
		Surface treatments	🟩 E1, E2, E3, E5	🟩	🟩		🟩 E1, E4
	Detail design	Documentation		🟩 E2	🟩 E2	🟩	🟩 E1, E2, E3
		Identification		🟩	🟩 E1, E2	🟩	🟩 E3, E4, E5
		Monitoring	🟩 E1	🟩	🟩 E2, E4		
		Standardisation		🟩 E2	🟩 E2, E4	🟩	🟩 E1, E3, E5

A few design aspects were not used in any of the cases. Functional packaging, malfunction signalling, and redundancy were not used because these were out of scope for the studied cases. We observed three additional design aspects being used for Long Life, E1 and E5 implemented Cleanability, and E2 addressed Ergonomics and Fault Isolation. These aspects were not previously identified as being relevant to the Long Life strategy and thus supplement earlier findings [16]. At the end, selection and implementation of design aspects depend on multiple factors, such as the nature of the case and the achieved level of detail.

4.2. Evaluation of Method Effectiveness

To evaluate the Circular Composites design method's effectiveness, we analysed the cases based on the integrity level (product or material) and the nature of the recovery system (open or closed) (Table 4). All cases explored both material and product integrity strategies. Mapping out the value chain showed additional recovery pathways, which led to exploring various product integrity strategies. Most notably, lifetime extension through repairs was addressed in all cases. As such, the design method, applied under guidance of the method developers, provided the designers with other strategies to those of long lifecycle and recycling.

Table 4. Aspects of effectiveness encountered in case responses.

Aspects of Effectiveness	Codes	Occurrence in Case
Level of integrity	Product integrity	E2, E4
	Material integrity	All
Circular system	Open	E1, E3, E5
	Closed	E2, E4

The designers considered both closed- and open-loop recovery strategies when developing the cases. The lifecycle mapping exploration connected the lifecycle stages, stakeholders, and recovery activities. These connections imply (additional) interactions. This led to E2 considering the inclusion of retailers in the collection and redistribution of used furniture, and E4 considering refurbishment and closed-loop recycling. E1, E3, and E5 considered closed-loop recovery, but found that this approach did not match their business model and industry setting. E1 developed a business model involving the licensing of (re-)processing technology to local vendors, and as such had no further activities in the product lifecycle after production. E3 and E5 were bound by recycling regulations for the automotive industry, and chose to conform to existing vehicle recycling infrastructure. Overall, we found that the method stimulated designers to make an informed choice on which circular strategy to choose and which model to pursue—either open- or closed-loop recovery.

To generate design solutions, the designers used both the strategies and the design aspects to generate ideas. The strategies relate to business models that facilitated the parallel development of business models and product design. The design aspects then relate these strategies to actionable design interventions. One designer (E4) used the design aspects as a guide while designing the case product. This helped to generate ideas outside of their focus on material recycling. E1, on the other hand, mentioned that the method "could have" led to specific design decisions, but ultimately did not apply it because the design was already too constrained prior to their knowledge of the method. This indicates that the Circular Composites design method facilitates circular product design, but that its effectiveness also relies on the context of the design project.

4.3. Evaluation of Method Accessibility

Accessibility of the design method was assessed by evaluating past theoretical knowledge of design for a circular economy, the practical knowledge or prior experience designers might have, and finally how the designers familiarised themselves with the method. The interview results are summarised in Table 5 and discussed below.

Table 5. Aspects of accessibility encountered in case responses.

Aspects of Accessibility	Codes	Occurrence in Case
Prior experience	Recovery considered in design	E3; E4; E5;
	Use of retrieved materials in production	E1; E2; E3; E5;
Accessing the method	none	-
	Ellen MacArthur Foundation	E1; E4
	Open Courseware	-
	Reading	E4; E5;
	Videos	E4;
	Courses	-
	Other	E1; E2; E3; E4;
Understanding the method	Terminology	E1; E2; E3; E4;
	Framing of circular economy	E3; E4; E5;
	Match with design practice	E1; E3; E4;

The designers developed their knowledge and understanding in several ways. In general, they indicated that they relied more on face-to-face knowledge transfer rather than on reading. Courses were not mentioned at all. Of the five experts, three mentioned past professional experience as their only source of theoretical knowledge on CE, while two mentioned personal reading as a source of limited prior theoretical knowledge on CE. For E3 and E5, this was the first time they had engaged in circular economy design activities, and as such these designers had no practical knowledge or prior experience in circular product design.

During the project it was found that the circular design aspects connected to existing and well-known practices from general design and engineering, as well as to related design approaches. Three designers (E2, E3, E5) mentioned that they already had a practical understanding of parts of the method (from previous experience), and so it was easy to apply it in their work. Eco-design [36] was, for example, mentioned as a related design approach. E3 noted that the technological concepts of eco-design are the same, but the circular economy method provided a different framing of the design goal. Thus, while the framing of the circular economy strategies was new, the design aspects were built on existing practices and technological background in the companies.

The circular product design method was considered well-structured by the experts. E2 commented that the left-to-right listing of circular strategies communicates a visual hierarchy, whereby product integrity strategies are favoured over material integrity. This also brings a clear distinction between strategies and design aspects. It was found that the connection to well-known design and engineering practices made it easy to understand what the design aspects entail and how they can be used. However, the terminology was sometimes found to be confusing. For example, some experts had different definitions of modularity, ranging from enabling parts exchange to reorganising subassemblies. Over the course of the design case studies, these definitions of terms and concepts were clarified and agreed upon by the stakeholders. Thus, the overall structure of the method is clear, but its contents need better descriptions to convey the underlying concepts and definitions.

4.4. Evaluation of Method Usability

To assess usability, we evaluated the method's applicability to the design cases and its use (Table 6). The method was used for different purposes in the various cases: to explore opportunities or challenges, as an idea generator, as an evaluation checklist, as a communication tool, and to detail product concepts.

Table 6. Aspects of usability encountered in case responses.

Aspects of Usability	Codes	Occurrence in Case
Use in design process	Opportunities found using the method	E2; E3; E4; E5;
	Challenges found using the method	E1; E2; E3; E4; E5;
Basic design cycle tasks	Analysis	all
	Synthesis	all
	Simulation	all
	Evaluation	all
	Decision making	all
Method manifestations	Idea generator	E4;
	Evaluation checklist	E2; E4; E5;
	Communication tool	E1; E5;
	Detailing product concept	E4;
	Backing up choices/building confidence	E4
Suitability to case	Circular strategies	Case mapping onto framework (Table 3)
	Design aspects	

Four designers (E2, E3, E4, E5) mentioned that they used the method to find opportunities within the design activity. E2 mentioned that the method was useful to help designers consider things they had not considered, “*for example, surface treatment*”, while E4 mentioned that “*it helps the designer understand all the opportunities*” presented to them. E3 noted that the method was helpful for understanding the challenges and barriers to creating a circular product: “*Many of the strategies are pre-defined by the carmaker, besides recyclability*”; as such, the method helped to frame the available design space and its boundary conditions.

The Circular Composites design method was used in all stages of the basic design cycle. In analysing the case, the lifecycle mapping sheet helped designers to better understand extended time horizons and multiple use cycles. In synthesising, the design aspects were used to generate ideas and develop concepts. In addition to the generative setup of the method, three of the designers (E2, E4, E5) used the framework as an evaluation checklist. The design aspects helped the designer to locate problems in the design and point to specific areas that needed further attention, highlighting missed opportunities for circular product design. In addition to checking the design, it also gave the designers the confidence that they had addressed relevant concerns for circular product design.

Interactions with internal and external stakeholders signalled the need for a common language and shared goals. The circular strategies listed in the method relate to business models and stakeholder actions. The experts further valued the Circular Composites design method as a communication tool to stimulate discussions between stakeholders and departments in the organisation, and with external stakeholders along the product value chain. E1 stated that "*the framework [works] more as a communication tool than a design tool*".

5. Discussion

In this study, we evaluated the effectiveness, accessibility, and usability of the Circular Composites design method in practice. The method was tested in five design case studies in an industry setting, giving insights into the prevailing boundary conditions and ways of working. The method aimed to increase product circularity by design intent through exploring circular strategies and generating associated product concepts.

As expected, there were differences in the method's effectiveness and the way designers accessed and used it for their design tasks. Some aspects of the method need further development to meet the demands of and approaches to design practice.

5.1. Validating the Circular Composites Design Method

The first aim, exploring circular strategies, was achieved in all the five design case studies. All cases explored circular strategies by mapping out their product lifecycles on the product lifecycle exploration sheet. The mapping exercise stimulated the designers' discussions and their assessments of the various recovery routes. Two of the five cases generated circular product proposals. In implementing circular strategies in the design, both cases used design aspects suggested by the method. At the same time, the business models were co-developed to arrive at a circular product proposal. The other three cases explored and considered additional product-integrity-level recovery routes but experienced too many constraints to implement circular solutions. In one case, a strong technological focus contributed to a product development process that was already constrained at the start of the project. The other two cases were constrained in developing circular product solutions by their industry setting.

We recorded unanticipated use of the design method. We also noticed that the designers tended to use the method to evaluate and communicate design choices, in addition to generating ideas. The method also encouraged iteratively expanding the scope in consecutive design cycles. Changes could be made in a controllable way, increasing the circularity of the product in question step-by-step without overwhelming the designer. Thus, the method allowed for some flexibility in use. Such flexibility in applying a method in the design process is likely to increase its effectiveness [27].

Overall, we saw a number of strategies and design aspects not being selected in the cases. This was not unexpected, as the framework targets composite products in general [16]. This means that it should be applicable for designers from various backgrounds and industry settings. On the other hand, this broad scope implies that not all content is relevant to each case. Both the method and the design framework could be adapted to meet specific demands; for example, by selecting design aspects based on a specific industry sector.

The company, policy, and industry contexts determined the implementation of the circular principles. The context in which a design method is used is an important but often overlooked factor for its success [22]. By developing the design method in context, we have addressed some of these concerns, but still improvements can be made. The method could improve on the terminology, for example, by illustrating design aspects with examples to show its typical implementation in design.

5.2. Designing Products for a Circular Economy

The scope for redesign in our cases was large; they were developed in an industry innovation project that stimulated participants to experiment with circular product design and its associated business models and materials. However, the existing infrastructure for recovery and reprocessing creates a lock-in that is hard to break with [25], especially for the large companies—such as in automotive cases E3 and E5. These systems are typically set up in a linear rather than a circular fashion, and as such do not support circular design strategies [13]. Thus, a broader perspective on the production and consumption system is necessary to actually make the shift to circular products. Such systems thinking has been the basic premise of transitioning to the circular economy [1].

We noted a heavy focus on recycling as a key strategy for four of the five cases. Recycling has a low preference in the waste management hierarchy and R-frameworks [37,38], while it is a well-understood approach to circularity. It also is an easy approach to incorporate into existing business models, albeit with a need to comply to industry-specific regulation, such as the End-of-Life Vehicles Directive [33]. Thus, the governing policy and existing industry structures create a lock-in, which may restrict the outcomes of a circular design processes.

5.3. Contributions

The findings in this study contribute to both research and practice in the field of designing products containing composite materials for a circular economy. The design case analysis provides a further grounding of the circular strategies and design aspects identified for products containing composites in a circular economy. The developed design method supports designers in exploring, selecting, and realising circular strategies for their specific product case, and was validated here in five industry cases. This validation showed that the method is considered accessible, usable, and effective. It is expected that these validation results, together with the developed product demonstrators, will contribute to the further acceptance of the method in practice.

Earlier studies stressed the importance of collaboration along the product value chain to instill change and move towards a circular economy [1,12]. The Circular Composites method addresses this need, as it helps to keep stakeholders involved with the design activities and to broaden their view to other expertise areas, such as logistics and business models. On the other hand, the presented design case studies confirm the limitations posed by the existing policy and industry context [13].

5.4 Limitations and Recommendations

The interview and questionnaire enabled reflection on the design results and process as a whole. The responses, however, may have been biased by the reflective nature of the method. Moreover, the expert's confidence, combined with the high level of freedom in the design process, may have lowered the perceived impact of the method on the design process [27]. Such subjectivity in reflection was partially counteracted by inviting the participants to share intermediate results in the interview, anchoring their reflections to achieved results.

Throughout the interviews it appeared that the terminology related to composite design in a circular economy is yet to be fully developed. The strategy of structural reuse and several design aspects were not well understood by the designers. Some designers found the terminology too academic. On the other hand, academics argue that the concept of circular economy has been developed too much in practice and falls short on scientific grounding [2–4]. We, therefore, recommend that the terminology be developed and agreed on within a stakeholder group to remove barriers to implementing the circular economy, including the Circular Composites design method. To improve the accessibility of the method to a broader audience, the strategies and design aspects need more elaborate clarification.

In this study, we analysed 5 design cases from 3 industry sectors. This number of cases limits the generalisation of the results to the composites industry at large. Nevertheless, the study provided interesting insights on using the design method in industry practice. We recommend performing similar design case studies in other industry sectors and product categories. These cases can also be used as examples to present and disseminate the method, an approach also taken for other design guidelines (see e.g., [39]). Further case studies could also elicit and detail the implementation of circular strategies and design aspects, extending the relevance of the method to more sectors.

6. Conclusions

Despite the opportunities and challenges composites offer for designing products for a circular economy, this materials group was not yet explicitly addressed in circular design methods. To address this gap, we developed a novel design method. With this method, we aimed to increase product circularity by design intent through (1) exploring circular strategies using a lifecycle exploration sheet and (2) generating associated product concepts by indicating relevant design aspects based on a strategy-design aspect framework. In this study, we evaluated the effectiveness, accessibility, and usability of the Circular Composites design method in five design case studies.

The Circular Composites design method provided an entry point to approach the circular product design process. This starts with mapping out the product lifecycle and recovery opportunities. The method can be used to iteratively extend the scope of the design project to include additional lifecycle and reuse concerns. In addition to its direct use in exploring and generating design solutions, the method provides a framing of the circular design process that supports project organisation and communication.

The first aim, exploring circular strategies, was achieved in all five design case studies. The method seemed effective in exploring circular strategies in the product lifecycle. The lifecycle exploration sheet stimulated discussion among stakeholders and aligned business model development with product design. These interactions delivered explicit product design requirements and an initial selection of strategies to be considered in the design. The second aim, generating circular product concepts, was partially achieved. The method effectively supported designers in developing circular product design solutions; however, for some cases the implementation was restricted by the context in which they operated. Even though product-level recovery strategies were considered, three of the five cases remained within the existing material recycling pathways. The product recyclability relied heavily on the materials selection, with small adaptations made to other design aspects.

The design method was considered accessible. The method, with its underlying lifecycle mapping sheet and design framework, is well-structured and reflects the prioritisation of recovery strategies in a circular economy. The design aspects build on well-known industry approaches and practices, and support the designers in realising circular economy strategies in their product designs.

Composite materials present many opportunities and challenges for a circular economy, and specific attention has to be paid to material development, design, business models, and recovery processes. The method presented in this article supports designers in integrating these aspects in the design process for composite-containing products in a circular economy.

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Chapter 4

Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades

This chapter was published as Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades. Resources, Conservation and Recycling, (167). https://doi.org/10.1016/j.resconrec.2020.105393

Abstract

Composite materials, in particular fibre reinforced polymers, present a challenge when reaching their end of life. Current recycling processes are unable to capture the high-end material quality, thus challenging (re)use of composite materials in a Circular Economy. Structurally reusing segmented parts of end-of-life products as construction elements has been demonstrated to provide a promising alternative. However, reflection on the consequences for the initial design of composite products is still missing. This study investigates the effect of the original product design on the recovery and reuse of composite products, taking wind turbine blades as case material. Construction elements were cut from a decommissioned blade and reused in a design study. Observations from the recovery and design process were connected to decisions made in the original product design. The insights were discussed with experts from the field of blade design. This resulted in identification of design aspects that enable multiple lifecycles of the composite material as construction panels, if considered during initial product design.

Keywords - Composite Materials; Circular Economy; Structural Reuse; Design Strategies; Wind Turbine Blades

1. Introduction

Composites, specifically fibre reinforced polymers, provide many advantageous properties to use in product design [1]. The high stiffness to weight ratio and form freedom enables lightweight designs and large structures with complex shapes. The material is mostly found in applications where weight savings or efficient structural design bring an advantage. For example, lightweight designs reduce fuel consumption or increase payload capacity in aerospace and automotive applications [2]. For construction industry, weight reduction goes hand in hand with extending a structures' maximum span, as demonstrated by the use in bridges and wind turbine blades [3–5].

Design of composite products is currently optimised for mechanical performance in the use phase [6]. This focus, combined with the complex and heterogeneous nature of the materials, leads to problematic end-of-life (EoL) processing [1,7]. In particular for Glass Fibre Reinforced Plastics (GFRP), which dominates the composites market, no clear recycling route is available even though various options exist [8,9].

Composite materials can be recycled using mechanical, thermal or chemical processes [1,10,11]. Mechanical recycling, i.e. shredding and grinding, yields fragments that can be reused as filler material in new plastics, or as feedstock for further thermal or chemical processing. Thermal processes range from co-combustion in a cement kiln, retrieving energy and ashes, to pyrolysis which retrieves fibres while polymers are converted into small hydrocarbons. Chemical processing results in clean fibres, while the matrix is converted into monomers, but this is not yet feasible as bulk recycling method. Overall, currently little reprocessing capacity is available and the recyclate value does not offset the costs [10,12]. Consequently, the majority of composite waste is landfilled or incinerated [13–15].

Landfilling and incineration are undesirable from many perspectives. Landfilling is at the bottom of the Waste Management Hierarchy, banned in an increasing number of countries and prevents further use of the material [16]. This option is not further considered in recovery frameworks, such as 9R [17]. Incineration recovers energy, but presents additional problems with release of toxic gases, fly-ash and the need to process the solid residue [11,15]. To prevent such treatments, we need reprocessing options that are efficient, cost-effective and have minimum environmental impact [11,18].

Designing out waste and keeping products and materials in use at the highest possible value are the core principles of a Circular Economy. By recovering products, components and materials, the Circular Economy aims to preserve resources functionality and value [19]. Most value is preserved when the product or material remains close to its original state; preserving its integrity [20]. Recycling is eventually necessary to prevent loss of materials, but is also the least preferred loop, as the effort invested in manufacturing is lost [21]. This is especially relevant for composites, which derive their high quality mechanical properties from a specific combination of materials, manufacturing process and design [22].

Structural reuse, sometimes referred to as “structural recycling”, presents a promising alternative EoL solution for composite products [23–27]. The process reuses the material as large parts or construction elements. Such reuse or “repurposing” of (partial) components is preferred over recycling [17,28]. Structural reuse prolongs the material lifetime, and potentially substitutes use of virgin materials. It preserves the structural integrity of the composite and needs relatively little reprocessing effort [23]. However, it is unclear how the original design of a composite product affects reuse of structural parts.

Design for structural reuse needs to be further investigated. Recent studies demonstrated the recovery strategy, but did not reflect on the original and successive product design [24]. Also, design aspects that facilitate structural reuse are addressed in the Circular Product Design framework for composites, but received little input from design practice [27]. Thus, there is still a clear gap between the concept of structural reuse and actual application in product design.

This study aims to gain insight into design of composite products for structural reuse in a Circular Economy and evaluate the Circular Product Design framework for composites [27]. To gain insight into design of composite products for structural reuse in a Circular Economy, a design case study was carried out. This explorative approach provides insights in the recovery process in relation to the initial design. The findings are of interest for design, engineering and recovery of complex composite products, as it offers potential for higher material yield and quality. Wind turbine blades were taken as carrier product as these represent a challenging case of composite material recovery [9,24].

This study followed three main phases which constitute the outline of this article: exploration, design case study and evaluation. First, the background of current blade design and the concept of structural reuse are explored in Section 2. Then the applied methods and materials are given in Section 3. Subsequently, the results of our design case study are presented in Section 4.1. Finally, the acquired design insights are evaluated in section 4.2, and the potential for implementation is discussed in Section 5.

2. Background

To gain insight into the context of structural reuse, this section provides a background on blade design characteristics and repurposing of decommissioned blades. The last part of this section expands on relating circular strategies, such as structural reuse, to design aspects, as this is a main framework for analysis of the results.

2.1 Wind turbine blade design characteristics

Wind turbine blades integrate aerodynamic and structural design [29,30]. The shells on the leading edge (1) and trailing edge (2), as well as the shear webs (3) use a sandwich structure to provide high stiffness for minimum weight (Figure 1). The spar caps (4) have a monolithic layup to provide longitudinal stiffness to the blade. Adhesive bonds (5) join the upper and lower half of the blade, which are produced separately. A Polyurethane surface coating (6) shields the materials from the environment and reduces wear.

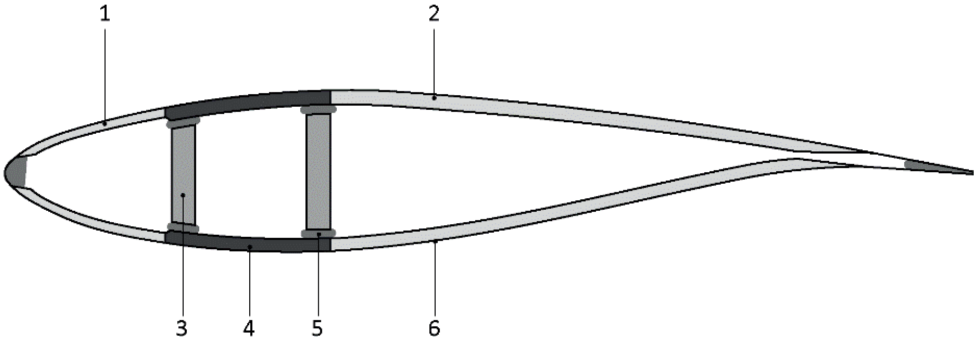

Figure 1 Sections in a blade cross-section: 1) leading edge, 2) trailing edge, 3) shear webs, 4) spar caps, 5) adhesive bonds, 6) coating

There are variations in design and materials composition. Siemens produces blades in one piece, using a closed mould and temporary insert, thus eliminating bond lines [31]. LM introduced a two-piece blade design to reduce transport cost and increase configuration options [32] and more developments are expected in this field [33]. While predominantly made of GFRP, blades over 50 m in length also use carbon fibre [34], as unidirectional reinforcements in spar caps or hybrid weaves for the shells [30].

Blade technology developments continue to maximize efficiency and lower overall lifetime costs. The product lifetime, high and cyclic loads make fatigue a main design driver [35]. Design and certification guidelines stipulate a design life of 20 to 25 years [36,37]. But, decommissioning is often primarily an economic decision [38]. This indicates that blades can still be in sound physical condition when decommissioned.

In addition to its initial design, the blade state depends on operation conditions like loads, number of cycles, environmental conditions, accumulated damage and maintenance history. Fatigue modelling, residual lifetime prediction and inspection technologies are therefore topics of ongoing research [39,40]. Measurements on a decommissioned blade showed the material retained its original stiffness and strength [23], but this may in particular hold for older blades. Newer blades have smaller safety margins and likely suffer more extensive degradation of strength and stiffness.

2.2 Repurposing of decommissioned wind turbine blades

The wind energy sector is one of the major consumers of composite materials. In 2017 this amounted to an estimated 150.000 tonnes used in Europe alone [41]. Considering market growth, the annual decommissioning of wind turbine blades is expected to reach 2 Megatons by 2050 [42]. These volumes require recovery at industrial scale. Even though it is expected that regulations will be put in place to extend the producer responsibility to the manufacturer of the blade [4,16], recovery is currently lacking in the design and certification guidelines for wind turbine blades [37,43].

Recent publications show a range of blade repurpose concepts, mainly in one-off applications: housing [34], power transmission line poles [44] and bridges [24,45]. Such studies demonstrate the feasibility of reuse, but point out that actual larger scale realisation needs to be studied further in terms logistics and costs, reprocessing technology, traceability of specifications, (residual) material quality and social acceptance in relation to the intended reuse application.

A well-known example of repurposing large parts is the Wikado playground in Rotterdam (Figure 2) [23,46]. The blades are generally considered safe to use in such a different application [24]. But precautions, e.g. surface treatments, are required to prevent exposing users to sharp glass fibres, and degradation of the resin from exposure to UV and moisture [47]. Such applications are, however, challenging to upscale. Beauson & Brøndsted (2016) [23] conclude that reuse of wind turbine blades as an entity or in parts is largely coincidental. As result, the volume of repurposed blades stands in bleak comparison to the surplus of EoL blade material [3,42].

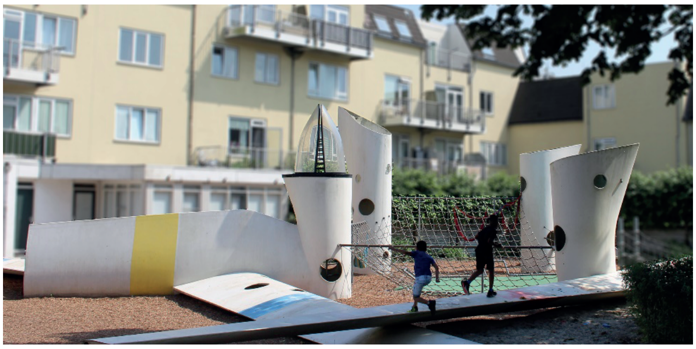

Figure 2 Wikado playground Rotterdam, photo by J. Joustra

Beauson and Brøndsted (2016) expect that cutting large blades into practically usable construction elements will diversify the potential applications . This could simulate larger demand, as construction elements are commonly used for diverse applications in building and construction, infrastructure and furniture industry. Initial experimentation showed that several high valued object can be made, as for example furniture [23,24]. This requires a two-step approach. First, the blade is segmented into reusable construction elements like panels (from shells and shear webs) and beams (from the spar caps). Second, the obtained elements are used in a next product lifecycle.

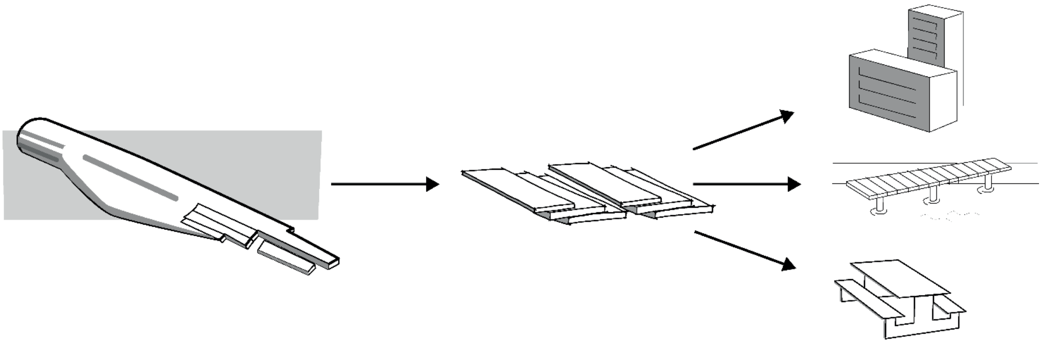

Figure 3 Structural reuse of a wind turbine blade: segmentation into construction elements, reuse in diverse applications. Building on [23,24]

2.3 Relating circular strategies to design aspects

To analyze how initial blade design affects the opportunities for circular strategies, a framework connecting circular strategies to design aspects is needed. The Circular Product Design framework for composites has been developed for this purpose [27]. The framework relates 5 circular strategies to 20 design aspects. These connections indicate how aspects in new product design can support recovery of products, parts and materials through particular circular strategies. For example, designing a product for adaptability and dis- and reassembly were found to facilitate structural reuse. In this study, we used the design aspects from this framework to code and analyse observations made in the design case study. Appendix A lists the design aspects and their descriptions.

3. Methods

Structural reuse of wind turbine blades and its relation to the initial design was investigated following a Research through Design approach. In this methodology, design plays a formative role in the generation of knowledge [48]. Research through Design, closely related to Design Inclusive Research, regards the act of design as essential for knowledge generation, in particular when the design task is carried out by the researcher himself [49,50]. Physical prototype development plays an important role, but is not a goal in itself. While it may result in interesting spin-offs, the prototype is an object of study. It is used to integrate knowledge from various fields and make a future situation observable [48]. In this case, insights on blade design, manufacturing, materials and recovery were elicited using a furniture prototype.

A design case study was done with recovered wind turbine blade material. This provided rich data on design, manufacturing and recovery, as well as on social acceptance of the resulting construction materials. Finally, insights were derived on how composite products can be designed to facilitate recovery of structural elements. The applicability of these insights were evaluated with experts from the field of wind turbine blade manufacturing.

3.1 Design Case Study

The design case study started by acquiring materials and formulating design requirements for the next lifecycle of the material in a new product. These two are strongly connected, as the material properties and prototyping possibilities set boundary conditions for the design project [50]. Blade material was made available for this study by a composite recycling company. The 80 m. long blade was originally made for testing purposes, its design specifications and origins were not disclosed. It was uncoated, making the Balsa core material clearly visible through the transparent GFRP laminate. The recycling company segmented the blade into pieces ranging from 0.3x0.5 m^2 up to 6x2 m^2 using a portable waterjet cutter. In these segments, we distinguish between panels and beams. Where, following the definitions of Ashby (2015) and Mallick (2007) [5,51], a panel resembles a flat slab, like a table top, and a beam is a slender structural member which can come in many shapes. The panels are retrieved from the blade shells, the beams are found in the spar caps.

3.1.1 Prototype design

We developed a prototype product using the panels from the blade shell. Furniture is identified as one of the potential sectors for reuse of structural elements in previous studies [23]. Moreover, it has the additional advantage of being recognisable to a broad audience, enabling discussions on the acceptation and perceived value of recovered materials. A picnic table was chosen as an appropriate example of a next lifecycle product, as such tables are typically made of standardised construction elements, yet allow for exploration of construction and shape.

Design for multiple life cycles is a distinguishing aspect in circular product design strategies [52]. Thus, subsequent structural reuse at EoL of the second lifecycle product was also considered. To enable successive recovery and use cycles, the next lifecycle product (i.e. the picnic table) was designed to enable both subsequent structural reuse as well as materials recycling. The design therefore had to allow for disassembly and prevent materials degradation during use. To enable recycling, addition of foreign materials was minimised to prevent further complicating the materials mixture for recycling.

Various prototypes were used in the design process. 1:20 scale models, including 3D printed parts of a wind turbine blade, were used to explore shape and segmentation into construction elements. Larger models (1:6 scale) were used to evaluate assembly and joints. These models were lasercut from 5 mm plywood, which corresponded to an average shell panel thickness of 30 mm. After detailing in Solidworks, a full size prototype was made to evaluate manufacturing and user perception.

3.1.2 Prototype manufacturing

The full-scale prototype was made with recovered blade materials. Components were cut from the blade material using a CNC waterjet cutter. The prototype was finalized and assembled by the researcher at the model building workshop of Industrial Design Engineering at TU Delft. The dimensional drawings are provided as supplementary materials to this article.

The manufacturing quality was evaluated by visual inspection of the cutting edges and measuring part dimensions. The cutting accuracy was then determined according to dimensional standard ISO 2768-m [53], a common standard for design drawings and component specifications.

The process was documented according to the critical journaling guidelines for Research through Design projects [54]. The documentation captured rich information on the evolving design, the materials at hand, and the structural reuse process as a whole. This design documentation included both observations and intermediate reflections on the process. As such it can be regarded as a combination of both field notes and analytical memos as described by Saldaña (2009).

3.2 Design insights and expert opinion

Design challenges were identified by tracing back observations from the design documentation to the original blade design. The design documentation was coded to reveal design features affecting recovery of construction elements. This was done for the original design (wind turbine blade), the recovery process (reuse as construction panels), the next lifecycle prototype (picnic table) and feedback notes (exhibition responses). This analysis followed a provisional coding approach [55], using codes derived from the Circular Product Design framework for composites [27].

Analysis of the coded observations resulted in design insights for structural reuse. These insights were annotated to a wind turbine blade drawing to directly connect them to the blade design and to trigger discussions with experts from the field. Two experts were selected based on their experience in design and engineering of wind turbine blades, for the manufacturing as well as the end of life stage. Both have working experience in industry as well as academia and contribute to innovations in the field, many of which aim for optimisation of manufacturing or recycling technologies. Expert 1 works in academia on new blade design and production techniques, and has an industry background in blade engineering. Expert 2 works at the research and development department of a large blade manufacturing company, and has a background in materials research. Expert responses were collected in a semi-structured interview [56] in which the annotated blade drawing served as interview guide. The interviews were conducted through a video call and took one hour each. Notes were taken during the interviews and connected to the proposed design insights afterwards. This reflection connected the design case study insights to industry practice.

Social acceptance and perceived material value was evaluated with potential users by exhibiting the prototype at the Dutch Design Week 2019, a week-long national design event held in

Eindhoven, The Netherlands [57]. The context of structural reuse was further presented with other exhibition artefacts. including a blade segment and scale models. Visitors were invited to talk through the project with the authors and share their views. Since it is of particular interest how "imperfections" in the shape and materials are appreciated, we indicated those and asked the visitors to explicitly reflect upon them. Responses were documented informally and reflected upon at the end of each day as described by Sadokierski (2019) [54].

4. Results

4.1 Design case study: Next Lifecycle Product design

The design case study started with acquiring segments cut from a wind turbine blade. The shape and structural properties of individual construction elements depend on where and according to which pattern they have been cut from the blade [24,34].

Due to the lack of specifications linked to the original design of the blade, the segmentation pattern was based on directly measurable and visible material properties: material composition (sandwich versus monolithic), surface quality, curvature and outer dimensions. From the segmented blade, we selected shell panels which showed no obvious surface damage, were portable and had dimensions that allowed reuse in furniture. The selected segments had a sandwich structure and ranged from 0.3x0.7 m^2 up to 2.5x1 m^2. The thickness ranged from 18 up to 40 mm, the core thickness transitioned stepwise.

4.1.1 Prototype design

In this design case study, the sandwich panels were reused for a picnic table, which served to explore opportunities and barriers for segmented reuse. The table consists of a table top and two seats, mounted to two frames. The effect of the blade's curvature was explored using 1:20 scale models (Figure 4). On scale, 0.3 m wide leading edge segments were used for the seats, a 0.8m wide trailing edge segment for the table top. In this way, both sections with strong and little curvature were used. As such, the sectioning pattern and next lifecycle product design were adapted to each other to deliver required components.

The design was then detailed and prepared for manufacturing. Rails and diagonal stringers were added to shorten the leverage arm on the joints, reducing loads and slack in the construction. Detailed designs were prototyped at 1:6 scale by laser cutting 5mm plywood. From these prototypes, it became apparent that the joining methods selected for the next lifecycle design (in this case the picnic table) are essential for performance in manufacturing, use and recovery.

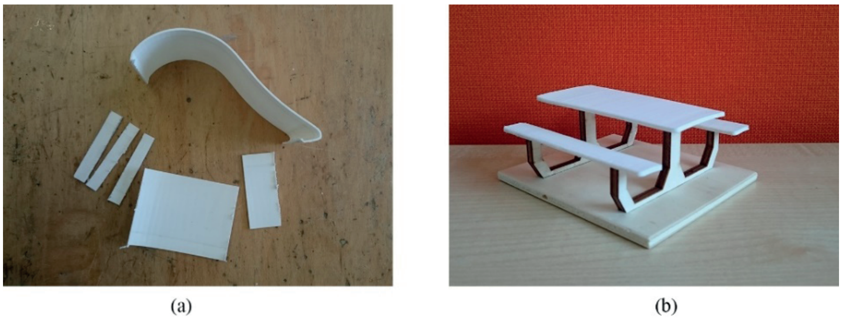
(a) (b)

Figure 4 Segments cut from a 1:20 scale blade(a) and used in a model (b)

Three connection types were investigated in the table: form fits, fasteners and adhesive bonding (Figure 5). Form fits, i.e., slotted joints, eliminate the need for additional processing and fasteners. However, these joints depend on part thickness for a good fit. In contrast to the 1:6 scale models, made of standard 5 mm plywood, the recovered construction panels exhibit variable thickness. This implies that the joints have to be dimensioned for each individual combination of panels. Fasteners on the other hand allow tolerance on mated parts, which is an advantage in this construction. These connections introduce additional materials (stainless steel) to the product. But upon disassembly, fasteners are directly separated from the composite parts, facilitating further reprocessing. Adhesive bonds connect the table top and seats to their respective support frames. These bonds avoid holes and thus water leaking into the sandwich material, especially on horizontal surfaces where (rain)water doesn't run off immediately. As Balsa wood is likely to deteriorate in moist conditions, adhesive bonds effectively prolong product lifetime by preventing water ingress. The adhesive bonds are designed to be disassembled by applying a perpendicular force, loading the bond in peel rather than shear. All connection types had their pros and cons, and not a single solution was ideal for all joints. Attention for recovery and reuse in design and prototyping led to selecting connection types that preserve material integrity and facilitate disassembly.

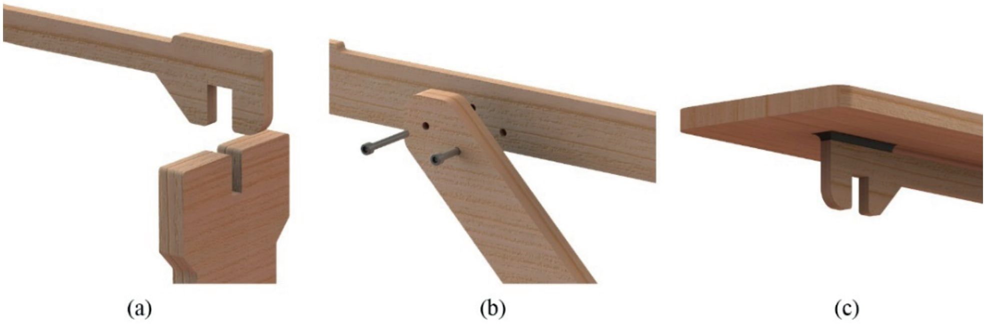

Figure 5 Connection types used in the table design. Form fits (a), fasteners (b), adhesive bonds (c)

4.1.2 Prototype manufacturing

A full scale prototype was made to test the material in manufacturing and use. The materials composition, a sandwich of Balsa and GFRP, can be cut with standard tools like (circular) saws and drills. Processing (i.e. resizing) of the panels was discussed with multiple workshops. Contrary to expectations, none was willing to work with the material. GFRP is known to cause excessive wear on tooling (e.g. sawing blades) and to generate fine dust, which irritates skin and respiratory system, as well as pollute dust extraction systems. Finally, waterjet cutting was found to address these concerns. In this process, the GFRP did not degrade tooling and dust was collected in the runoff water. The material supplier, a recycling company, used a portable waterjet cutter to cut construction panels of various sizes. Individual prototype parts were cut from these panels in a flatbed CNC-controlled machine. In the flatbed machine, the water was collected and cutting residue filtered out.

The prototype was finished by chamfering off the edges of table top and seats under a 45° angle, using P80 sandpaper. The thru-holes were accurately positioned and these parts were bolted together directly. The slotted joints needed additional sanding to account for local thickness variations and curvature of mated parts. Despite the high processing accuracy, new approaches need to be employed to deal with curvature variations induced by the initial design.

Figure 6 Picnic table prototype, made from construction elements cut from a wind turbine blade.

Waterjet cutting delivered high sectioning accuracy but inflicted minor damage to the core material. In general, the linear dimensions remained within 0.5 mm of the design specifications, and as such complied to tolerance class ISO 2768-m [53]. However, splinters broke away from the cutting edge due to the inhomogeneous nature of Balsa wood. Also, piercing points caused delamination of GFRP laminate faces, probably due to - brief- accumulation of water under high pressure within the sandwich material. This was prevented by pre-drilling through-holes at cutting path starting points. Thus, waterjet cutting delivered accurate sectioning lines, but needs improvement on piercing and cutting-edge quality.

Cutting the blade into construction panels and subsequently into table parts exposed materials that were sealed from the environment during first use (i.e. core materials and bare GFRP). Long term exposure to UV radiation is known to accelerate ageing of the matrix material, which may lead to discolouring (epoxy turning yellow or brown) or release of fibres. Moisture absorption of core material will lead to deterioration as well. In particular natural materials, like Balsa, are prone to rot. Thus, when the construction panels are used for outdoor applications, additional surface treatment is necessary.

4.2 Design insights and expert opinion

Notes were taken during the design, manufacturing and exhibition of the prototype. The notes were coded using the design aspects defined in the Circular Product Design framework for composites [27]. This resulted in insights on how to design a blade for structural reuse. In addition to the design aspects identified from the framework, two additional design aspects emerged: *Embedded markers* and *design for multiple use cycles*. The identified design aspects were annotated to a blade drawing (Figure 7), which served to trigger discussion with experts.

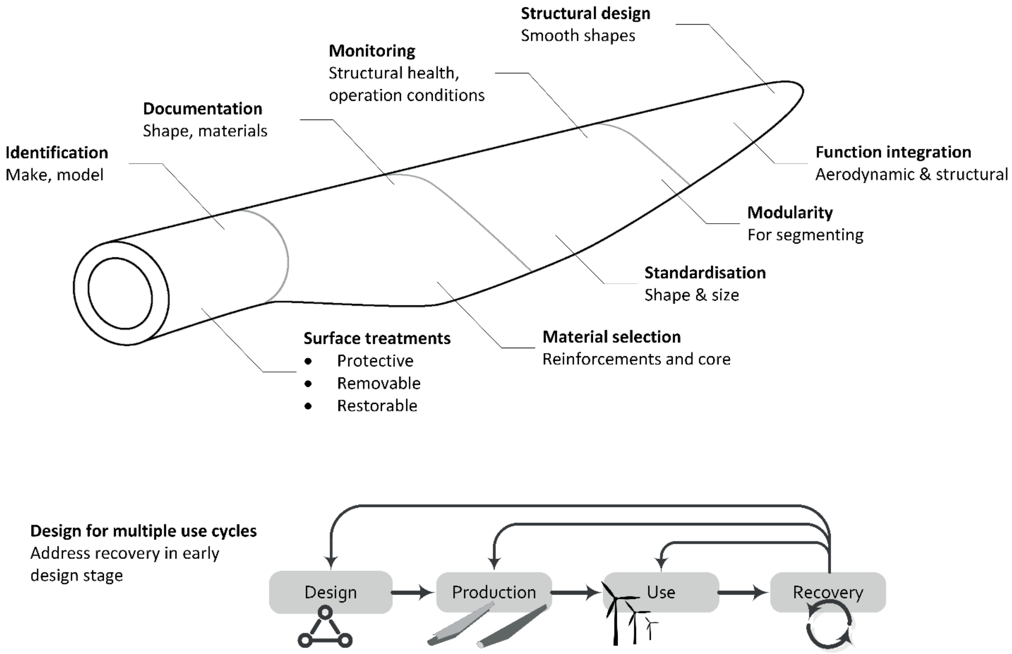

Figure 7 Blade annotated with Design for Structural Reuse aspects.

The design insights were evaluated with experts from the field of wind turbine blade manufacturing. Table 1 lists the observations from the design case study and expert evaluation per identified design aspect. The insights are further reflected upon in the discussion section.

Table 1 Observations and expert opinion on design aspects that facilitate Structural Reuse of wind turbine blades

Design aspect	Implementation, based on observations	Expert evaluation
Design aspects based on Joustra et. al. (2019) [27]		
Identification	Markers, labels or tags, enable tracing back the blade to its original design documentation.	Blades are labelled and listed in the manufacturer's database. In addition, blades are traceable through their (type) certification.
Documentation	Specifications like dimensions and layup enable setting out segmentation patterns and thus optimal recovery of construction elements. However, availability is often uncertain due to confidentiality. Also in this study we were unable to retrieve the blade specifications.	Design specifications could probably be made available for older models. Especially directly visible or measurable properties like shape, thickness and start of main laminate and balsa core.
Monitoring	To extend original design specifications into actual product state, its operational conditions should be known, e.g. from structural health monitoring systems, as well as damage and maintenance history.	Operating conditions are usually logged at nearby weather stations. Fully integrated blade measurements with corresponding logging and analysis are generally considered too costly.
Structural design	The blade structure makes for useful construction material. Using the right tools, it can be machined with good accuracy. The GFRP laminate acts as a protective layer for the softer core material. The blade could be prepared for structural reuse by designing curvature and laminate layup in line with a prospective segmentation pattern.	Gradual shape transitions are employed in blade design to avoid stress concentrations and provide good aerodynamics. Local changes to the structure likely introduce undesirable stress concentrations and complicate manufacturing. Expert 1 suggested spacing the core material in the cutting paths, so that the water jet will pierce solid matrix, rather than core material.
Function integration	Integration of aerodynamic shape and structural design complicates segmentation into construction elements. Although difference in scale between the original blade and table limits curvature over a single part.	The integration of aerodynamics and structure is optimised for the initial use case, and blade performance will remain a leading design objective.

Design aspect	Implementation, based on observations	Expert evaluation
Standardisation	Standardisation of curvature, dimensions, laminate layups and tolerances, construction materials will make construction elements less dependent on the original blade shape and size.	Curvature will remain subject to aerodynamic design requirements. Sandwich material thickness on the other hand is almost standardised, as core materials usually come in multiples of 5 mm.
Modularity	Modularity could facilitate disassembly and processing the blade.	Load concentration on joints, especially close to the root of the blade, challenge the feasibility. But for the tip section it is possible and has been applied.
Material selection	Both reinforcements and cores could be adapted to facilitate cutting, for example by locally applying monolithic laminates and/or homogeneous and water resistant core materials. Release of fibres and matrix deterioration needs to be prevented.	Glass fibre and carbon fibre composites are notoriously hard to cut once cured. For the core materials, polymer foams (i.e. PET) are used and continue to be developed for use in wind turbine blades.
Surface treatments	Precautions need to be taken to protect resins and core materials that are sensitive to environmental degradation, including edges exposed by segmenting. Balsa core material, clearly visible through the transparent GFRP, was found aesthetically pleasing.	If the underlying (core) material is visually less attractive, the blade could be produced with a coating that can easily be touched up or restored for the extended lifetime. Expert 1 proposed that the original coating can be removed and replaced by a transparent coating to reveal the underlying core material, to achieve an appearance similar to the material in this design case study.
Previously not reported design aspects relevant to segmented reuse		
Embedded markers	Integrating information within the product itself supports reprocessing in a later stage.	Marks, like small indents and lines, are already made in the mould to assist material placement during production. These marking points remain in the product as an imprint and are used for finishing work (e.g. drilling holes) and aligning connections. In the reuse stage, these markings can indicate the position of materials (e.g. start of main laminate) and segmentation patterns

Design aspect	Implementation, based on observations	Expert evaluation
Design for multiple use cycles	Taking a lifecycle perspective on new product development, anticipating recovery and reuse actions	Such planning is expected to be feasible in industry, and adopted if motivated by a business case or legislation. However, the longevity of composite blades creates uncertainty about future recovery scenarios. This uncertainty complicates decision making on which recovery scenario to design for. Changes in e.g. technology and policy can affect the business case and reprocessing options.

To evaluate acceptance and perceived value of the structurally reused materials, the prototype was placed at a design exhibition. The exhibition attracted about 25.000 visitors. Blade specific features, like panel curvature and imperfections visible through the transparent GFRP composite, went initially unnoticed by most visitors. When questioned, these features were found to contribute to the narrative and perceived value. Frequently, visitors expressed their interest, asked for the selling price and suggested potential other application areas for the material. Overall, visitors appreciated the reuse of wind turbine blades and perceived the structurally reused material and secondary application as valuable.

5. Discussion

Previous case studies demonstrated structural reuse as a viable and interesting recovery route for high end composite products. However, these cases were all occasional and, in practice, resulted in end of pipe solutions. This means that these demonstrators were developed coincidentally, based on available “waste” materials. In contrast, the current design study aimed to relate observations from structural reuse to the original design of a product and thus elicit how in the original of a complicated composite product reuse can be facilitate through design intent.

5.1 Design aspects

We established that construction elements of various size and shape can be retrieved from a single blade. By using the Circular Product Design framework for composites for analysis of the design documentation [27], we identified opportunities for purposeful segmentation and reuse. The insights obtained in this design case study largely match the design aspects connected to structural reuse in the framework. This provides grounding in design practice for the framework. In addition, we identified two previously not mentioned relevant design aspects. Below we will discuss a number of aspects that are specifically relevant when taking design for multiple lifecycles into account in the initial product design.

Documentation: While often considered confidential, the long lifespan of the blade may make design details less sensitive. Experts expected that basic specifications could be made available at the time of decommissioning. Finally, type certification, obligatory for all operational blades, may be used to retrieve specifications [43], although these do not reveal design details or structural specifications.

This study demonstrated basic reuse, based on limited information; the prototype was produced based on directly visible or measurable properties. We expect that more detailed information will enable more optimised reuse cases, more effectively reusing the material's mechanical performance.

Monitoring: Various measurement techniques are used to monitor a blade's structural health during operation. These logged data could be used to estimate end of life material quality, which might have suffered from fatigue and occasional damage. When not available or of insufficient detail, desired specifications could be revealed by testing or reverse engineering approaches [58,59].

Modularity: Modularity was discussed as potential feature to facilitate disassembly and segmenting the blade. The concept was proposed before as a solution for production and transport of increasingly large blades [33]. A more radical approach would be to move towards a modular design, where structural functions are integrated in the aerodynamic shape, yet constructed in segments. Experts expressed their concerns regarding load concentration on joints. Thus, the implementation and objectives need to be carefully weighed in the design process.

Embedded markers: Embedded markers can be an effective means to transfer product information to the recovery stage. This could be small indents, lines or colour markers placed during production. These can indicate material positions, segmentation patterns or to align a coordinate system. The latter could enable defining the cutting pattern at the decommissioning stage. Embedded markings build on existing production techniques and require, according to the experts, little change to be implemented, but do require attention to recovery in the early stages of product design.

Design for multiple use cycles was recognised as prerequisite for successful incorporation of structural reuse in design. Structural reuse opportunities are affected by shape, materials and structure of the original product. Thus, anticipating multiple use cycles is required in the early design phase and will result in additional design criteria for the original product design. When regarding reuse from the perspective of construction elements instead of fully functional products, the need for detailed product specifications is replaced with basic dimensions, properties and tolerances for elements to be retrieved.

Some design aspects mentioned in the framework, notably selection of connections, dis- and reassembly, and manufacturing were not explicitly discussed by the experts. However, the experts addressed these aspects implicitly when discussing modularity. The relation between these design aspects and modularity is known for wind turbine blades as well as for other product types [21,33,60]. Reusing recovered construction elements as-is was one of the starting points of this design case study. As a result, the design aspect of adaptability was not addressed in this study, nor discussed by the experts.
In general, thermoset-based composites do not lend themselves for shape adaptation in the sense of re-moulding, but this could be an interesting option for thermoplastic composites [5].

In the case of wind turbine blades, the design constraints determined by effectivity in the use phase leave little room for adaptations to facilitate reuse. With the industry focus on lowering the cost of energy, it is realistic to pursue design interventions that do not impede the primary function of the product. However, availability of documentation, and use of embedded markers, could facilitate reuse in a straightforward way. Adapting the materials position in the product to facilitate cutting of predefined construction panels may seem straightforward, but might have major effects on load paths and structural performance. Nevertheless, developing a smart segmentation pattern to deliver reusable construction elements from existing blade designs seems feasible.

5.2 Circular Economy perspective

The discussed insights indicate that Design for multiple use cycles is an important step in designing for structural reuse and should be taken into account in the original blade design. This is in line with Circular Economy principles, which emphasize the importance of systems thinking and designing for multiple use cycles [19]. Both have been identified as core competencies and major challenges for designers in a Circular Economy [52]. Unfortunately, experts and literature note that the full product lifecycle is difficult to grasp for designers [61]. Ongoing developments change the context of manufacturing, use and decommissioning. This results in uncertainty about future scenarios, which complicates decision making in the design process. In this study, this has been managed by not reusing the product as an entity, but by dividing the product in construction panels that allow for more versatile next life cycles.

To establish recovery pathways for wind turbine blades in a Circular Economy, many stakeholders have to collaborate. Recovery can be organised in a closed system or an open system [62]. In a closed system, the control over the product remains with the manufacturer. Being responsible and carrying the costs, the manufacturer directly benefits from design adaptations that facilitate collection and reprocessing.

The open system is currently in effect for wind turbine blades; recovery of products, components and materials is not pre-defined but left to the market. However, the incentive in the open system relies on direct profitability of the recovery process, which thusfar is questionable for composites. The manufacturer has little stake in the end of life of the blades and thereby has little incentive to act. Future policy regarding waste management is likely to change the context for decommissioning of wind turbine blades. Regulations have already been put in place for the automotive and electronic industry; composite materials, and wind turbine blades in particular, are expected to follow [16,63].

5.3 Future outlook

The structural reuse concept aims for the production of large series of standardised construction panels and beams. The prototyped picnic table is just an example of the many product applications that can be envisioned for structural reuse of composite plate materials. Other possible applications can be found in architecture (e.g. façades, roofs), infrastructure (e.g. jetties or bridges) but also in transport (e.g. cargo-loading floors in barges and trucks). The exploration of additional product categories might lead to the identification of additional relevant material requirements and design aspects.

The annual volume of decommissioned blades calls for a systematic approach that enables upscaling of the structural reuse process to an industrial scale. Further research into structural reuse could include determining prospective reuse applications, evaluating (residual) properties and defining sectioning patterns. These topics are relevant for processing various blade types and sizes, as well as other complex composite products. We expect that the same design aspects will apply, but further research is necessary to verify this. The minimal mechanical quality of the blade material to warrant reuse needs to be defined and related to the initial design. A smart segmentation pattern and evaluation of the design specs can classify recovered segments into categories and types of reuse. Cutting patterns and mechanical performance of resulting construction elements are further explored in a complementary study [64].

6. Conclusion

Insights on design for structural reuse of composite products have been obtained through a design case study investigating the relation between structural reuse of segmented plates derived from a wind turbine blade and its original design. Wind turbine blades were taken as case product, as these represent a challenging and pressing recovery problem. Panels from a decommissioned wind turbine blade were reused in a next product lifecycle, in this case a picnic table, aimed to explore design related opportunities and barriers regarding manufacturing, recovery and user perception in segmented reuse.

Current design of wind turbine blades does not take structural reuse into account, even though the potential of this recovery strategy is acknowledged and has been demonstrated in occasional applications. However, construction materials with valuable mechanical and aesthetic properties were retrieved with relatively little processing effort. In fabricating the physical prototype, waterjet cutting delivered high sectioning accuracy but the quality of the edges can be improved. Despite the high accuracy, new segmentation approaches need to be employed to deal with curvature and thickness variations induced by the original design.

The original shape and material composition affect the options for a next use cycle. We derived design aspects that enable structural reuse by design. The presented design aspects build on and expand the Circular Product Design framework for composites. The design case study and evaluation with experts grounded these insights into design practice and resulted in the identification of two additional design aspects: *Embedded markers* and *Design for multiple use cycles*. The first aspect builds on composite manufacturing practice, the second is necessary but challenged by uncertainty about future recovery options.

This study investigated structural reuse as recovery route for high-end composite products from a design perspective. Overall, it is advised to take the next use cycle into account in the design stage. The insights presented in this paper enable designers to contribute to establishing a Circular Economy for composite products.

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Chapter 5

Structural Reuse of Wind Turbine Blades Through Segmentation

This chapter was published as Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. Composites Part C, 5(100137). https://doi.org/10.1016/j.jcomc.2021.100137

Abstract

Composite materials offer many advantages during the use phase, but recovery at the end of a lifecycle remains a challenge. Structural reuse, where an end of life product is segmented into construction elements, may be a promising alternative. However, composites are often used in large, complex shaped products with optimised material compositions that complicate reuse. A systematic approach is needed to address these challenges and the scale of processing. We investigated structural reuse taking wind turbine blades as a case product. A new segmentation approach was developed and applied to a reference blade model. The recovered construction elements were found to comply to geometric construction standards and to outperform conventional construction materials on specific flexural stiffness and flexural strength. Finally, we explored the reuse of these construction elements in practice. Together, the segmentation approach, structural analysis and practical application provide insights into design aspects that enable structural reuse.

Keywords: Composite materials; Circular Economy; Recovery; Structural reuse; Design; Design Strategies; Wind turbine blades

Abbreviations: Circular Economy (CE), End of Life (EoL), Glass Fibre Reinforced Plastics (GFRP), Uni-Directional (UD), Double-Bias (DB)

1. Introduction

Composite materials, known for their lightweight properties, are often used to make products more sustainable. Lightweight designs reduce fuel consumption in transport applications, and thereby effectively reduce the carbon footprint [1]. Lightweighting also allows efficient material use, and makes large spans in building and architectural applications possible [2]. Composites are used to maximise performance of these structures. However, when the complete lifecycle is taken into account, the environmental advantage of using composite materials becomes less evident [3,4].

The lifecycle perspective is central to the Circular Economy (CE) concept. The CE aims to preserve resources by keeping products and materials ‘in the loop’. This can be done through extending product lifetime and recovering products, components and materials when they reach their end of operational life [5]. Maintaining product integrity, through e.g. reuse, repair or remanufacturing, is considered most desirable. Material integrity, i.e. recycling of material, is a necessity when products can no longer be kept alive. Preferably, recycling retains material properties and avoids downgrading [6,7].

Composite materials enable long product lifespans and require little maintenance. High quality repairs can be made in situ: restoring original strength and appearance [1,8]. Reuse at product level is more difficult because the material composition is often optimised to a specific application. This maximises the performance in the use phase, but complicates reuse in another context. For example, wind turbine blades cannot readily be exchanged between wind turbines. Consequently, material recycling remains as the only recovery option.

Recycling composite materials is challenging due to the way in which various materials are structurally combined at a sub-millimetre scale. Thermoset resins and glass fibres, Glass Fibre Reinforced Polymers (GFRP), constitute the majority of composite materials in today’s market [9]. For these materials, co-firing in a cement kiln remains the advised recovery route [10]. However, the energy gain is low, the material is lost for further use and the economic perspective is limited [11–13]. Thus, much of the material is landfilled, resulting in a loss of materials and value; and as such landfilling is at the bottom of the waste management hierarchy. To prevent such loss, landfilling of composites has already been prohibited in a number of countries [14,15].

There are various explorations into circular systems for composite materials. For example, current research programs include demonstrators for circular composite products [16,17] and recovery of End of Life (EoL) wind turbine blades [18]. Moreover a number of companies have developed new reprocessing methods to close the composite material loop [19–22]. At a governmental level, the increased use of composite materials is likely to lead to new policy targeting recycling [23–25]. In the meantime, composite products nearing their EoL present a pressing problem. Current recycling capacity is insufficient while in coming decades the composite waste volume will increase strongly [26,27]. Better solutions to deal with EoL composite products are therefore urgently required.

Structural reuse, also referred to as structural recycling, is an attractive alternative solution for EoL composite materials [28–32]. Rather than shredding the product and attempting to separate reinforcements from the matrix, as is done in current recycling processes, the composite is reused as a structural material. Compared to current recycling practices, structural reuse requires relatively little reprocessing effort and, to a large extent, retains the material quality [29]. As such it is a compelling alternative route to recapture value and extend the lifetime of the material. Reuse can be done by directly harvesting large parts or by cutting construction elements from the EoL product.

Structural reuse has been demonstrated for wind turbine blades, see e.g. [29] for an overview. Blades are interesting objects for this reuse approach as they retain high structural quality, even after 20 years of use. Moreover, blades consist of multiple materials and layup types, which can be reused in many different applications.

Large structural parts have been repurposed for example for outdoor applications such as street furniture and a playground [33]. However this practice is regarded as being difficult to upscale. The large size, complex shape and complex material composition all restrict reuse opportunities [34]. It is expected that cutting-up these large structures into practical and usable construction elements like beams and panels will diversify the potential applications [28].

In an earlier design study we explored the reuse of construction elements from a wind turbine blade [35]. We found structural reuse to be feasible, but new segmentation approaches need to be employed to deal with the product's complex shape and structure. In addition, we expect that the yield of reusable construction elements from a blade can be higher and, with a good patterning approach, the reuse process can be made more efficient. This gave rise to the following questions concerning structural reuse of composite product, which are addressed in this paper:

- How to determine a segmentation pattern to obtain reusable construction elements?
- How to compare structural quality of recovered construction elements to conventional construction materials?
- Which design aspects enable or limit structural reuse?

2. Materials and methods

For this study, we took wind turbines blades as case product as these represent a real and pressing recycling problem. We studied structural reuse of composite materials from a wind turbine blade using the following approach. First, segmentation patterns for construction elements were determined based on the structural and geometric specifications of the wind turbine blade. Then, the structural properties of these construction elements were evaluated and compared to conventional construction materials. To test the reuse approach, a relatively simple product was made from retrieved panels. Observations made during this process were then related to design insights.

2.1 Materials

A reference blade model was used to analyse blade design and to determine segmentation patterns and structural properties of recovered materials. The blade model was developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, based on a study by the Dutch Offshore Wind Energy Converter (DOWEC) project [36–38]. This model was used, because in contrast to commercial blades, this blade was developed for research purposes and its specifications are publicly available [39]. The blade measures 61.5 m in length and was designed for a 5MW turbine. Turbines of this size are found both onshore and offshore, which makes it representative for current installations [27,37].

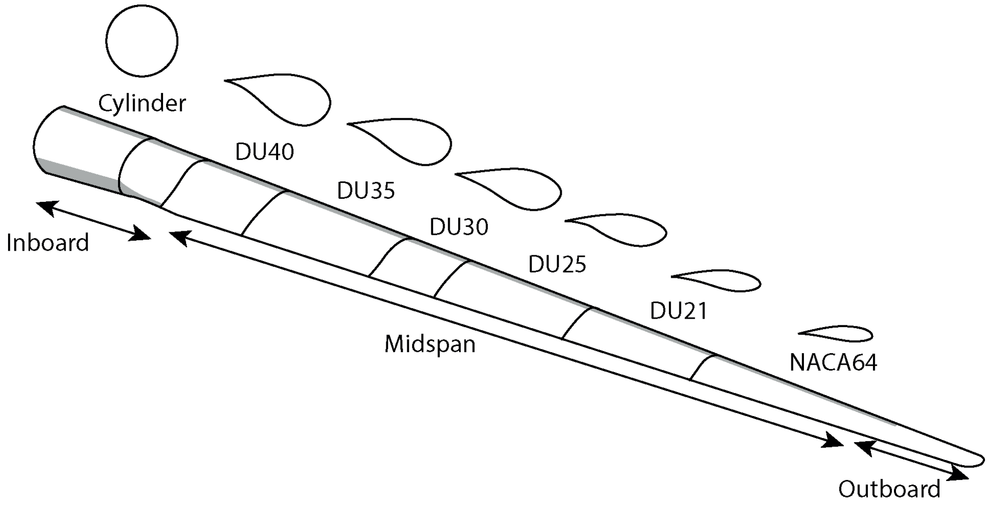


Figure 1 Schematic representation of NREL 5MW blade, showing airfoils and main sections [36,40]

The blade consists of three sections from root to tip: inboard, midspan and outboard (Figure 1) [36]. The largest bending moment is exerted on the inboard section, where the blade is joined to the turbine axis. This section starts at rotor radius r=1.8 m (taking hub diameter into account). It is a plain cylinder with a wall thickness of 61 mm, made of a solid glass fibre reinforced epoxy laminate with a triaxial layup. The midspan starts at r=10 m and ends at r=54.5m. The shells, made with a sandwich layup, taper from 100 mm to 25 mm thickness. The spar caps taper from 48 to 20 mm. The layup consists of triaxial GFRP skins, foam core and glass fibre as well as carbon fibre UD reinforcements. The midspan section comprises six airfoil profiles, five of which were selected from the Delft University (DU) systematic airfoil series. The aerodynamic profile tapers towards the tip to meet aerodynamic and structural requirements. The outboard (tip) section has a relatively flat airfoil profile because it has to cope with high air speeds. In commercial blades, this section is often pre-bent to prevent collision with the tower when the blade deflects under load.

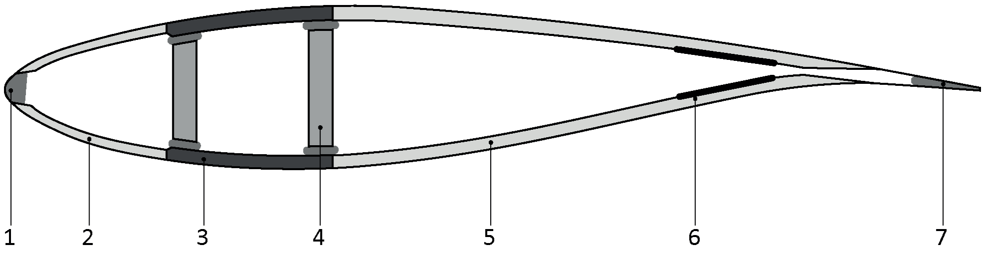


Figure 2 Cross-sectional profile of a wind turbine blade, showing parts and structural design.

The structural and aerodynamic performance primarily determine the design (Figure 2) [34,37]. The spar caps (3) and shear webs (4) make up the main structural elements of the blade and function as a box beam to provide longitudinal stiffness. The panels of the leading edge (2) and trailing edge (5) give the blade its aerodynamic shape. The trailing edge has additional reinforcements (6) to alleviate edge-wise bending moments. The blade top and bottom shell are produced separately and joined at the leading edge (1) and trailing edge (7), as well as on top and bottom of the shear webs (4). The panels (2, 5, 6) and shear web (4) are made with a sandwich structure. Spar caps (3) are made with a monolithic carbon fibre laminate and covered with the same GFRP face laminate as the panels.

We retrieved material properties for calculating the structural characteristics of blade segments from the original blade design specifications [37]. Specifications missing from the design report were supplemented with values from equivalent materials in the CES Edupack level 3 database [41]. Table 1 lists the materials and specifications. Density of carbon fibre UD was calculated using from the material datasheets using the rule of mixtures [42–44].

Table 1 Properties of materials used in 5MW blade [37] used to calculate mechanical properties of recovered construction elements. Values marked (a) are supplemented from CES database, (b) calculated from material datasheets.

Material	E-modulus	Shear modulus	Poisson's ratio	Density	Tensile strength	Compressive strength
	[MPa]	[MPa]	[-]	[Kg/m^3]	[MPa]	[MPa]
GFRP UD	41,800	2630	0.28	1920	972	702
GFRP Triax	27,700	7200	0.39	1850	700	292_a
GFRP DB	13,600	11,800	0.49	1780	144_a	213
Foam	256	22	0.3	200	5.6_a	4.4_a
CFRP UD	114,500	5990	0.27	1545_b	1546	1047

2.2 Methods

We investigated structural reuse by developing a segmentation pattern, analysing the structural performance of the retrieved elements, and exploring their application in practice. Using the segmentation approach, we can explore various cutting patterns and calculate how effective they are in delivering reusable construction elements. The structural analysis allowed a comparison of the retrieved elements with conventional construction materials. Exploring the application of reused construction elements gave insight into its practical feasibility and the role of design.

2.2.1 Segmentation patterns

The NREL 5 MW model was analysed for recovery of construction elements by evaluating the structure and form. The NuMAD wind turbine blade design tool [45], was used to calculate the weight of individual parts like leading edge panels and spar caps. The calculated properties were verified with distributed blade properties provided by Sandia [37]. In addition, a physical decommissioned blade was inspected to investigate practical implications of construction and recovery which were not addressed in the design report [37].

The succession of aerodynamic profiles along the blade length indicates where the cross-sectional profile is constant or where shape transitions occur. Changes in pitch and chord length indicate the twist and tapering of the blade surface. The twist is constant for the majority of the blade length, but the cross-sectional curvature needed to be calculated.

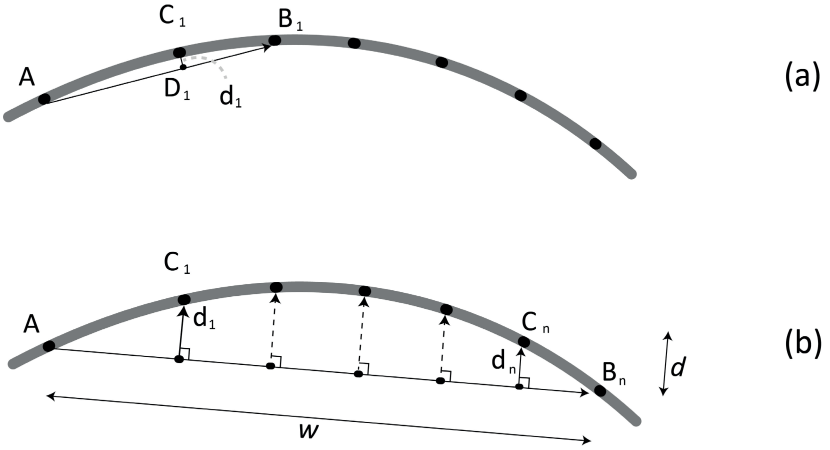


Figure 3 Calculating panel deflection d between points A and B on the airfoil profile.

We calculated the closest distance between a point and a line using vector calculus [46]. The calculation started with a set of 3 points: start point A, endpoint B and intermediate point C (Figure 3a). Here, length AB corresponds to the segment width *w* and the maximum perpendicular distance from line AB to a point C on the curve AB corresponds to segment deflection *d*. The objective of the function was to achieve the largest possible segment width *w* for a given curvature *d/w* or deflection *d* (Figure 3b).

We applied two segmentation approaches to determine panel segmentation patterns based on curvature and deflection (Table 2). The first approach is governed by *d/w* and delivers panels with equal curvature [47]. The second approach is governed by *d* and delivers panels with equal segment deflection. The cutting pattern is aligned with the blade's longitudinal axis, perpendicular to the airfoil section.

The dimensional standards for construction timber were used as boundary conditions as standards have not yet been established for the recovery of composite materials. Timber element shapes depend, like the recovered composite segments, on raw material shape as well as prospective application areas. The tolerances are given in Table 2. The goal of the segmentation was to obtain panels with a width and curvature suitable for reuse as construction material.

Table 2 Boundary conditions for dimensional deviation of a curved construction element, based on NEN 5461 timber standards [47]

Dimensional deviation	NEN 5461	Curvature *d/w*	Deflection *d [m]*
Small	$d/w < 0.02$	$d/w < 0.02$	$d < 0.02$
Medium	$0.02 < d/w < 0.04$	$d/w < 0.04$	$d < 0.04$
Large	$d/w > 0.04$	$d/w < 0.08$	$d < 0.08$

The cross-sectional segment shape also depends on the cutting angle, for example perpendicular to the local blade surface, airfoil chord or panel chord. Although this affects the cross-sectional shape of the resulting panels, calculation shows minimal effects on cutting losses (<<1wt%). Furthermore, the alignment does not affect segmentation patterns or material performance, and is therefore not further detailed in these analyses. In practice, the alignment will depend on the processing context (i.e. cutting tools and handling equipment) and intended panel reuse applications.

2.2.2 Structural properties

The material properties of the recovered elements were calculated and compared to conventional materials. The goal was to evaluate the material's performance and identify potential application areas. The materials were compared using the level 3 database of Granta CES Edupack 2019 [41]. Properties of the recovered materials were calculated using the Granta CES Hybrid Synthesizer and the blade design specifications given in Table 1. The sandwich material model was used for all parts and properties, except for the density (ρ) and flexural modulus (E_{flex}) of the trailing edge reinforcements. There, the multilayer model was used to account for the additional UD layers. The calculation used a distributed load condition and a segment length of 4.1m, which corresponds to the spacing between consecutive aerodynamic profiles in the blade model.

To evaluate structural quality at end of use, we considered a range of material properties, rather than a single value. For the minimum value, we assumed the blades can still operate under the design load case at the point of decommissioning. For the maximum value we used the original design specifications, which included additional safety factors. Thus to get the minimum values, the original design specifications for stiffness and strength were divided by their respective safety factors. To reflect the blade design specifications, we used the safety factors as stated in the original design report: 1.485 for stiffness and 1.755 for strength [37]. The material density remains constant along the product lifespan.

The calculated values were then plotted on material property charts to enable comparison with conventional construction materials. The materials were compared based on density (ρ), flexural modulus (E_{flex}) and flexural strength (σ_{flex}) [44]. These properties combined indicate the performance of the materials for lightweight constructions loaded in bending [44].

2.2.3 Application

To explore the implications of structural reuse in practice and the role of design, we conducted a design study on a decommissioned wind turbine blade [35]. Panels from a blade were used to design a simple furniture product, which was subsequently built and evaluated. The study followed a research through design approach [48,49] which provided rich data on recovery, design and manufacturing, as well as on user acceptance of the resulting construction materials. The design and reuse of the blade were evaluated using a preliminary set of design aspects [32]. Together, the segmentation approach, structural analysis and practical application provided insights into design aspects that enable structural reuse.

3. Results & discussion

The structural reuse of composite parts was evaluated using a reference wind turbine blade. The segmentation approach starts by assessing the product shape and structure, followed by a more detailed approach, which takes local curvature into account. The segments are then evaluated for their structural performance. The segmentation and structural evaluation provide insight into design aspects that facilitate structural reuse.

3.1 Segmentation patterns

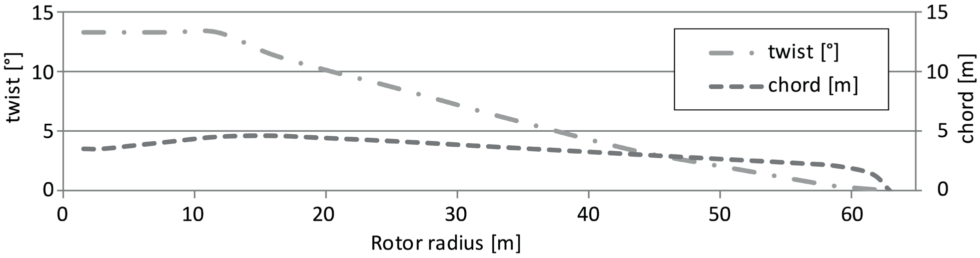


Figure 4 Twist angle [°] and chord length [m] of the airfoil profiles along the blade length.

The blade midspan section, which comprises nearly three-quarters of the blade length, offers the best opportunities to retrieve continuously shaped construction elements. In this section, all profiles are selected from the same systematic airfoil series. The linear decrease of chord length (3 cm/m) and twist angle (0.25°/m) indicate continuous tapering and twist of the blade towards its tip (Figure 4). Together, these form factors allow for smooth shape transitions along the blade length. Thus, construction elements recovered from the midspan section will have relatively straight shapes, despite their aerodynamic origins.

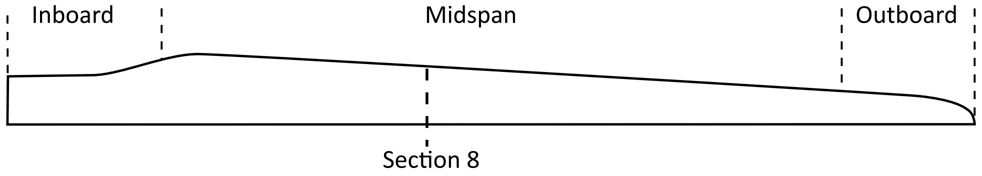


Figure 5 Sketch of the blade and its sections. Cross-section 8 is used for further analysis.

To find the types of construction elements and their properties, the blade structure was reconstructed for section 8, as shown in Figure 6 and Table 3. This section is positioned in the middle of the blade, at radius r=28.15m (Figure 5). Here, airfoil DU25-A17 is used with a chord length of 4.01m. Two composite layup structures were used: a sandwich layup for the panels and shear webs (2, 4, 5 and 6), and a monolithic laminate for the spar caps (3) as well as bonding areas at Leading Edge and Trailing Edge (1 and 8). This structural design provides a starting point for segmentation.

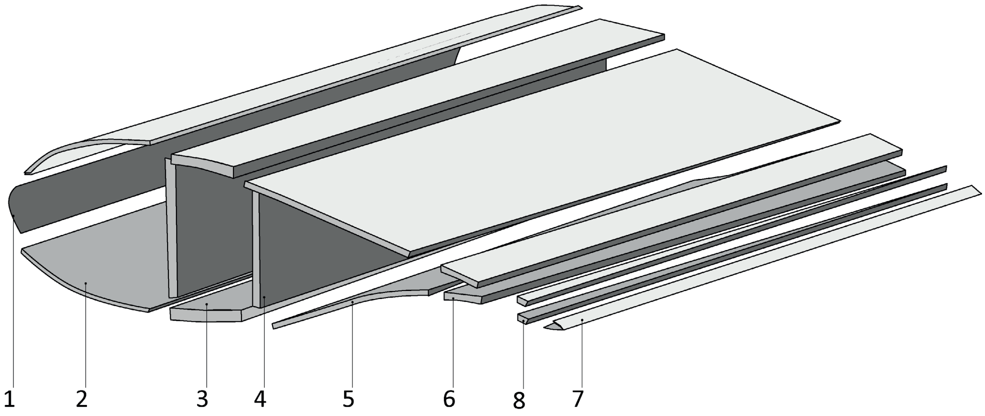


Figure 6 Structural segmentation of the blade

Table 3 Parts, weight, weight percentage, structure and construction element types found in blade segment 8.

#	Part	Materials	Mass [kg]	Weight [wt. %]	Element type
1	Leading Edge	Solid GFRP, adhesive	17	2%	None
2	Leading Edge Panels	Sandwich	151	14%	Panel
3	Spar caps	Solid GFRP & CFRP	340	33%	Beam
4	Shear webs	Sandwich	132	13%	Panel
5	Trailing Edge Panels	Sandwich	304	29%	Panel
6	Reinforced Trailing Edges	Sandwich	73	7%	Panel
7	Cutting losses (tapering)	Sandwich	16	1%	None
8	Trailing Edge	Solid GFRP, adhesive	9	1%	None
	Total		1042	100%	

As a starting point for the patterning, the blade cross-section can be divided into two types of construction elements: panels (63 wt%) and beams (33 wt%). Panels can be recovered from the leading edge panels, shear webs, trailing edge panels and reinforced trailing edge (2, 4, 5 and 6). Beams are found in the spar caps. Alternatively, the spar caps and shear webs can be retrieved as-is, to be reused as box-beam. In this study, we chose to take them as separate parts, as this permits a clearer structural comparison.

Some cutting losses will occur, caused by the adhesive bonding areas (3 wt%), tapering of the panels due to decreasing chord lengths (1 wt%) and processing (minimal). The adhesive bonds at the leading edge and trailing edge (1 and 8) obstruct recovery of construction elements. These parts have a mixed materials composition, a strong curvature, and the structure transitions from sandwich to monolithic. Moreover, physical inspection of a decommissioned blade revealed poorly defined bonding areas and abundantly applied adhesives, which challenges the recovery of uniform materials. Tapering of the blade results from decreasing airfoil chord lengths and causes triangular shaped offcuts (7). For the weight calculation, we assumed these to be deducted from the trailing edge reinforcements. The processing losses were found to be negligible; the waterjet cutter used in the application test had a jet diameter of 0.7 mm, and thus minimal cut losses. As such, these were not further taken into account. Still, even after excluding these bonding areas and offcuts, 96% of this section could be cut into reusable construction elements.

However, it is not realistic to assume that 96% of the complete blade can be reused; this estimate is based on a profile in the blade midspan, which constitutes 58% of the complete blade mass. The blade root (40 wt%) and tip (2 wt%) cannot be directly segmented into construction elements. The root is a cylinder with an average diameter of 4m and length of 10m, it is challenging to cut due to its thick and solid GFRP walls. The blade tip is made of relatively flat airfoils but is pre-bent to prevent tower collision. This pre-bend adds to the shape complexity and thereby complicates segmentation and reuse. Thus, focusing on the blade midspan, and accounting for offcuts, we expect up to 55 wt% of the blade can be segmented into construction elements.

The original design determines what kind of construction elements can be recovered in terms of size, shape and structural layup. These properties gradually taper towards the tip of the blade which leads to a large distribution of properties of the recoverable construction elements. In addition to properties imposed by the original design, the reuse application can also present design requirements. These requirements are usually defined in terms of size, mass, stiffness and strength, accompanied by tolerances and safety factors. These can then be used as boundary conditions for the segmentation pattern. To extend reuse opportunities beyond a single product, we used construction industry standards for this purpose [47].

The spar caps (3) and shear webs (4) are positioned directly above and aside from the blade reference axis, which is aligned with the maximum airfoil thickness. Along the midspan, the spar caps have a constant width of 0.6 m. The shape of these elements is predominantly determined by blade twist and layup thickness. A beam, cut from the spar cap will twist 0.002m per metre length, which corresponds to a “very small” dimensional deviation [47]. Thus, beam elements can be recovered directly from the spar cap. The surface panels (2, 5 and 6) however, have a more complex double-curved shape and need further assessment. Table 4 and 5 show the results for segmentation using the two boundary conditions, based on curvature *d/w* and deflection *d,* for tolerance criteria small, medium and large respectively.

Table 4 Segmentation patterns using curvature d/w as boundary condition

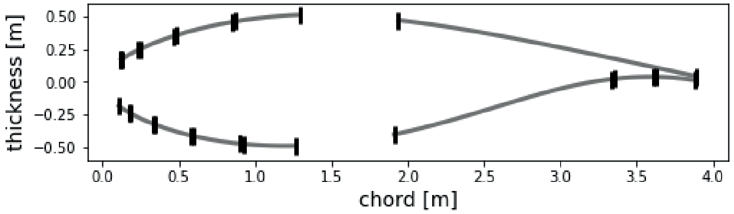
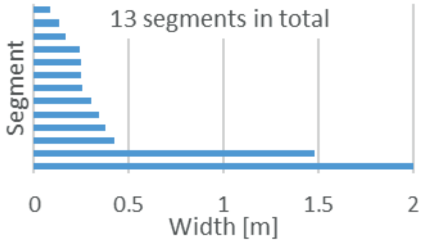
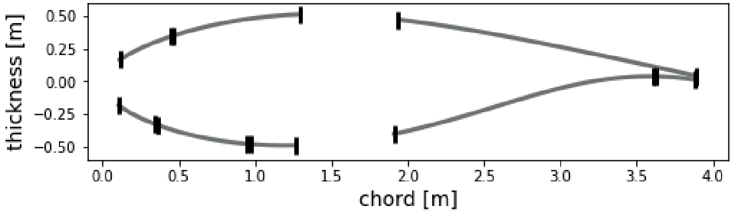
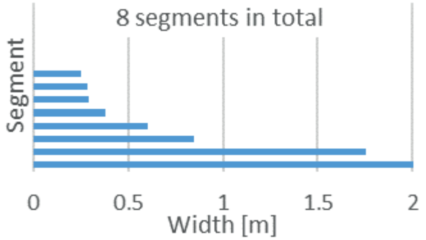
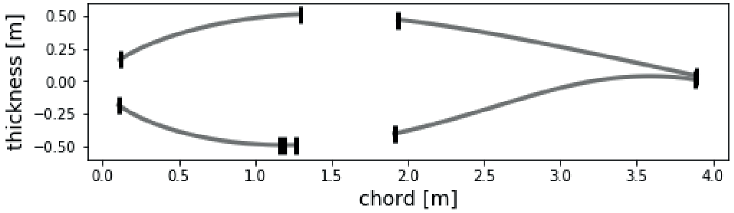
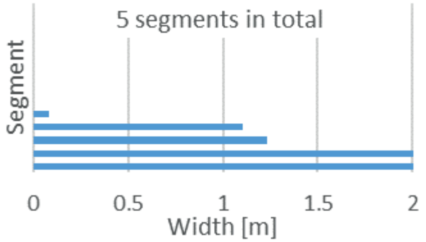
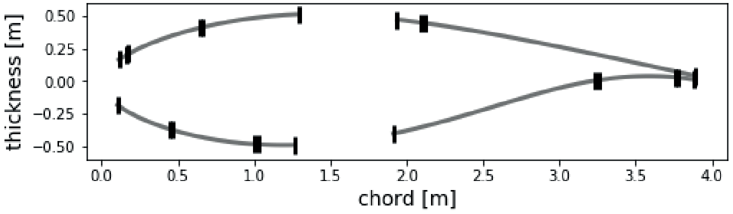
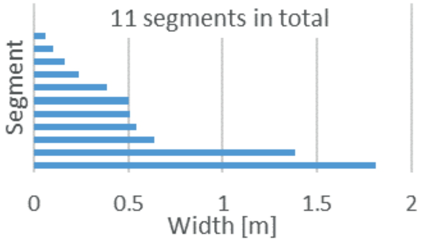
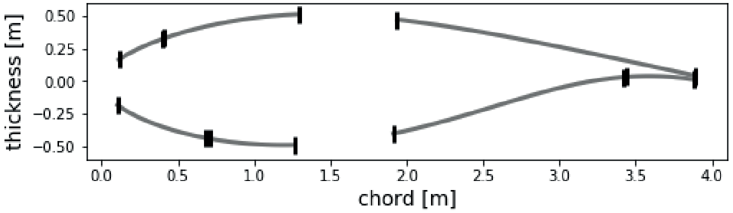
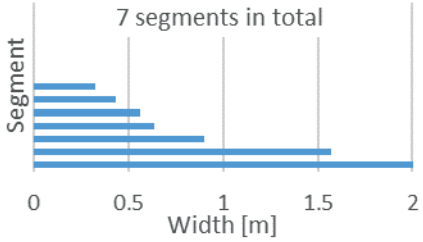
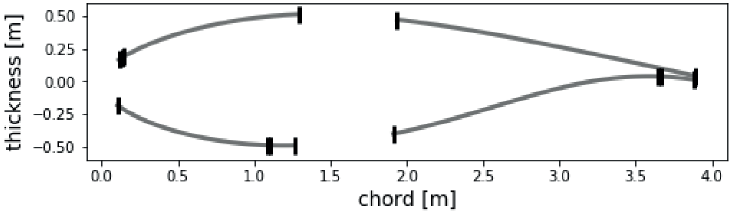
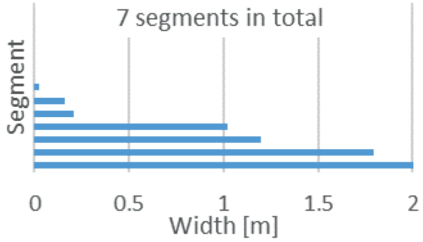
d/w	Segmentation pattern for maximum curvature, *d/w*	Segment width *w*
0.02		
0.04		
0.08		

Table 4 shows the segmentation patterns and resulting segment widths for blade section 8 with d/w<0.02, 0.04 and 0.08 respectively. d/w<0.02 results in 13 segments, ranging in size from 0.08 to 2.0 m . The strongly curved leading edge section is divided into 9 panels with widths under 0.5 m. In the trailing edge section, we find two large panels of 1.5 and 2.0 m and two smaller segments. This clearly shows how curvature affects segment width: a strong curvature makes for narrow segments. d/w<0.04 results in 8 segments, with four small panels around 0.3 m wide, two medium-sized of 0.6 and 0.8 and two large panels of 1.8 and 2.0 m. For d/w<0.8 we found 2 panels of about 1.2 m and the trailing edge divides into two panels of 2 m. Unexpectedly, this pattern also delivered the narrowest segment for these boundary conditions, just 0.08 m wide.

Such a narrow segment is the result of the chosen patterning approach. The leading edge panel is now divided in a panel with a curvature of 0.08 and a small “leftover” piece. This indicates an opportunity to improve on the segmentation pattern; by not going for the maximum possible width, the leading edge panel could be divided into two or more smaller panels with a lower curvature. This is shown in the cutting patterns for *d/w*<0.04 and *d/w*0.02.

As was to be expected from the airfoil curvature, the narrow segments are found at the leading edge, and the wider segments at the trailing edge panels. The maximum width remained the same for all tolerance bounds, as this part is confined between the spar cap and trailing edge bonding area. Where the lower tolerance criterion results in a set of distributed widths, the upper tolerance level results in a segmentation pattern that almost directly follows from removing spar caps and bonding areas. However, this increased width comes at a cost; the wide panels have a large curvature which may limit application areas where the panels can be reused.

Table 5 Segmentation patterns for maximum panel deflection d

d [m]	Segmentation pattern for maximum deflection, *d*	Segment width *w*
0.02		
0.04		
0.08		

The boundary condition on deflection *d* showed similar results. Table 4 shows the segmentation patterns for section 8 with a maximum deflection *d* of 0.02, 0.04 and 0.08 m. $d<0.02$ m resulted in a pattern of 11 segments, most of which were below or just above 0.5 m wide. The trailing edge section delivers two wider panels of 1.4 and 1.8 m. $d<0.04$ m resulted in 7 segments with widths almost evenly distributed between 0.3 and 2.0 m. Lastly, $d<0.08$ m also has 7 segments, two of them are around 0.2 m wide, two around 1.1 m, and the largest at 1.8 and 2.0 m. Here again, the largest tolerance bound resulted in the narrowest segment, just 0.02 m wide. Considering the tapering of the blade and cutting tolerances, a narrow strip like this is likely to be lost in processing.

The narrow segments found in $d/w<0.08$ and $d<0.08$ m were for the same reason: the leading edge panel deflection was just outside of the given tolerance bound, and was thus divided in a piece of maximum width, and a very small remainder. A better option would be to divide the panel into two or more elements with a lower deflection. Thus it may be beneficial to apply multiple boundary conditions on a given cross-section to optimise the cutting pattern.

The varying segmentation patterns provide insights in the relation between boundary condition and panel width. The segmentation approaches show that the blade panels can be reused within standardized tolerances. However, it also resulted in a range of variable panel widths and some un- or barely usable segments. Thus, to deliver practically reusable panels the boundary conditions need to be refined. To do so, commonly used panel widths can be imposed as an additional boundary condition. These standard widths can function as ‘bins’ when calculating the optimal pattern. Combining the boundary conditions of curvature and panel size will result in a segmentation pattern for construction elements with standard size and accuracy. The boundary conditions can then be used to explore patterns to find one that optimally uses the available material and delivers readily reusable construction elements.

3.2 Structural properties

With regard to the structural properties, we found four sandwich panel layups and one solid laminate beam in the blade mid span. Only the leading edge panel and the shear web have a constant layup along the blade, the other parts taper towards the blade tip by reducing the thickness of the core material and the number of plies. Table 6 shows the resulting ranges for thickness, density , flexural modulus and flexural strength of all blade parts. The minimum and maximum thickness are given for each part, because the thickness of the core material (foam) largely determines the effective material properties.

Table 6 Properties of blade parts, calculated from blade design specifications, including safety factors, using Granta CES Edupack 2019. The equivalent density, flexural modulus, and flexural strength depend on the thickness of the sandwich, which is dominated by core material thickness.

Part	Thickness [mm]	Density ρ [x10^2 kg/m^3]	Flexural modulus E_{flex} [Gpa]	Flexural strength σ_{flex} [x10^2 MPa]
Leading & Trailing edge panels	26	5.6	9.8 - 14.6	5.1 - 8.9
	96	3.0	3.2 - 4.7	1.6 – 2.8
Trailing edge reinforced panels	26	5.9	15.1	5.1 - 8.9
	103	4.1	6.7	1.6 – 2.8
Shear web panels	54	3.2	2 - 3	2.8 – 4.9
Spar cap beams	20	16.5	37.1 – 64.9	7 – 11.7
	48	16.1	52.2 - 99	8.1 – 13.3

The following charts compare the blade segments to conventional construction materials, using the equivalent material properties. Figure 7 sets out the Flexural modulus (E_{flex}) to the density (ρ). This charts shows that the blade materials have a flexural modulus comparable to timber. Figure 8 plots the Flexural strength (σ_{flex}) versus density (ρ). Noteworthy is that the blade elements are characterised by their high specific strength (σ_{flex}/ρ). The spar caps are positioned in the top-middle in both charts, indicating a relatively high specific stiffness as well as strength compared to conventional materials. Both the panels and the beams do not fully overlap on both characteristics with other structural materials, thus direct substitution of other materials by the retrieved blade materials is not evident.

Using material indices, we compared the performance of the material in specific functions: panels and beams. The performance indices for a beam and panel of minimum mass, loaded in bending, are $E^{\frac{1}{3}}/\rho$ for stiffness limited design and $\sigma^{\frac{1}{2}}/\rho$ for strength limited design [44]. These indices are plotted as lines with respectively slope 3 (Figure 7) and 2 (Figure 8). The lines connect materials that have equal performance regarding stiffness and strength, respectively. Materials above the line exhibit better performance, while materials below the line perform less well.

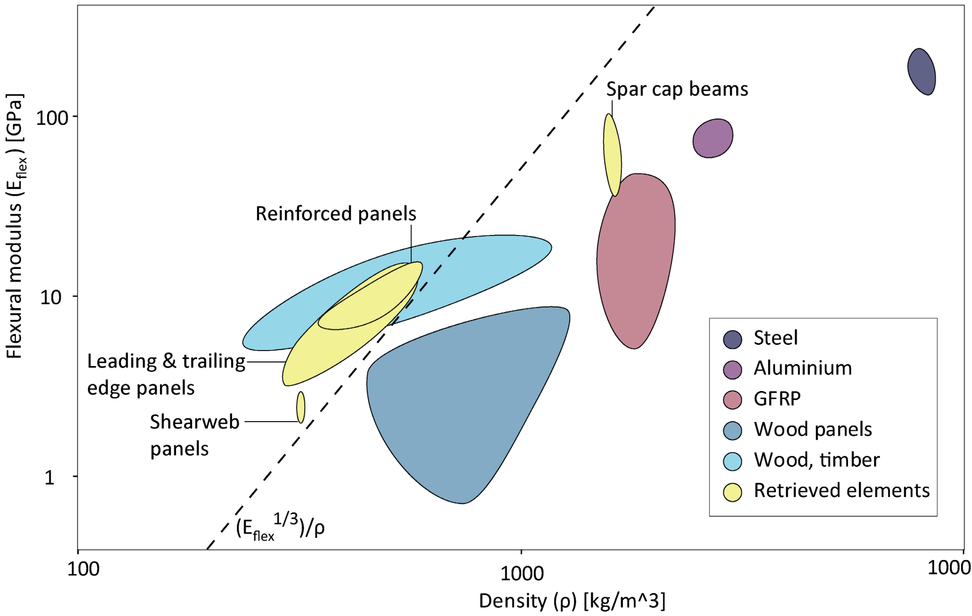


Figure 7 Comparing conventional construction materials to retrieved blade elements on Flexural modulus (E_{flex}) vs. Density (ρ)

For stiffness limited design (Figure 7) timber is the only material with a material index similar to the recovered blade segments. As such, the retrieved materials outperform all other conventional construction materials for lightweight constructions loaded in bending. This indicates that structurally reused composites can be used to substitute timber panels and beams in bending-dominated structures, and that they will enhance performance compared to other materials.

For this reason, Ashby [44] and Beukers [2] argue for the use of composites in architecture. High-rise buildings especially require materials with a high structural efficiency, which composites can fulfil. Architects have now adopted composite panels for cladding building façades [8] and composites are gaining ground in infrastructural projects, for example in bridges and lock doors [50]. However, thus far the cost of composites in comparison to today's bulk construction materials remained prohibitive for large-scale implementation. Structural reuse however, has the potential to lower the material cost and as such unlock composites for application in building applications.

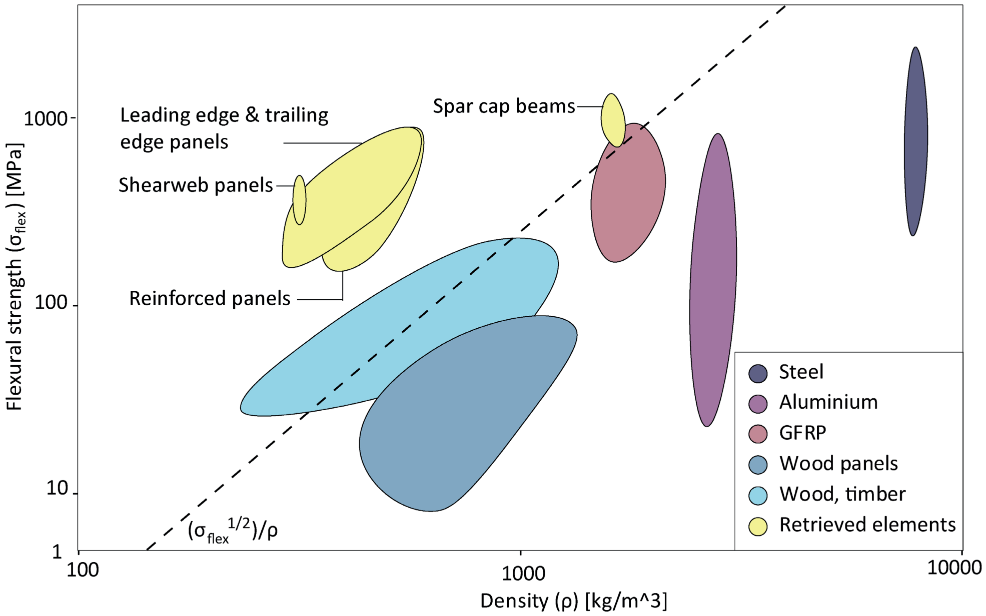


Figure 8 Comparing conventional construction materials to retrieved blade elements on Flexural strength (σflex) vs. Density (ρ)

Figure 8 shows performance for strength limited design. The blade panels are above the performance index line, the beams and timber are intersected by it and all other materials fall below. Thus, the blade panels outperform all other materials for constructions loaded in bending. The CFRP spar caps perform equal to some timber types. The spar cap position, to the top-left of GFRP materials, shows the higher strength and lower density of CFRP compared to GFRP.

Figure 9 sets out the material indices for lightweight design; the vertical axis for stiffness-limited design, and the horizontal axis for strength-limited design [44]. The best performance, minimum mass for a prescribed stiffness and strength, is found when maximising the indices; at the top-right of the chart. Even though timber can achieve higher performance for stiffness limited designs, the blade panels excel in strength-limited designs. All panels are found at the top-right of the chart, which indicates these provide the best combination of stiffness and strength for lightweight designs. As such, the retrieved construction elements outperform all other materials for a lightweight construction loaded in bending.

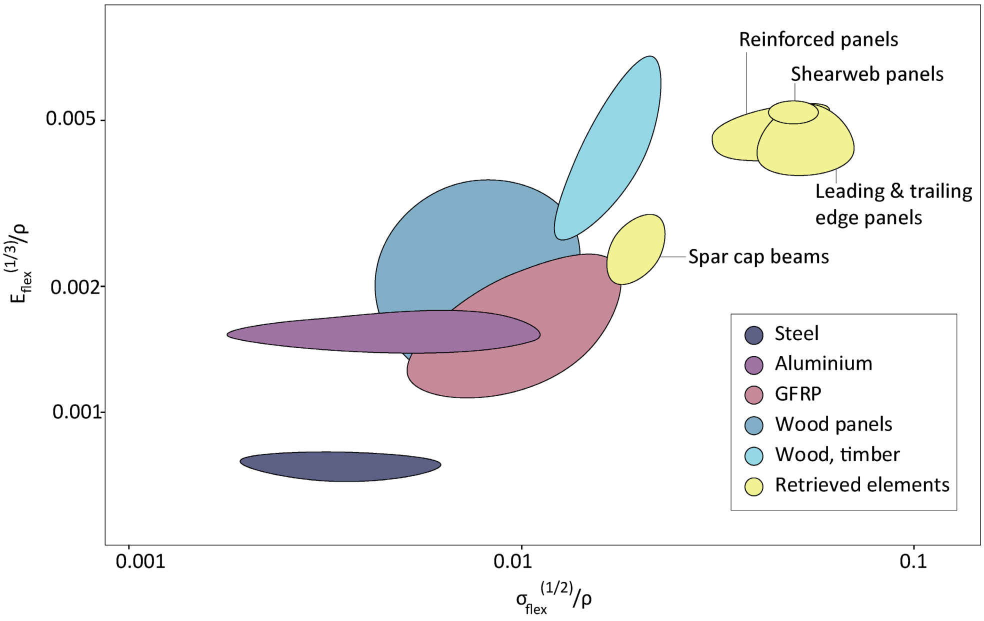


Figure 9 Comparing the stiffness and strength performance of conventional construction materials to retrieved blade elements for a construction loaded in bending.

The shape and material properties of the retrieved segments are most reminiscent of panels and beams found in construction, infrastructure and, in smaller sizes, furniture. Indeed, the occasional applications for which these materials have been used are mostly found in these sectors [28,29]. This "occasional" application is attributable to the restrictions imposed by the original size and shape.

The safety factors were used to calculate the expected range of material properties. These were used on the assumption that the blade would still be in safe operation at the point of decommissioning. Still, the material will have suffered from fatigue and potential impact damage. This range could be further narrowed down through modelling and inspection [51]. However, determining the degradation of material properties through fatigue and the extent of damage is challenging for composites [52,53]. Insights from the fields of fatigue life prediction, structural health monitoring and damage inspection could improve the definition of post-use material properties. Also, identified weakened areas could then be excluded from the cutting pattern.

Using curvature to determine a segmentation pattern and to evaluate structural quality using material indices were promising first steps that can be developed further. Structural analysis shows that the retrieved materials have excellent properties in comparison to conventional construction materials. However, the structural shape of the composite product is already defined, while that of raw materials can still be chosen. In the structural comparison charts, shape factors can be used to expand the material envelopes [54], but such an extensive comparison is outside of this paper's scope. The defined shapes also affect finding the right application for the construction elements, a process that needs to be further explored.

3.3 Applications

In addition to the size and structural performance, we need to consider the practical usability of the material. For reuse in practice, the construction elements will have to be machined (cut to desired size and shape), joined and finished. We tested structural reuse in practice, by designing and building a simple furniture product from a wind turbine blade, retrieved from a recycling company.

Cutting cured GFRP laminates requires specialised equipment. When developing the furniture, we consulted a number of workshops for producing the prototype, but none was willing to process the material. The main objections were: tooling degradation, personal health and safety, and contaminating the dust extraction system and machinery with GFRP residue. This reflects the concerns raised on reprocessing wind turbine blade material in earlier studies [28,29]. We found waterjet cutting to address these concerns; there is no risk of tooling degradation, and dust is collected in the water filtration system.

The prototype was produced in two steps. First, the blade parts (spar caps, shear webs and panels) were separated using a portable waterjet cutter at the recycling company. Then, we had the components cut out from the panels using a CNC waterjet cutting table. These cuts were made perpendicular to the panel chord, which resulted in near-rectangular part cross-sections, especially for relatively flat panels. Overall, we found that waterjet cutting delivered good cutting quality, high accuracy and few cutting losses (the jet diameter was 0.7 mm.). The piercing points however, where a cutting track starts, needed to be pre- drilled, to prevent pressure build-up between core and bottom laminate, and thereby delamination of the GFRP faces from the core material.

Figure 10 Picnic table, made of recovered blade segments.

Three connection types were used in the construction of the table, where special attention was paid to preventing water ingress during use and maintaining structural integrity. Slotted joints were used to minimise screw holes, and adhesive bonds were used to eliminate joints on exposed, horizontal surfaces. Fasteners, placed on unexposed positions, were used to facilitate dis- and reassembly.

This construction was chosen because the largest threat to the product in its use phase is the environmental exposure. The core material of these sandwich panels was balsa wood, which is prone to moisture degradation. And the matrix material, epoxy, is sensitive to UV ageing. So by ensuring no holes on exposed surfaces, the risk of water seeping in was minimised. A coating will shield the materials from humidity and UV radiation. The loads during use will not cause any problems, because these are well below those in its initial application in the wind turbine and the material safety limits.

The picnic table can be disassembled at the end of its use phase. Then, large parts can be reused, because these are still structurally sound and largely unaffected by the cutting pattern, smaller components can be processed in the GFRP recycling stream, as no additional or foreign materials are added or connected. From this application, we learned structural reuse is feasible in practice. The blade delivered reusable construction materials, which were processable with high accuracy, using the right tooling.

Prefab building could be another application area for the recovered construction elements. A typical timber frame building uses timber beams and wood panels. These parts are fabricated to specifications, enabling quick assembly on-site. The segmentation pattern complied to timber construction standards, and panels sizes were in line with trade standards. The panels can substitute the timber as well as wood panel parts given their structural performance. The need for specialised cutting equipment is solved by pre-fabricating parts and eliminating on-site rework. The gains made in weight come to the benefit of transport and installation. Prefab construction sees wide-spread use in various building types, including roofing and industrial warehouses, as well as public buildings and housing. Thus, concerning dimensional standards, structural quality, processing and scalability, we expect prefab building to be a promising sector for reuse of blade segments.

The segmentation patterning method, structural analysis and application example provide insights into what is needed for structural reuse. The reuse of construction elements relies on the availability of product specifications. Determining segmentation patterns requires data on overall dimensions and (aerodynamic) shapes. The structural comparison needs materials and layup schedules which also implies identification of the product and collaboration along the value chain, to retrieve this information. These factors may seem evident, but in industry practice, intellectual property and commercial considerations may prevail over sharing information among stakeholders. Moreover, the use phase inflicts wear, damage and fatigue on the product, introducing additional uncertainty about residual material quality at end of use. Additional information on the material state, e.g. through (embedded) monitoring, inspection and certification may reduce these obstacles.

The design of wind turbine blades is driven by aerodynamic and structural performance; there is no room for design adjustments that impair these elements. The design aspects presented here do not need to have adverse effects on product performance, as they are largely contextual and easy to implement. Thus, the recovery potential for a such a complex composite product as a blade, can be improved by relatively simple interventions:

- Documenting product specifications
- Enabling traceability through identification
- Sharing information along the product value chain

3.4 Future research

To improve on the proposed approach, further research could expand on additional product (sectors), more detailed product features, boundary conditions and design for reuse. Other sectors, like marine and aviation, also use high end composite parts, and face similar end of life challenges. Further research could detail structural reuse of parts from these sectors. Additional product features to include could be composite layup schedules, 3D shapes, connections and sub-assemblies. The segmentation boundary conditions could also be expanded to meet requirements for successive applications more accurately. Where possible, elements of the approach could be implemented in the design of new products, to prepare them for reuse.

The presented structural reuse process could be adapted to variations in blade design and materials composition, which vary per model and manufacturer. For example, the NREL blade used safety factors for onshore deployment based on IEC standards [55]. These factors will have to be adapted for analysis of blades using other standards, such as DNVGL-ST-0376 [56]. Also, as blades get larger, use of carbon fibre reinforcements increases in spar caps and shells [34]. This improves the mechanical performance of the recovered segments, and thereby their economic value. Also, the size, configuration and number of shear webs may increase with blade length [57]. This affects the boundary conditions of the cutting pattern (i.e. cutting lines along the spar caps) as well as the reuse opportunities. Bank (2018) explored direct reuse of these as doors and window frames [58].

A segmented blade concept [59] may facilitate reprocessing, while at the same time introducing bonding areas which are difficult to reuse. An integrated blade concept by contrast, could improve the reuse rate by eliminating bonding areas at the leading edge and trailing edge [60]. Although the presented segmentation approach could be adopted to meet these variations, this further signifies the need for available design documentation at the reuse stage, in order to define optimal segmentation patterns.

To improve the reuse rate, recovery of the root and tip sections need to be further investigated. This could be structural reuse as other construction element types or applications, which are in line with the geometry and material characteristics. Alternatively, other recovery routes may need to be found in the domain of thermal, chemical or mechanical recycling.

Future research could also pursue more ambitious applications for structural reuse. The reuse case in this study, furniture, served to evaluate the process and manufacturing in practice. The expected loads were well within the material specifications. Building on the insights of the structural property evaluation and additional materials testing or modelling will enable reuse at the materials full potential.

Structural reuse adds another use cycle, and thereby extends the material lifespan. This preserves energy and value embedded in the composite, and potentially substitutes use of virgin materials. To fully close the resource loop, recovery routes in terms of reuse or reprocessing of the construction elements need to be further investigated.

4. Conclusion

In this study, we explored a systematic approach for structural reuse of complex composite materials. Structural reuse is complicated by the large size, complex shape and complex material composition of composite products. To address this, a systematic method was needed to define segmentation patterns and evaluate structural quality.

We proposed an approach for the structural reuse of complex composite products through segmentation, structural analysis and reuse applications. We applied this approach to a typical wind turbine blade made of glass and carbon fibre composite. The segmentation pattern showed that high accuracy construction elements can be cut from a double-curved product, in such a way that 95% of the analysed blade section, and 55% of the complete blade are eligible for reuse. The structural analysis revealed good performance in terms of flexural stiffness and flexural strength in relation to weight, with the retrieved panels exceeding the performance of conventional construction materials for constructions loaded in bending. Reuse of blade panels in another product showed the need for specialised cutting equipment, and delivered accurately dimensioned parts.

A number of design aspects limit retrieval of construction materials from end of use wind turbine blades. Converting a large structure into smaller, reusable segments, relies on availability of model details to generate cutting patterns. The materials' fatigue behaviour and (variations in) operating conditions complicate determining residual structural quality, signifying the need for structural health monitoring. These design aspects are mostly contextual in nature, and could be addressed without infringing the performance of the blade in its initial use.

To facilitate recovery of construction materials, designers can address structural reuse by documenting product specifications and facilitating traceability. During product life, reuse is supported by collaboration along the value chain and reducing uncertainty about the product's state through e.g. monitoring or inspection. Testing the structural reuse approach in a furniture application showed its feasibility. In addition to identifying relevant design aspects, the presented segmentation and structural analysis approach brings a new perspective to structurally reusing composite products.

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Chapter 6

Discussion and Conclusion

1. Introduction

The main aim of this dissertation was to develop a methodology to design products with composite materials to enable reuse and recycling. Within the domain of composite materials, we focused on fibre-reinforced polymers. We defined four research questions which are reported on in Chapters 2, 3, 4 and 5 of this dissertation. Table 1 shows the research questions, the main insights gained, and the outputs for each of these studies.

Following a review of the existing literature and expert consultation, we identified different circular economy strategies and product design aspects and connected them in a circular composite design framework, described in Chapter 2. In addition, we developed a product lifecycle exploration sheet to map out and explore circular economy strategies for a case product. The framework and lifecycle sheet form the foundations of a design method for products containing composite materials in a circular economy. This Circular Composites design method was then tested in design practice and is reported in Chapter 3. Structural reuse, identified as an interesting circular strategy for composite products, was further explored in a Research-through-Design approach in Chapter 4, and by developing a systematic segmentation approach, as described in Chapter 5.

Section 2 starts with a brief summary of the four studies. Section 3 discusses the development of the Circular Composites design method and its validation in industry practice. Section 4 elaborates on the strategy of structural reuse and its implications for design. We conclude with the contributions to science (section 5), design practice (section 6) and education (section 7). Lastly, in section 8 we provide recommendations for further research.

2. Main research results

Composite materials find themselves at odds with the circular economy. On the one hand, these materials provide opportunities for efficient materials use and creating products with a long life span. But on the other hand, they represent a recycling challenge. The position of composites in a circular economy could be improved by designing for recycling and reuse. However, at the start of this research project, designing products containing composite materials for a circular economy was unexplored. This led to the formulation of the main research question: *How to design products containing composite materials for a circular economy?* To address this question, we developed a design method and a circular economy strategy dedicated to composite materials.

To start, we had to bring together knowledge from the fields of composite materials, circular economy and product design, and ground the available theory in design practice. This resulted in research question 1: *Which circular strategies and related design aspects can be identified for products containing fibre-reinforced polymers?* To answer this question, we consulted the literature and experts in the composites industry. This delivered a subset of circular strategies and design aspects relevant for products containing composite materials, shown in Table 2. The framework in Table 2 refines the more generic circular product design framework developed by Den Hollander (2018) [1]. To account for the distinct features composite materials offer in design and during (re-)processing, we adapted the materials integrity strategies and design aspects. Within materials integrity, we added the strategy of structural reuse and detailed the approaches for materials recycling. The design aspects were extended with seven new aspects, these are identified in Chapter 2, with another two aspects added in Chapter 5. These additions mostly build on the specific opportunities that composite materials offer for tailoring materials and manufacturing, and integrating form and functionality. In total, we identified 26 design aspects as relevant for design of products containing composites for a circular economy.

Table 1 Main insights and outputs of the studies in this dissertation

Chapter	2	3	4	5
Research Question	Which circular strategies and related design aspects can be identified for products containing fibre-reinforced polymers?	How effective, accessible and usable is the circular composites design method in design practice?	How to design composite products for structural reuse in a circular economy?	How to segment complex composite products into reusable construction elements?
Insights	– Circular strategies for products containing composite materials are largely similar to reported strategies as far as product integrity is involved. – Recovery pathways focusing on materials integrity show some distinct opportunities for composite reuse. – Structural reuse, positioned between product recovery and materials recycling, has the potential to preserve composite material performance and value at a relatively low cost.	– The design method was accessible to designers, and connected well with known industry practices. – Descriptions and terminology could be elaborated by including exemplary case results, and/or adapting to specific industries. – The design method for composites provides guidance and inspiration in the design process. – Results of design case studies were highly affected by their industry context, reflecting the importance of setting adequate boundary conditions for circular product development. – The systems transition to a circular economy can be supported by the method's explorative, generative and communicative aspects.	– Structural reuse of panels recovered from a wind turbine blade is feasible. – The retrieved materials were accepted and appreciated by exhibition visitors and experts from wind industry. – To prevent in-use degradation of the reprocessed material, special attention should be paid to shielding the material from harmful environmental exposure. – Identification of aspects that enable structural reuse by design intent; embedded markers and design for multiple use cycles.	– 55% (by weight) of the complete blade is eligible for reuse within conventional building tolerance standards. – The retrieved panels outperform conventional construction materials in bending-dominated structures. – Recovery potential for a complex composite product can be improved by relatively simple interventions: documenting specifications, enabling traceability and sharing information along the value chain.

Chapter	2	3	4	5
Outputs	– A circular product design framework, adapted for composites, including ○ 5 circular strategies ○ 24 design aspects	– Circular Composites design method for products containing composite materials in a circular economy. – Five design demonstrators of (partly) circular industrial products containing composite materials.	– Design aspects which provide guidance on implementing structural reuse in design. – Demonstration of structural reuse through segmentation: picnic table prototype.	– A segmentation approach delivering construction materials within conventional building tolerance classes. – Design aspects that facilitate structural reuse.

In the framework, cells shown in green indicate which design aspects have been identified as relevant for a specific circular strategy. This framework supports both designers and researchers when either integrating circular design measures or analysing products containing composite materials. To make these findings usable in design practice, we further developed this into the Circular Composites design method. The Circular Composites design method combines the framework with an explorative lifecycle mapping sheet; the procedure for using the Circular Composites design method is summarised in section 6.3.

To deliver results in practice, the Circular Composites design method has to be used effectively by designers. This led to the question: *How effective, accessible and usable is the circular composites design method in design practice?* The design method was evaluated in five design cases with the composites industry. The results of this study, summarised in Table 1, are promising considering the complex nature of composite materials, while the composites industry is highly competitive and has many lock-ins. The use of the Circular Composites design method in design practice is further discussed in section 3.

The circular strategies in the circular product design framework (Table 2) are specifically suitable for products with composite materials. In addition to known strategies, structural reuse was identified as a potentially interesting recovery strategy for composite materials. This strategy preserves material integrity and value at a relatively low cost. However, the literature only describes occasional cases, and does not relate recovery activities to design aspects. Thus, the remaining question to be answered was *How to design composite products for structural reuse in a circular economy?* To answer this question, we performed a design case study on wind turbine blades, developing a prototype to elicit insights on reprocessing and reuse of composite structures. The case demonstrated the feasibility of structural reuse and grounded structural reuse as a design approach by relating the strategy to relevant design aspects.

The design case study into structural reuse also showed the need for new segmentation approaches to handle complex structural composites, leading to the question *How to segment complex composite products into reusable construction elements?* To answer this, we modelled a segmentation approach which enables reusing the largest part of a typical wind turbine blade as standardised construction elements. The retrieved panels outperform conventional construction materials in bending-dominated structures. This offers many opportunities for reuse across a variety of applications.

Table 2 Design framework for composites in a circular economy. Design aspects relevant for a particular strategy indicated with green.

			Circular economy strategies				
			Design for preserving product integrity			Design for materials integrity	
			Long life	Lifetime extension	Product recovery	Structural reuse	Materials recycling
			Reuse Long use Physical durability	Repair Maintenance Upgrade Adapt	Refurbish Remanufacturing Parts harvesting	Repurpose Resize Reshape	Remould Mechanical Thermal Chemical
Design aspects	***Concept design***	Accessibility		🟩	🟩		🟩
		Adaptability	🟩	🟩	🟩	🟩	
		Cleanability	🟩	🟩	🟩		🟩
		Dis-&reassembly	🟩	🟩	🟩	🟩	🟩
		Ergonomics	🟩	🟩	🟩		
		Fault isolation	🟩	🟩	🟩		🟩
		Functional packaging		🟩	🟩		🟩
		Interchangeability		🟩	🟩	🟩	🟩
		Malfunction signalling	🟩	🟩	🟩		
		Multiple use cycles				🟩	
		Simplification	🟩	🟩	🟩		🟩
	Embodiment design	Connection selection	🟩	🟩	🟩	🟩	🟩
		Embedded markings				🟩	
		Function integration	🟩	🟩		🟩	🟩
		Keying		🟩	🟩		
		Material selection	🟩	🟩	🟩	🟩	🟩
		Manufacturing		🟩	🟩		🟩
		Modularity		🟩	🟩	🟩	🟩
		Redundancy	🟩	🟩	🟩		
		Sacrificial elements	🟩	🟩	🟩	🟩	
		Structural design	🟩	🟩	🟩	🟩	🟩
		Surface treatments	🟩	🟩	🟩	🟩	🟩
	Detail design	Documentation		🟩	🟩	🟩	🟩
		Identification		🟩	🟩	🟩	🟩
		Monitoring	🟩	🟩	🟩	🟩	
		Standardisation		🟩	🟩	🟩	🟩

3. Designing products containing composite materials for a circular economy

The Circular Composites design method is intended to support designers in developing products containing composite materials for a circular economy. The method contains an explorative lifecycle mapping sheet and a circular product design framework, both can be found in Chapter 2. The design method and its effectiveness, accessibility and usability in practice are described in Chapter 3.

The procedures for using the Circular Composites design method are shown in Figure 1. The Circular Composites design process starts with (1) the intent to (re)design a product containing composite materials for a circular economy. The designer uses the lifecycle mapping method (2) to explore recovery loops, including stakeholders and activities. The recovery loops relate to circular strategies such as long life, lifetime extension or materials recycling (3). The framework connects these circular strategies and design aspects and, as such, directs the designer to a subset of design aspects relevant to a particular circular strategy (4). The designer can use this subset to conceptualise, embody, and detail the design proposal (5). The steps and tools provided in the method support designers in realising a circular product design with composite materials (6).

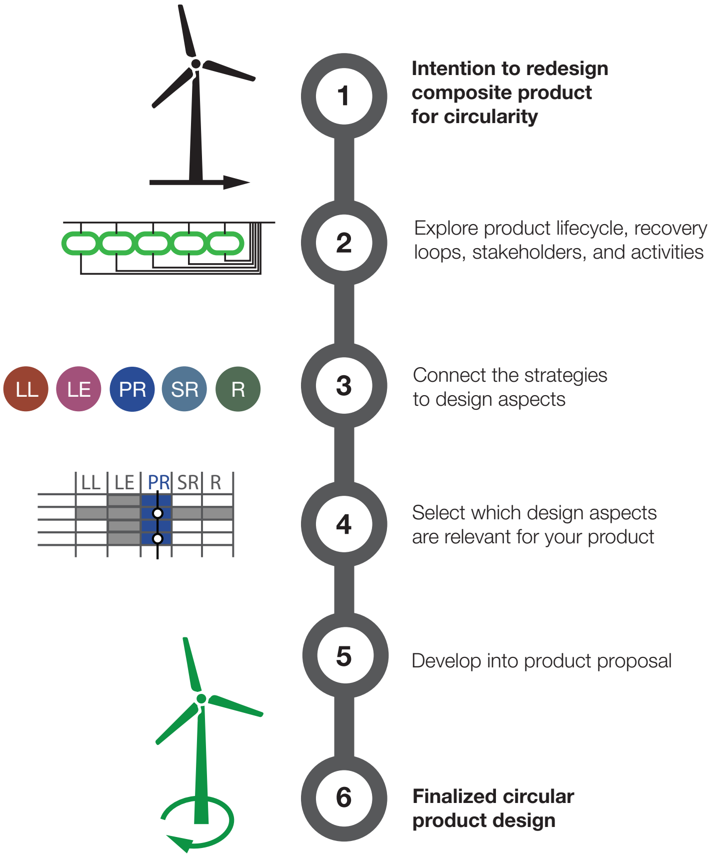


Figure 1 Procedure for using the Circular Composites design method.

The method was developed with and validated in industry which increases the likelihood of finding acceptance and use in design practice. Often, design methods are developed out of their use context, resulting in methods that are poorly described, difficult to use, with their actual performance remaining unknown [2,3]. The Circular Composites design method was developed in the context of an industry innovation project: Ecobulk. Ecobulk is a Horizon2020 project aiming to close the loop of composite products in the automotive, furniture and building sectors. The project ran from 2017 until 2021 and included stakeholders from all stages of the product lifecycle for each of the product sectors [4]. The collaboration with industry partners and industrial product designers in particular resulted in a design method that is considered accessible and , usable and has proven shown to be effective in practice. The developed case products demonstrate the added value of the method, which will increase its acceptance in design practice.

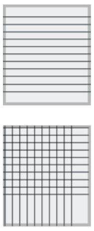
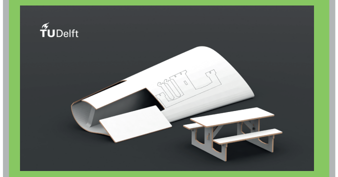
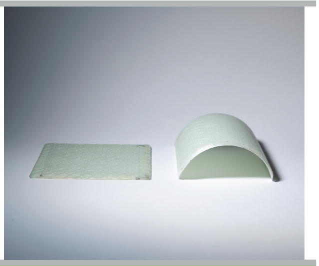
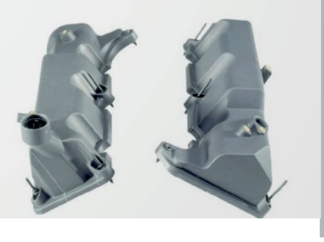
The design case studies with industry showed limitations to the full implementation of circular strategies. Some of the cases were restricted in their circular design process due to governing policy and lock-ins created by existing recovery infrastructures. This aligns with the generally accepted view that the transition to a circular economy requires a system perspective and collaborative action [5]. This transition should result in a system in which incentives are shared rather than individually optimised [6]. For composite design, this means breaking with the practice of optimising for a single use phase and to include recovery activities, reuse scenarios, and interactions with associated stakeholders. This expands the design project scope, increases the process complexity, and requires additional skills from the designers [7].

Based on the many interactions I had during this research, I expect that the designers and manufacturers can develop and implement circular solutions for composite-containing products. However, in highly optimised designs, designing for reuse and recycling is likely to affect product performance. These knockdowns on performance make designers reluctant to implement these adaptations. To stimulate implementation of circular design considerations, designers, manufacturers, and researchers often call for (external) incentives and (regulatory) requirements to set targets and boundary conditions for achieving circular composites by design, which reflects the findings by e.g., Cherringtonet. al. (2012) and Ortegon et. al. (2013) [8,9]. Thus, implementing circular strategies may narrow the design space for composite products, while they are often designed on the edge of that very same design space. It is therefore advisable to use policy, technology, and design knowledge to set the right boundary conditions for creating circular products.

In this dissertation we distinguish four classes of fibre-reinforced polymers (Table 3; see also Chapter 1). In the first two Chapters we used cases of thermoplastic moulding compounds, in the last two Chapters we analysed laminated thermosets. Considering the materials classification, this leaves laminated thermoplastic and thermoset moulding compounds untested. Both represent a distinct group of product applications, each having distinct design attributes and recovery practices. We expect the Circular Composites design method to also be applicable when designing products with thermoplastic laminates. In addition to their thermoset counterparts, thermoplastic laminates can be remoulded/reshaped when subjected to a heat and pressure [10], potentially offering additional reprocessing opportunities. This will be further elaborated upon in section 6.4.

Thermoset moulding compounds, known as bulk moulding compounds (BMC) or sheet moulding compounds (SMC) were not investigated, but these might be the hardest class to find circular solutions for. These materials neither possess the structural value of a laminate, nor the reprocessing opportunities of thermoplastics, complicating the economic and technological feasibility for recycling [11]. To date, co-processing in cement kilns remains the reprocessing route of choice for BMC and SMC [12,13]. In this process, the material is used to fuel the process and the residue as a filler in concrete [14]. However, the process incurs loss of material integrity and eliminates opportunities for further reuse. Future research should aim at preserving product and material integrity of products made with thermoset moulding compounds, with respect to design, materials ,and (re)processing technology.

Table 3 Cases of composite-containing products, classified by matrix type and reinforcement structure, those considered in the dissertation are indicated in green. Images by the researcher and [12,15]

		Thermoset	Thermoplastic
Laminated		🟩 	
Moulding compounds			🟩 

4. Structural reuse of products containing composites in a circular economy

Structural reuse was identified as a strategy to preserve material integrity. Structural reuse takes place when 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. Discarding product function sets the strategy aside from the strategy of parts harvesting. Further, structural reuse preserves material integrity, but differs from recycling processes in that it maintains the material structure. We therefore positioned structural reuse as circular strategy between product recovery and materials recycling (Table 2). Its feasibility had been demonstrated in a number of repurposing projects. However, with some design modifications, described in Chapters 4 and 5, products can be structurally reused more effectively in terms of reprocessing, quality, and the recovery percentage.

There is a growing need for effective recovery of products containing composites. The supply of end-of-use composite materials will increase strongly in coming years, as evidenced by the case of wind turbine blades [16]. But the reprocessing technology is currently insufficient to handle these amounts of materials [17,18]. In contrast to current recycling processes, structural reuse could immediately meet the basic requirements for a successful recovery system: balancing supply, processing capacity, and market for the recyclate [14]. The segmentation procedure and processing technology used in Chapters 4 and 5 are scalable and deliver reusable construction elements. The standardised geometries and high performance of these elements offer a large diversity of reuse opportunities and are expected to create a market for the retrieved materials. Moreover, the strategy can be facilitated with design aspects like traceability, identification, and information sharing, which can be applied instantly without affecting product performance.

The design case study described in Chapter 4 demonstrates the feasibility of the structural reuse strategy for wind turbine blades, and we expect this strategy to be applicable to other products containing composites. Wind turbine blades represent a durable, structural composite which integrates mechanical performance and aerodynamic form. In practical terms, it is a large product which has no other functional use when its operational life ends. However, the decision for decommissioning a wind turbine is based on economic and legal grounds, as well as technological developments, rather than the physical condition of the installation [19]. Thus, the product is rendered obsolete although the physical lifespan of the material has yet to expire, which provides opportunities for structural reuse. Similar characteristics are found for composite products in other sectors, such as marine (ship hulls), aerospace (fuselage, interior panels), construction (silos, storage tanks), and infrastructure (bridges, lock doors). We therefore expect that structural parts can also be reused in these product categories. This is supported by an initial study showing the feasibility of reusing aircraft interior panels in a secondary transport application [20].

Reuse across contexts and extending material use beyond its original design lifetime brings additional challenges in terms of performance, safety, and certification. Materials in use are subject to wear, most notably mechanical fatigue, and environmental degradation like ageing and surface erosion. Therefore, the quality of the material is not always exactly known when taken out of use. In addition, reuse in another context changes the loading conditions. This can be dealt with by not using the material to its primary full capacity. This is the approach described in Chapter 4: reuse of wind turbine blade material in the furniture piece did not raise any safety concerns since the loads were well within original specifications. However, although over-dimensioning may increase safety margins, it also implies less than optimal materials use.

To optimise reuse and warrant safety of structural elements in terms of mechanical performance, an improved assessment of residual material quality is desirable. We recognise three approaches to assess residual mechanical performance of composite materials. In the first approach, we assume the material is still within its original specification when recollected. This approach was used to evaluate material characteristics in Chapter 5. A second approach is to model the material quality based on original documentation and in-use monitoring, which can be facilitated by progress in modelling fatigue behaviour of composites [21,22]. In the third approach, samples of the acquired material are tested to experimentally to determine residual quality [23]. The first provides a rough estimate, the second a good indication, and the third approach an actual, albeit local and time consuming, measurement of residual properties. The desired level of accuracy will depend on the intended reuse case and required safety margins.

Structural reuse is not restricted to thermoset composites. An initial experimental study into structural reuse of laminated thermoplastics delivered promising results [24]. Thermoplastic composites are often produced as flat panels (blanks), which are subsequently thermoformed into a product shape. The forming process forces fibres, resin, and plies to move in the composite, affecting its material properties. Reversing the process, flattening out an existing part into a reusable blank, risks introducing material defects like fibre misalignment or delamination. However, we were able to demonstrate flattening out formed parts that while retaining material properties. These reclaimed blanks could then be used to produce parts for another use cycle. These subsequent forming actions widen the scope for reuse applications, as the material is no longer bound to its original shape, as is the case with thermoset resins.

Structural reuse is a circular recovery pathway specific to composite materials that can be used in several consecutive reuse cycles (Figure 1). For example, we explored three cases of blade reuse which could be placed in succession. First, the composite material is used in a wind turbine blade with a design life of 25 years. Second, major blade parts can be repurposed as load carrying beams in a slow traffic bridge. This bridge of blades [25] adds another estimated 50 years to the material life (Figure 2). Third, the structure can be segmented (resized) for reuse as construction elements. The blade-based table developed in Chapter 3 further extends the material life with approximately 15 years. These applications successively extend the material lifetime and avoid use of primary materials (e.g., wooden or steel beams for a bridge construction). And finally, keeping the materials in use delays the moment of recycling.

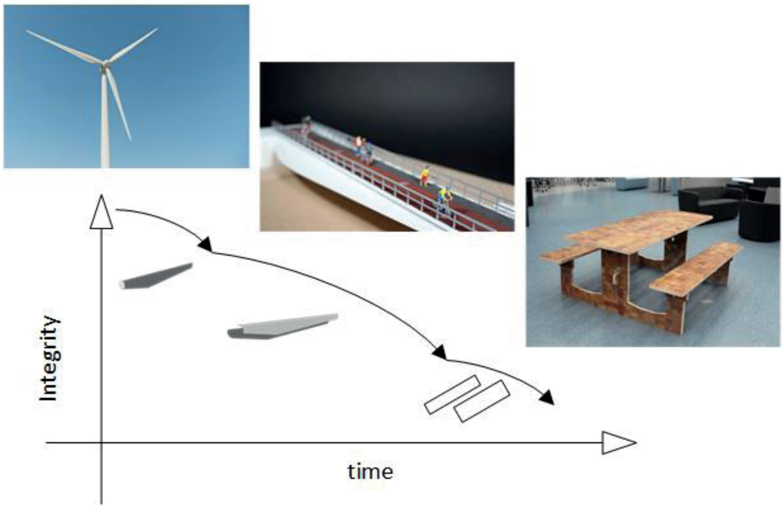


Figure 2 Structural reuse of wind turbine blades, extending lifetime and preserving value of the material. Images by the researcher and [26]

5. Contribution to science

With this dissertation, I contribute to the development of the field of circular product design, adding the design of products containing composite materials. Although product design, composite materials, and circular economy are established fields, I found little overlap. I investigated how to design with composite materials for a circular economy, which led to the following main contributions:

- A typology of circular strategies for recovery of products and materials dedicated to composite materials which helps prioritise recovery strategies in the design process.
- Expansion of the domain of composites design knowledge by addressing circular economy considerations.
- A reuse strategy that preserves the structural integrity of the material, while opening diverse reuse opportunities.
- Improved grounding of circular product design knowledge by providing an overview of design aspects relevant to the realisation of circular strategies by design intent.
- A circular product design strategy framework with which design case studies of products containing composite materials can be analysed.
- A validated design method based on this framework that supports designers in exploring, selecting, and realising circular strategies for their specific product case.

6. Contributions to and implications for practice

- In recent years, we have seen an increasing number of projects addressing the circularity of composite materials, reflecting the growing attention paid to this topic in industry and academia. Designers play an important role in developing circular composite products, thereby establishing a circular economy. This dissertation contributes to practice by developing the field of circular product design with composite materials and supporting designers in design practice. The main implications and results in practice are as follows:
- We demonstrated a systematic approach to structural reuse and positioned it as a design approach, expanding on its current occasional implementation to enable the large scale retrieval and value preservation of composite materials.

- Based on the framework developed in Chapter 2, we developed a design method that supports designers in exploring, selecting, and realising circular strategies for their specific product case. The Circular Composites design method was used in the design cases in the Ecobulk project (Chapter 3) and by industrial design engineering students at TU Delft.
- The studies and the prototypes developed in the design cases provided the groundwork for the Circular Composites design guide. This book guides practitioners in (re)designing their composite product for a circular economy. For a complete description of the design method, we refer to the “Circular Composites” design guide, publicly available through TU Delft OPEN publishing [27].
- This research has generated awareness on designing with composite materials for a circular economy. Through a number of channels directed towards both professionals and the general public, we demonstrated the possibilities of using the material from a design perspective. For example, we exhibited at the Dutch Design Week 2019, participated in community sessions, and held discussions with partners from industry and academia. In addition, I presented and discussed the work at both academic and industry conferences. These interactions have led to broad response and recognition of the importance of paying attention to the circularity of composite products in the design stage.

7. Contribution to education

Research at a university is intertwined with education. While working on this project, I enjoyed contributing to education through teaching and supervising student projects. These interactions led to mutual reflection on achieved results and developed students’ understanding of circular economy and (composite) materials in design. I used the knowledge of design for sustainability, circular economy, and designing with composite materials in the following ways:

- The preliminary framework was successfully used in a bachelor end project. Ten students designed a piece of furniture using the framework and reflected on the results. From these reflections we know that the framework stimulated their circular thinking and strengthened the relation of design to the circular economy. The method used to reflect on the design process (described in Chapter 3) was piloted with these student design cases.

- The Circular Composites design guide was used in a TU Delft master's course on designing with bio-based composites, with 60 participating students. The method stimulated them to explicitly consider product lifecycle and recovery opportunities. It provided an indication of the method's applicability to another group of composite materials, namely bio-based composites, as well as its use in an educational setting.

Throughout the period of this research project, I supervised students in their graduation projects, bachelor end projects and research electives. Through these projects, I supported the students in developing their understanding of circular economy and composite materials in design and obtained input for my own research. The projects considered multiple facets of my research, most notably:

- Two bachelor end project groups at Mechanical Engineering expanded on the structural reuse of wind turbine blades by assessing residual quality and exploring potential reuse applications.
- Three graduation students and one research student explored the circular strategies of structural reuse and repurposing through design cases in aerospace, wind energy, and personal transport, implementing circular economy strategies in these particular cases.
- One graduation project used the preliminary circular product design framework for products containing composite materials to develop a design case study in the automotive industry.
- Two research students developed materials and associated manufacturing techniques to enable recycling and structural reuse, reinforcing understanding of materials development in relation to design and recovery processes. The experimental work was a valuable addition to my research.
- Two graduation projects and two research projects focused on (future) recycling technologies for composite materials, developing a critical view on results presented in the literature.

8. Future research

We have developed validated strategies for the initial design stage of products containing composite materials to enable reuse and recycling in a circular economy. This resulted in the validated Circular Composites design method and the strategy of structural reuse.

Applying the method to other product categories and industrial areas could demonstrate the wider applicability of both the design method and structural reuse strategy. Both method and strategy can be extended with design case studies in other industry sectors. These cases could demonstrate the method and strategy for other product categories and material compositions.

The strategy of structural reuse and its implementation in product design can be further developed. Product designs could anticipate for structural reuse through repurposing and segmentation. But designing for structural reuse also includes technological and business development challenges. From a technology perspective, we could further develop segmentation patterns to deliver instantly reusable elements, fitting anticipated reuse applications. Another approach could be to develop a “kit of parts” that optimally reuses all elements of a composite structure; similar work has been done on reusing electricity power masts [28]. Ideally, this starts a dialogue between the designer of the original product and its users in subsequent use phases. In addition, we need improved approaches to assess residual quality, maximizing the recaptured structural value. From a business perspective, applications and markets need to be developed to absorb the annual volume of composite products reaching their end of use. These technological and business considerations can feed back into the design aspects for structural reuse by indicating valuable reuse opportunities and the product characteristics that facilitate them.

Ongoing improvements in materials and (re-)processing technologies are likely to open up additional recovery pathways and design opportunities. Three types of materials are particularly interesting for further exploration in a circular economy context: modified thermoset, biobased, and thermoplastic resins [29]. Modified thermosets can be reprocessed by reversing the crosslinks that form in the material during cure [30], which may improve their end of life perspective. Our initial studies using bio-based and thermoplastic resins showed promising results.

The recommendations in this dissertation focus on the design stage, but product development takes place in a broader context. In this context, many stakeholders now interact with each other, policies are being developed on the use of resources and emitting CO_2, and society is increasingly voicing its concerns about sustainability. This calls for a broad approach in which a myriad of interconnected sustainability issues are addressed across sectors, organisational levels, and stakeholder groups.

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Appendices

Chapter 2: Circular Design of Composite Products: A Framework Based on Insights from Literature and Industry

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 (bio based) 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 (poly mer OR plastic)))
Refine	AND NOT TITLE-ABS-KEY ("additive manufacturing") AND NOT TITLE-ABS-KEY (bio based) AND NOT TITLE-ABS-KEY ("consumer perception"))
Select	Read titles & abstracts
Result	[7,8,62,65,67,78,12,13,16,29,32,48,49,57]

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 (bio based 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

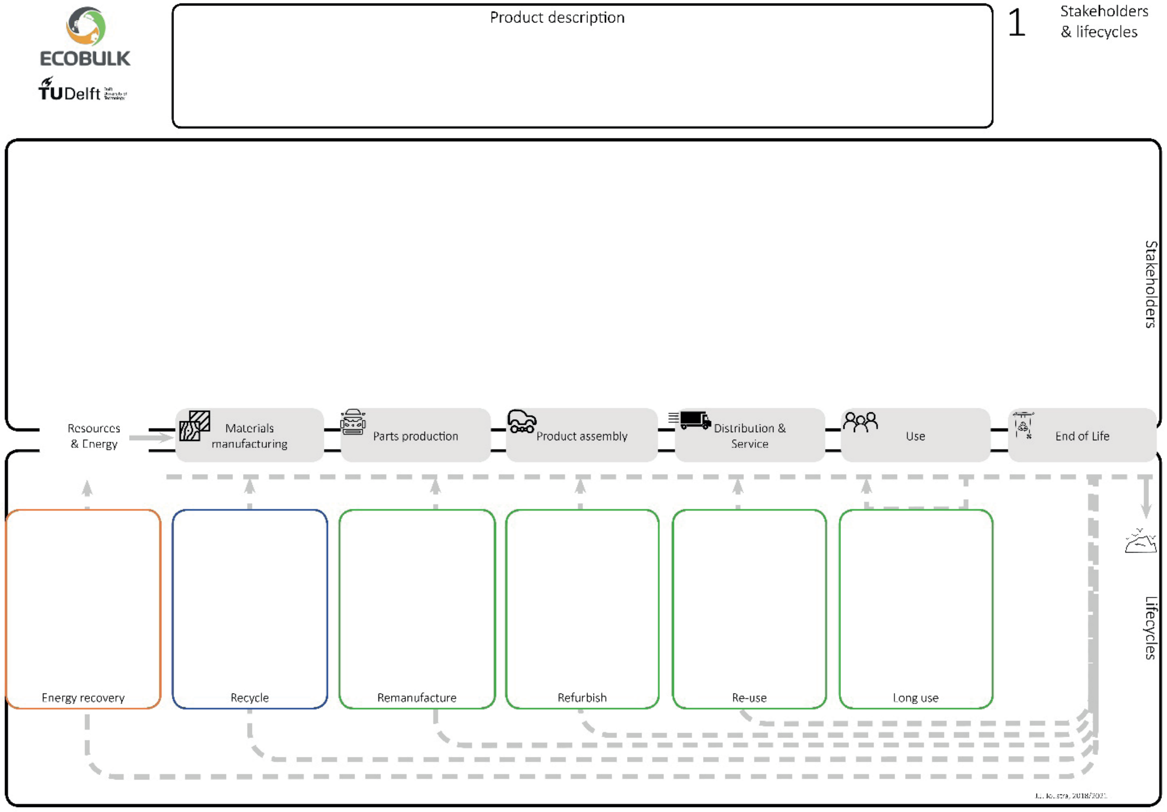


Figure B1. Lifecycle worksheet used during the focus group sessions. The participants added stakeholders, resources, and recovery actions The moderator used the worksheet to guide the discussion, by asking questions on which products, parts or materials would be recovered, and which stakeholders would be involved.

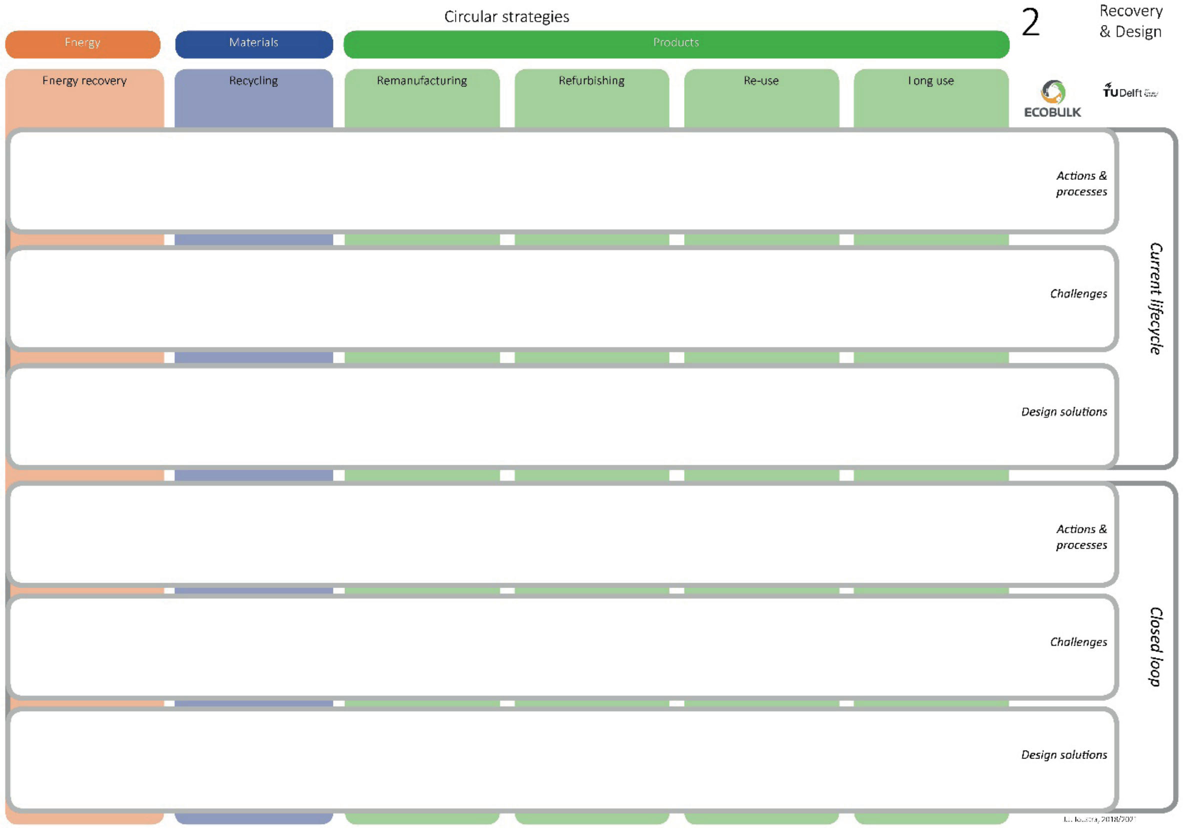


Figure B2. Design for recovery exploration worksheet used in the focus group sessions. The participants added intended recovery actions and processes, which led to finding challenges for recovery of the case product. The moderator asked questions to clarify the recovery case and intervened when the discussion went off-topic. Finally, the layout guided the discussion towards generating design solutions that would facilitate recovery.

Appendix C

Table C1. 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

Chapter 3 Circular Composites by Design: Testing a Design Method in Industry

Appendix A

Design strategy framework for composites in a Circular Economy [16]. Showing circular strategies, design aspects and (in green) where a connection was found.

			Circular economy strategies				
			Product integrity			**Materials integrity**	
			Long life	**Lifetime extension**	**Product recovery**	**Structural reuse**	**Material recycling**
			Reuse Long use Physical durability	**Repair Maintenance Upgrade Adapt**	**Refurbish Reman. Parts harvesting**	**Repurpose Resize Reshape**	**Remould Mechanical Thermal Chemical**
Design aspects	**Concept design**	Accessibility		🟩	🟩		🟩
		Adaptability	🟩	🟩	🟩	🟩	
		Cleanability		🟩	🟩		🟩
		Dis-&reassembly	🟩	🟩	🟩	🟩	🟩
		Ergonomics		🟩	🟩		
		Fault isolation		🟩	🟩		🟩
		Functional packaging		🟩	🟩		🟩
		Interchangeability		🟩	🟩	🟩	🟩
		Malfunction signaling	🟩	🟩	🟩		
		Simplification	🟩	🟩	🟩		🟩
	Embodiment design	Connection selection	🟩	🟩	🟩	🟩	🟩
		Function integration	🟩	🟩			🟩
		Keying		🟩	🟩		
		Material selection	🟩	🟩	🟩	🟩	🟩
		Manufacturing		🟩	🟩		🟩
		Modularity		🟩	🟩	🟩	🟩
		Redundancy	🟩	🟩	🟩		
		Sacrificial elements		🟩	🟩		
		Structural design	🟩	🟩	🟩	🟩	🟩
		Surface treatments	🟩	🟩	🟩		🟩
	Detail design	Documentation		🟩	🟩	🟩	🟩
		Identification		🟩	🟩	🟩	🟩
		Monitoring	🟩	🟩	🟩		
		Standardization		🟩	🟩	🟩	🟩

Circular Strategies	Description
Long life	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.
Lifetime extension	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.
Product recovery	Returning products or parts to working condition, thereby increasing the number of use cycles.
Structural reuse	Retrieving structural elements, preserving the material composition, through repurposing, resizing or reshaping product parts for reuse in another context or construction.
Recycling	Recovery of materials through thermal, chemical, or mechanical processes, resulting in raw materials ("recyclate"), aiming to close the materials loop.

Design Aspects	Description
Accessibility	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.
Adaptability	Anticipating and enabling changes and adjustments to be made to the product during its (successive) use cycle(s).
Cleanability	Making products, parts, and surfaces so that they can be cleaned or prevent accumulation of dirt.
Ergonomics	Ensuring the product can be used, maintained, reworked, and reprocessed in a safe and efficient way.
Fault isolation	Enabling tracking an occurring fault to its cause, e.g., a worn component, for quick and easy repair.
Functional packaging	Choosing packaging for the product and/or components to optimise transport and distribution.
Interchangeability	Making parts or subassemblies of the product readily replaceable or exchangeable.
Malfunction signalling	Indicating (imminent) product failure to facilitate inspection and subsequent actions.
Simplification	Minimising the complexity of the product in terms of functionality, assembly, appearance, and materials composition.
Connection selection	Selecting connections that can be accessed, opened, and reused where appropriate to facilitate use, rework, and recovery actions during product life.
Dis- and reassembly	Facilitating manual or mechanical disassembly and reassembly of the product to enable reuse of parts to improve the recovery rate.
Function integration	Combining multiple functions and (sub)components into one part.

Design Aspects	Description
Keying	Using product shape to facilitate alignment, e.g., holes and pins
Modularity	Grouping features within the product to create sub-assemblies that are accessible, removable, and interchangeable.
Redundancy	Adding additional materials or functionality to ensure continued operation and safety, even when parts degrade or are (partially) removed.
Sacrificial elements	Defining replaceable components and surface treatments to take up wear and damage, thus protecting other parts.
Material selection	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.
Manufacturing process selection	Selecting and optimising the process to minimise emissions and meet the material, functional, shape and recovery criteria.
Structural design	Optimising the material structure, shape, and product architecture to achieve the desired structural performance.
Surface treatments	Selecting coatings and other surface treatments appropriate for the use, reuse and reprocessing of the product and its materials.
Documentation	Providing information about the product, components, and functions to stakeholders in the value chain and actors in the product and component lifecycle.
Identification	Using labels, tags etc. to facilitate recognition of the product, parts, materials and/or its specifications.
Monitoring	Determining and logging of product properties and use conditions over the product lifetime.
Standardisation	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.

Appendix B

Questionnaire on prior knowledge and method usage. Content derived from [26] is indicated in italics.

TU Delft ECOBULK

Design strategies for composites in a Circular Economy

Questionnaire

1. Name: …

2. Please indicate if and how you learned about Circular Product Design *before* you started on the project (select all that apply and add additional details if available):

- I didn't have any prior knowledge
- Familiar with CE from Ellen MacArthur Foundation
- MOOCS: …
- Reading on the subject: …
- Explanatory videos
- (Students:) Courses at Industrial Design Engineering: …
- Other: …

3. In the project, you were given a Design framework for composite products in a CE. The framework connected circular strategies (e.g. remanufacturing or reconfiguration) to design principles (e.g. modularity and connection selection). Please indicate (tick the boxes) for which

actions you referred to the design framework:

In this design project, I used the circular product design framework for composites to …

Analysis	Circular Strategies	Design Principles
1. *... form an understanding of the problems surrounding product ideas.*		
2. *... explore design problems.*		
3. *... understanding design challenges*		
4. *... understand what to design.*		
Synthesis		
5. *... generate initial proposals for my designs.*		
6. *... generate ideas.*		
7. *... generate concepts.*		
Simulation		
8. *... try out proposals of my designs.*		
9. *... run through the properties of my designs.*		
10. *... develop prototypes of my ideas.*		
Evaluation		
11. *... test my design proposals.*		
12. *... evaluate my design proposals.*		
13. *... check the quality of my ideas.*		
Decision-making		
14. *... decide which of my ideas to continue with.*		
15. *... decide whether I need to redo designs.*		
16. *... aid me in taking important design decisions.*		

End of questionnaire

Appendix C

Semi-structured interview setup

Design strategies for composites in a Circular Economy

Contact details

Researcher: Participant:
Jelle Joustra

Semi-structured interview [With design object or photo's]

1. How did you learn about the design method ? (*coaching, paper, reading, learning by doing*)
    a. How did this help you to understand the design method?
2. Can you tell how you used the design strategy framework for your project?
    a. Which circular strategies did you select, and why?
    b. Which design principles did you use, and why?
3. Was the design method usable to the specific context?
    a. Did you find opportunities for the design?
    b. Did you find challenges for the design?
4. Which decisions you took were inspired by Circular Strategies or Design Principles?

Appendix D

Codes used to analyse the interview responses

Table S4.1. Aspects and codes used to analyse effectiveness of the design method in practice.

Aspects of effectiveness	Codes
Level of integrity	Product integrity
	Material integrity
Circular system	Open
	Closed

Table S4.2. Aspects and codes used to analyse the accessibility of the design method in practice.

Aspects of accessibility	Codes
Prior experience	Recovery considered in design
	Use of retrieved materials in production
Accessing the method	none
	Ellen MacArthur Foundation
	Open Courseware
	Reading
	Videos
	Courses
	Other
Understanding the method	Terminology
	Framing of circular economy
	Match with design practice

Table S4.3. Aspects and codes used to analyse the usability of the design method in practice.

Aspects of usability	Codes
Use in design process; Using the method to find…	Opportunities found using the method
	Challenges found using the method
Tasks in the basic design cycle After [12], Supplement 2	Analysis
	Synthesis
	Simulation
	Evaluation
	Decision making
Method manifestations related to design tasks	Idea generator
	Evaluation checklist
	Communication tool
	Detailing product concept
	Backing up choices/building confidence
Suitability to case	Circular strategies
	Design aspects

Chapter 4: Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades

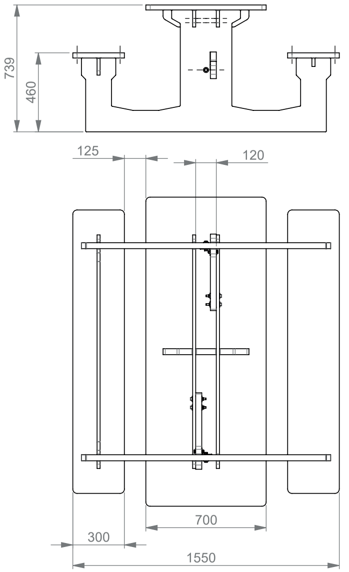
Appendix A: Design aspects and their descriptions

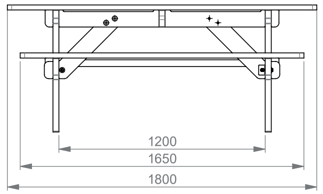
Table 2 Aspects for design of composite products in a Circular Economy [27]

Design aspect	Description
Accessibility	Ensuring (internal) parts can be reached for e.g. maintenance or repair operations.
Adaptability	Enabling changes and adjustments to be made to the product during its life.
Dis- and reassembly	Facilitating (manual or mechanical) disassembly and reassembly of the product.
Fault isolation	Facilitating fault finding for e.g. repair.
Identification	Using labels, tags etc. to facilitate recognition of the product and/or its specifications
Interchangeability	Making parts or subassemblies of the product readily replaceable
Keying	Using product shape to facilitate alignment, e.g. holes and pins
Malfunction annunciation	Indicating (imminent) product failure
Material selection	Selecting matrix, reinforcement, connections and other materials
Modularity	Grouping features within the product to create separable sub-assemblies
Sacrificial elements	Defining replaceable components to take up wear and damage, thus protecting other parts
Simplification	Minimising the complexity of the product, by e.g. appearance, assembly or materials
Standardisation	Using standard components, processes, dimensions etc. in the product design
Surface treatments	Selecting coatings and other surface treatments appropriate for the use and recovery of the product.
Connection selection	Selecting connections for the use and recovery actions during product life
Documentation	Providing information about the product to stakeholders in the value chain
Manufacturing	Selecting and optimising the process to meet the material, shape and recovery criteria
Monitoring	Measuring (and storing) product properties while in use.

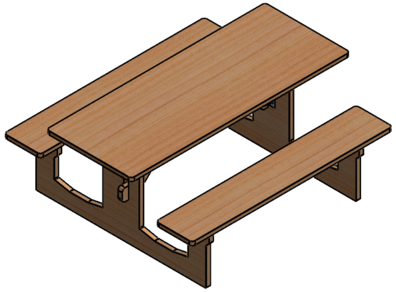
Design aspect	Description
Structural design	Optimising the shape to get the best structural quality.
Function integration	Combining multiple functions and (sub)components into one part.

Appendix B: Furniture prototype dimensions





ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	frame	Panel # 8, t=29 to 35 mm.	2
2	rail_table	Panel # 4, t=16 to 18 mm.	2
3	rail_seat	Panel # 4, t=16 to 18 mm.	2
4	toprail	Panel # 8, t=29-35 mm.	1
5	table	Panel # 7, t=29mm.	1
6	seat	Panel # 5, t=30 mm.	2
7	diagonal	Panel # 8, t=29 to 35 mm.	2
8	DIN 6902-B9.3	Plain washer	12
9	DIN 912 M10 x 80 --- 32N	Hexagon socket head screw	4
10	Hexagon Nut ISO 4032 - M10 - D - N		8
11	Angle bracket 40x60		2
12	DIN EN 24014 - M10 x 50 x 26-N		4

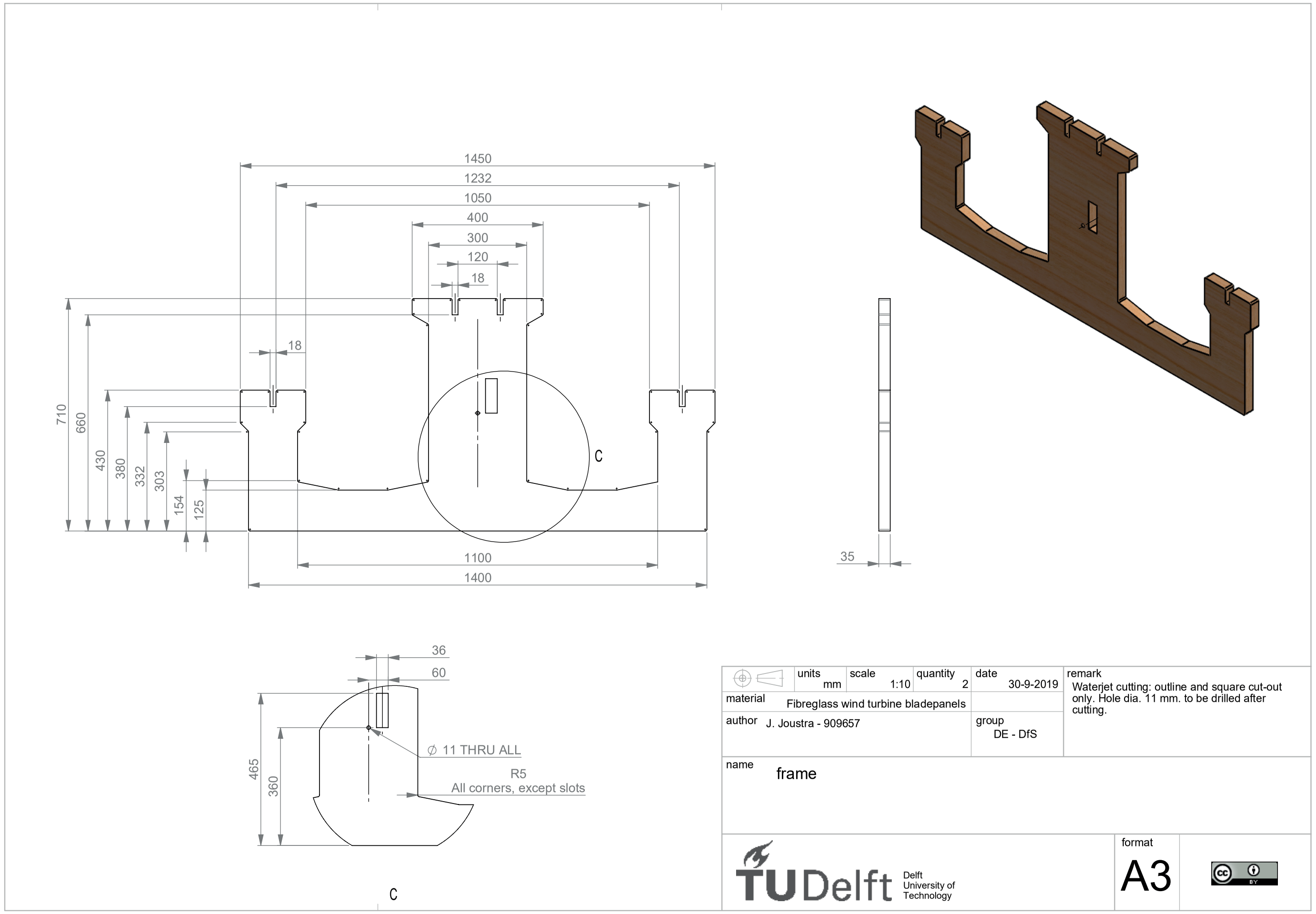


units	scale	quantity	date	remark
mm	1:20		30-9-2019	

material Fibreglass: wind turbine blade panels
author J. Joustra - 909657
group DE - DfS
name Picnic table set

Delft University of Technology

format A3

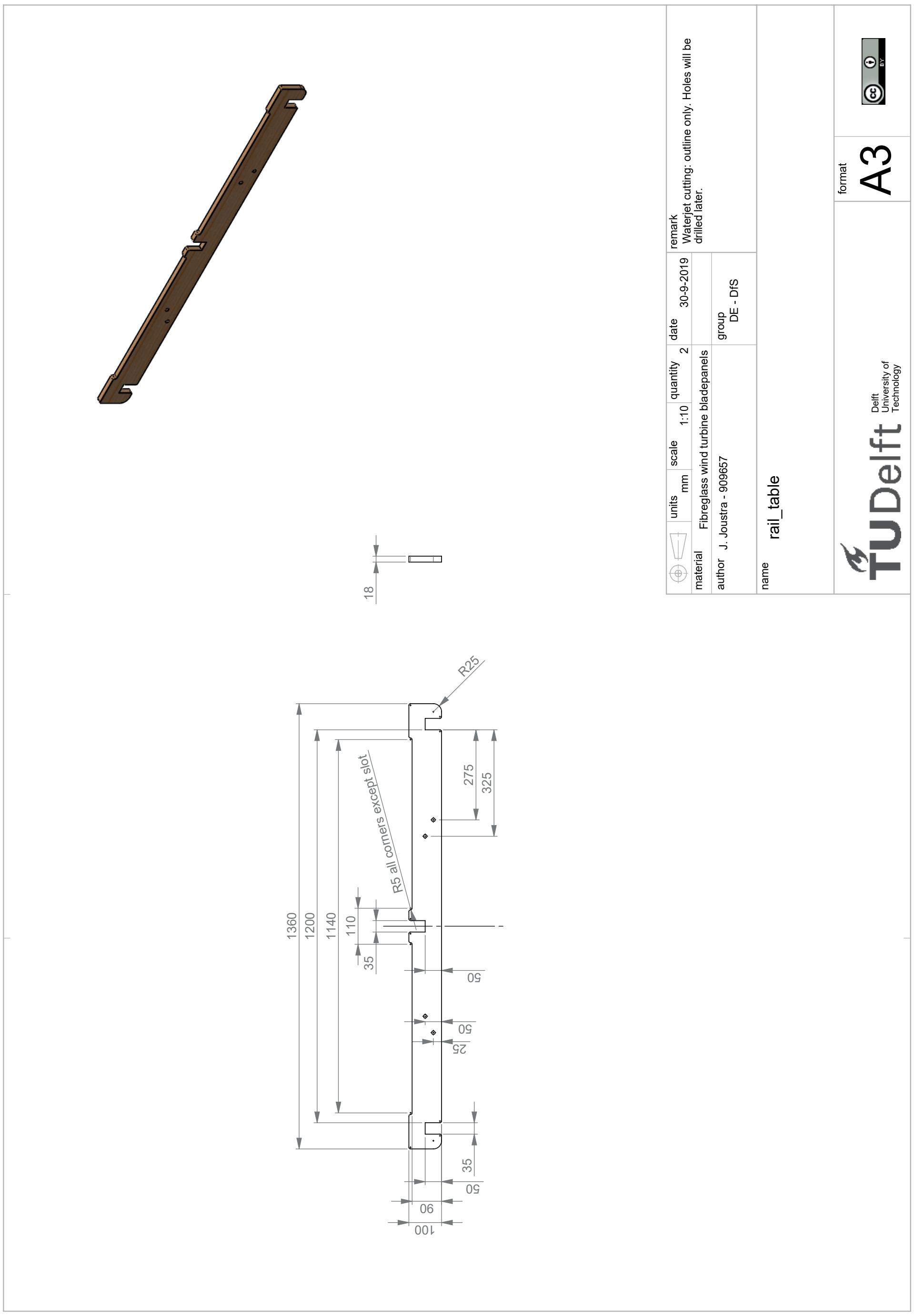


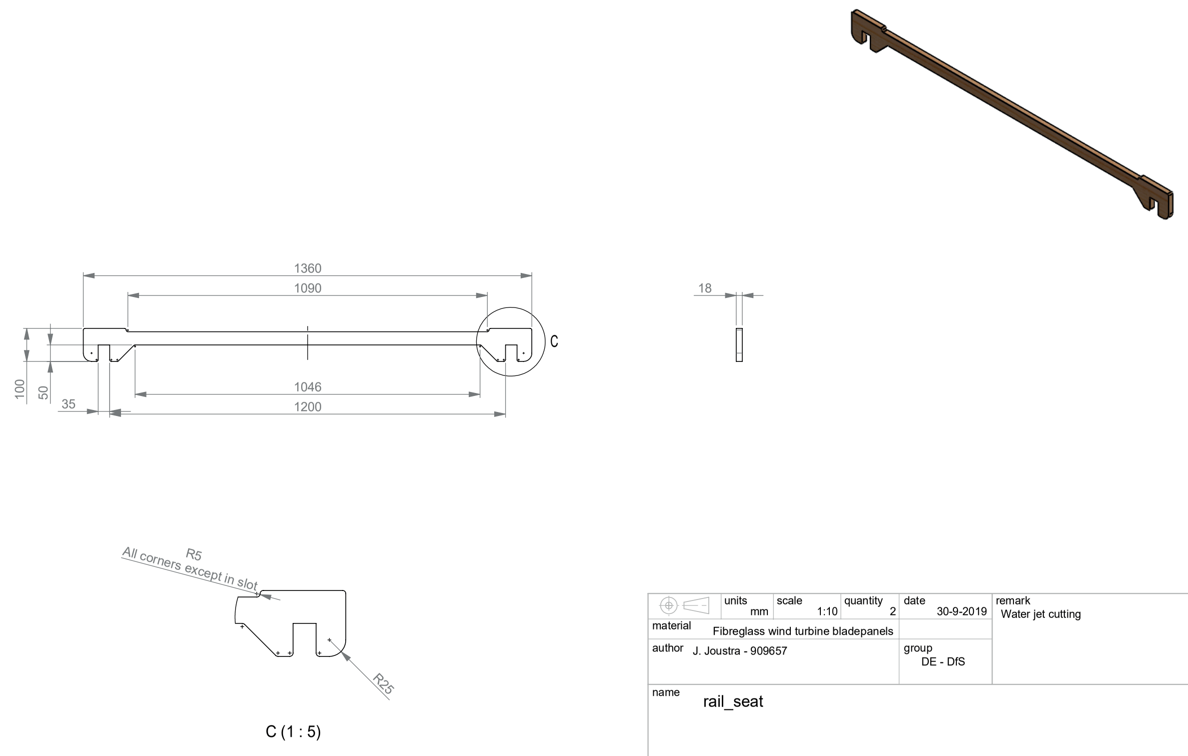
units mm	scale 1:10	quantity 2	date 30-9-2019	remark Waterjet cutting: outline and square cut-out only. Hole dia. 11 mm. to be drilled after cutting.
material	Fibreglass wind turbine bladepanels			
author	J. Joustra - 909657		group DE - DfS	

name
frame

TUDelft Delft University of Technology

format
A3


18
R25
275
325
R5 all corners except slot
1360
1200
1140
110
35
50
50
25
35
50
90
100
units
mm
scale
1:10
quantity
2
date
30-9-2019
remark
Waterjet cutting: outline only. Holes will be drilled later.
material
Fibreglass wind turbine bladepanels
author
J. Joustra - 909657
group
DE - DfS
name
rail_table
format
A3
TUDelft
Delft University of Technology



units	scale	quantity	date	remark
mm	1:10	2	30-9-2019	Water jet cutting

material Fibreglass wind turbine bladepanels

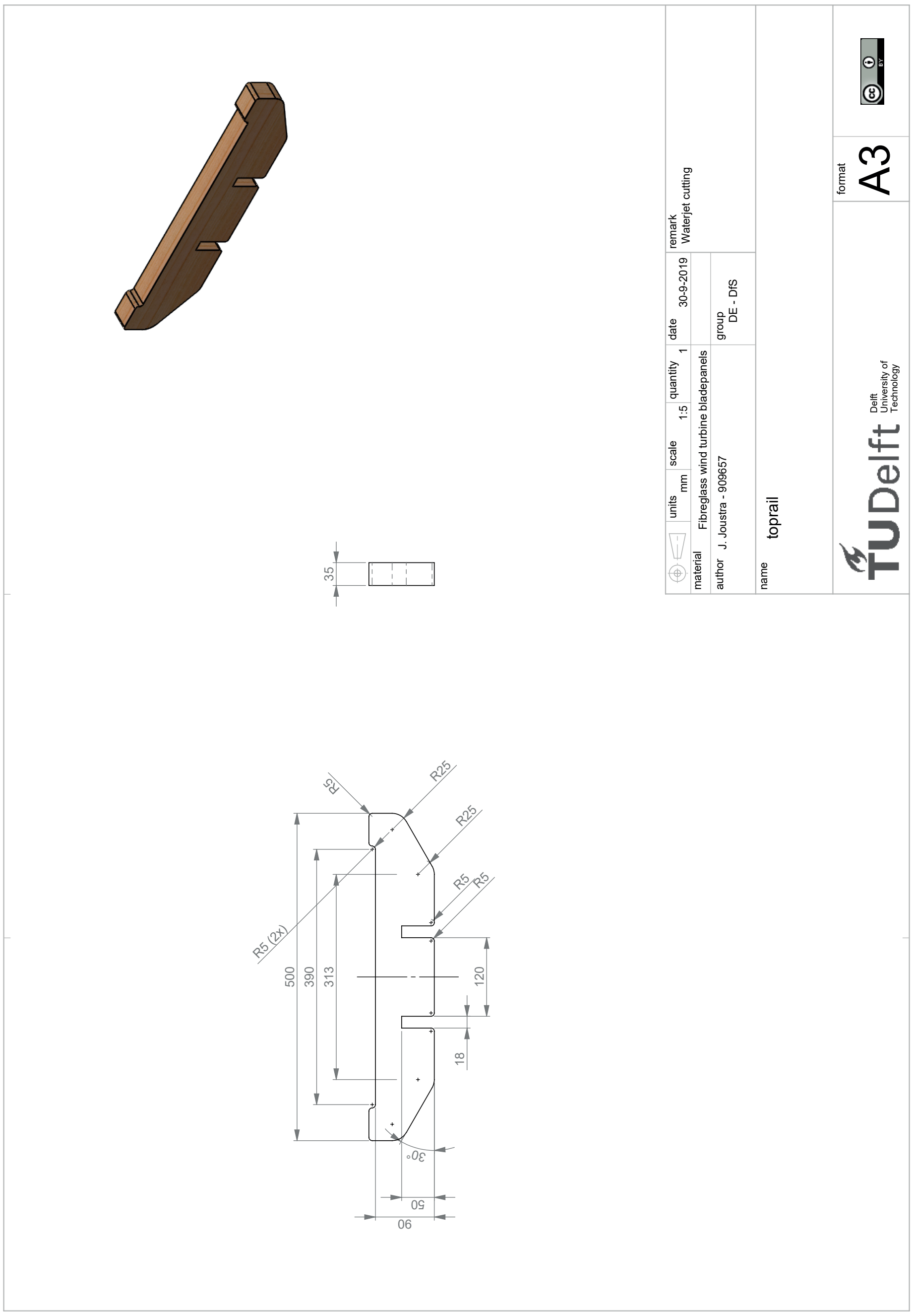
author J. Joustra - 909657

group DE - DfS

name rail_seat

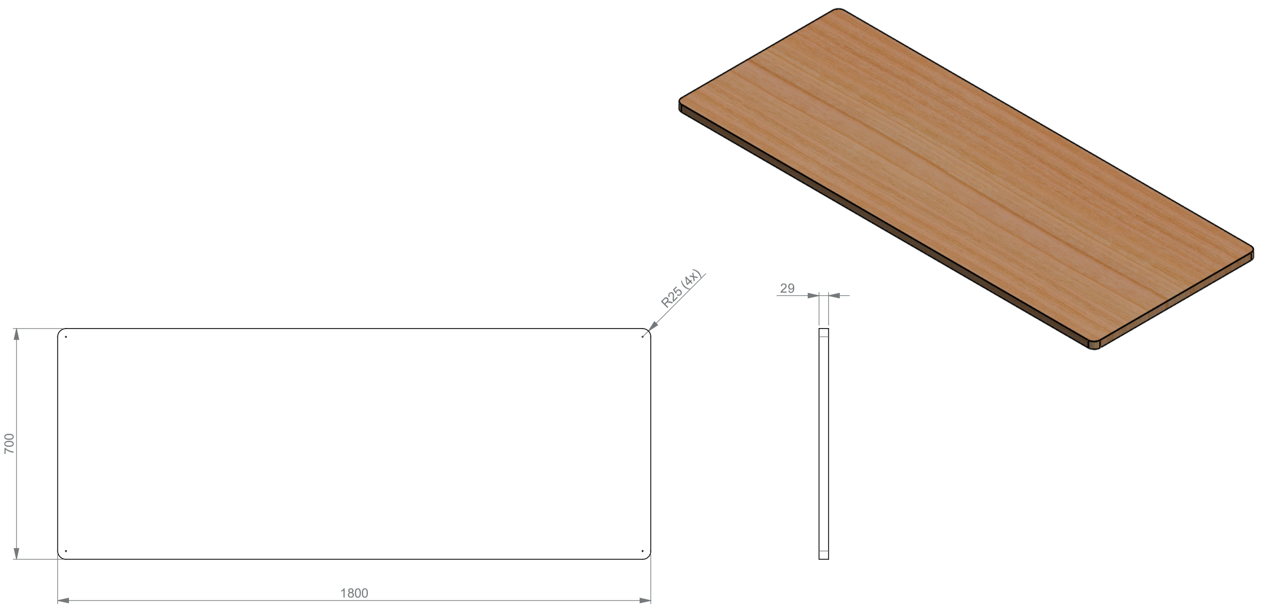
TU Delft Delft University of Technology

format A3

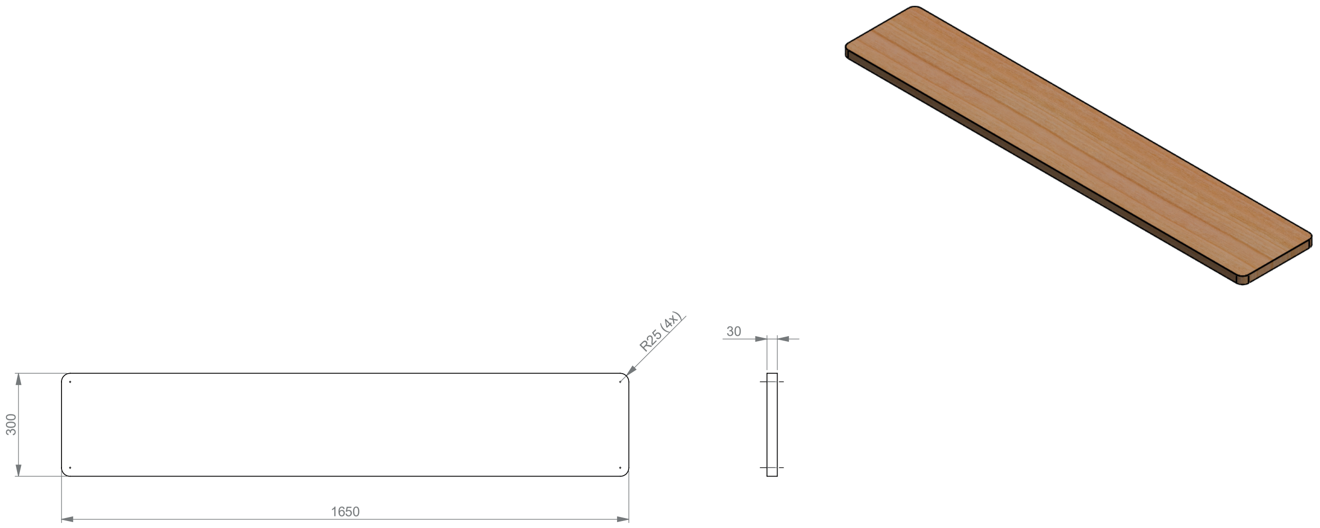


units mm
scale 1:5
quantity 1
date 30-9-2019
remark Waterjet cutting
material Fibreglass wind turbine bladepanels
author J. Joustra - 909657
group DE - DfS
name **toprail**
format A3

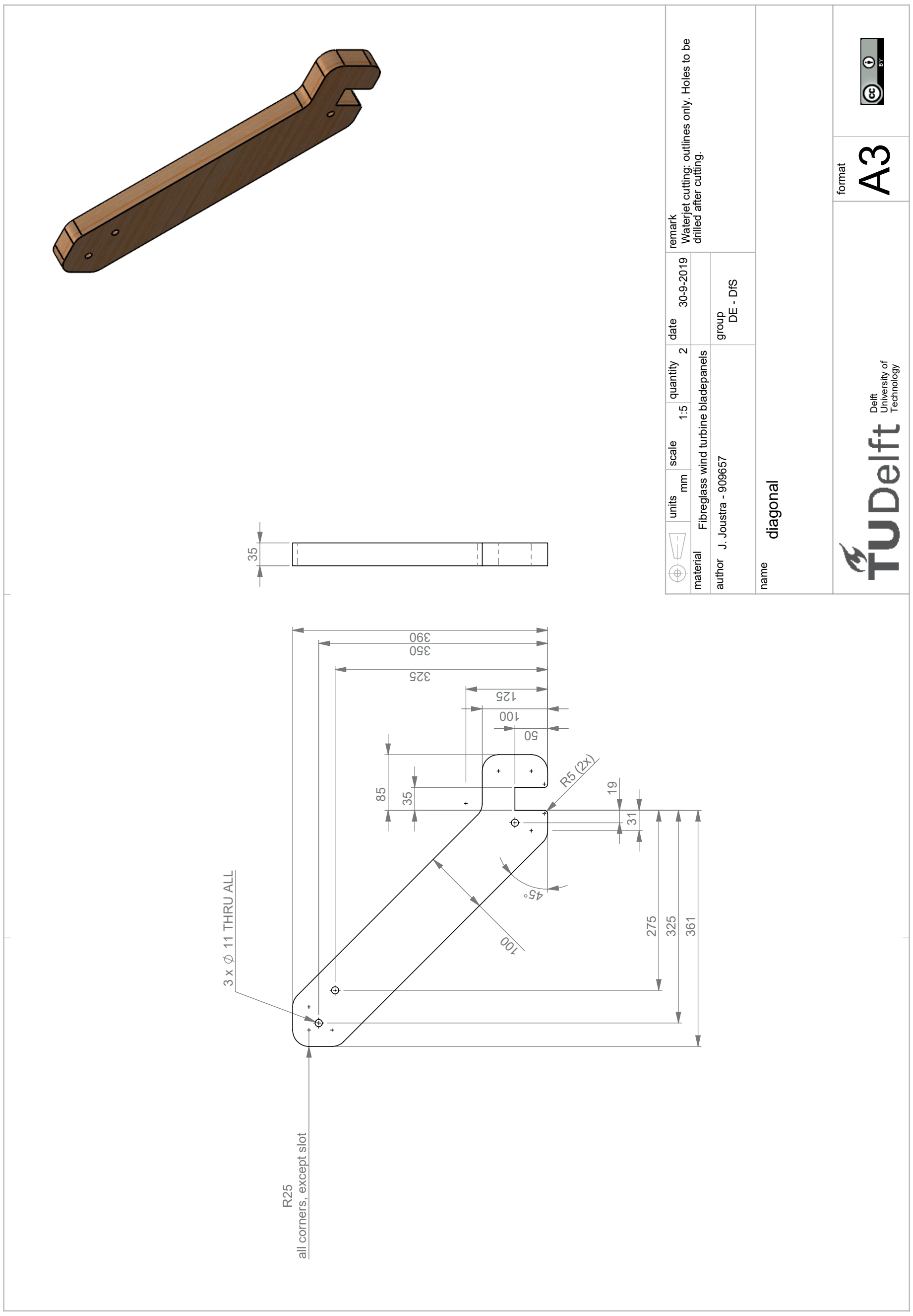
TUDelft Delft University of Technology



units mm	scale 1:10	quantity 1	date 30-9-2019	remark waterjet cutting
material	Fibreglass wind turbine bladepanels			
author	J. Joustra - 909657		group DE - DfS	
name	table			
TUDelft Delft University of Technology			format A3	



units mm	scale 1:10	quantity 2	date 30-9-2019	remark Waterjet cutting
material	Fibreglass wind turbine bladepanels			
author	J. Joustra - 909657		group DE - DfS	
name	seat			
TUDelft Delft University of Technology			format A3	


remark
Waterjet cutting: outlines only. Holes to be drilled after cutting.
units mm
scale 1:5
quantity 2
date 30-9-2019
material Fibreglass wind turbine bladepanels
author J. Joustra - 909657
group DE - DfS
name diagonal
format A3
35
390
350
325
125
100
50
85
35
R5 (2x)
19
31
275
325
361
45°
100
3 x ⌀ 11 THRU ALL
R25
all corners, except slot

Publications
Contributions
Acknowledgements
About the author

●●●●●

Publications

Journal articles

The chapters in this thesis are based on the following publications. Listed with reference to chapter number:

2. Joustra, J. J., Flipsen, S. F., & Balkenende, A. R. (2021). Circular Design of Composite Products : A Framework Based on Insights from Literature and Industry. *Sustainability*, *13*(The Sustainability Challenges in Polymer Composite Materials: Bio-Based Materials, Recycling, and Life Cycle), 7223. https://doi.org/https://doi.org/10.3390/su13137223
3. Joustra, J., Bessai, R., Bakker, C., & Balkenende, R. (2022). Circular composites by design: testing a design method in industry (under review). Sustainability.
4. Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades. *Resources, Conservation and Recycling*, (167). https://doi.org/10.1016/j.resconrec.2020.105393
5. Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. *Composites Part C*, *5*(100137). https://doi.org/10.1016/j.jcomc.2021.100137

Book publication

1. Joustra, J., & Bessai, R. (2022). Circular Composites: A design guide for products containing composites in a circular economy. https://doi.org/10.34641/mg.23

Conference papers and presentations

1. Joustra, J.J., Vilkki, M., (2018), Closing the loop for wind turbine blades, AMI conference on wind turbine blade manufacturing 2018, Düsseldorf
2. Joustra, J. J., Flipsen, S. F., & Balkenende, A. R. (2019). Circular Design of Composite Products : A Preliminary Framework Based on Insights from Literature and Industry. In N. F. Nissen & M. Jaeger-Erben (Eds.), PLATE Product Lifetimes And The Environment 2019 – Conference Proceedings. http://dx.doi.org/10.14279/depositonce-9253
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6. J.J.Joustra (2021), Ecobulk: Circular design strategies, Plastics Recycling Show Europe, Amsterdam, https://www.ecobulk.eu/news/ecobulk-at-prse2021/
7. R. Balkenende, J. Joustra, (2021), Ecobulk: Circular design, Ecobulk final conference (online), https://www.ecobulk.eu/news/ecobulk-final-event/
8. J. J. Joustra (2021), Design strategies for products containing composites in a Circular Economy, Walking the talk to a Circular Economy, webinar, https://www.ecobulk.eu/news/ecobulk-webinar-walking-the-talk-towards-a-circular-economy/

Reports

1. Petrucelli, L., Moretta, L., Joustra, J. J., & Balkenende, R. (2018). Ecobulk D2.1: Report on baseline description. Retrieved from https://wordpress.ecobulk.eu/wp-content/uploads/2018/04/D2.1-GRANTA-Report-on-Baseline-description-28022018.pdf
2. Joustra, J. J., & Balkenende, A. R. (2018). Ecobulk D2.2 (v1): Report on Design strategies and tools. Retrieved from https://www.ecobulk.eu/wp-content/uploads/2018/12/D2.2-Design-strategies-and-tools.pdf
3. Joustra, J. J., & Balkenende, A. R. (2021). Ecobulk D2.2 (final): Report on design strategies and tools. Retrieved from https://www.ecobulk.eu/wp-content/uploads/2021/10/D2.2-Design-strategies-and-tools-final-version.pdf
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5. Blasco, L., Moya, A., Joustra, J. J., Ferreres, I., Tosi, G., Vilkki, M., & Spinelli, D. (2018). Ecobulk D2.4: Report on Design Circular Framework Setting. Retrieved from https://www.ecobulk.eu/wp-content/uploads/2020/05/D2.4-Report-on-Design-Circular-Framework-Setting.pdf
6. Hajonides van der Meulen, T., Bastein, T., Krishna Swamy, S., Saraswati, N., & Joustra, J. (2020). Offshore wind farm decommissioning: an orientation of possible economic activity in

the south holland region and Rotterdam port area. Retrieved from https://smartport.nl/decommissioning-de-onderzoeksresultaten/

7. Lightfoot, J., Joustra, J., Bank, L., Russel, G., Berry, D., Beauson, J. (in progress), IEA Wind task 45 report on repurposing and reuse of wind turbine blades, https://iea-wind.org/task45

Projects

1. Ecobulk, a large scale demonstration effort for composite products in a Circular Economy. This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 730456. The project ran from 2017 to 2021.
2. Hybrid reuse of plastics and composites, an applied research project into reprocessing recovered thermoset composites for building and infrastructural purposes. This project received RAAK-MKB funding from the Dutch Research Council (NWO). The project ran from 2019 to 2021.
3. LICHEN-Blades, a research project focusing on innovations in wind energy. The project will see development of circular wind turbine blades and associated design strategies, materials, manufacturing techniques and business models. The project was granted NWO-KIC funding, starting in 2022.

Community sessions

1. Innovation program mattress recycling, NWO-TTW-SIA working session (2018), Utrecht
2. Composite upcycling, concept development session, Het Groene Brein (2018), Utrecht
3. Guideline for definitions and measurement methods for circular office and education environment, NEN (2019), Delft
4. Decommissioning wind farms, circularity and operational challenges, Smartport community session (2019), Rotterdam
5. Moonshot project circular wind farms, value chain meetings, ECHT (2020), online, https://www.echt.community/moonshot/
6. New materials and circular economy accelerator, stakeholder meetings, CSR Europe (2022), online https://www.csreurope.org/new-materials-and-circular-economy-accelerator

Exhibition

1. Dutch design week 2019, Embassy of sustainable design
2. Open days at the faculty of industrial design engineering (2019, 2020, 2021), TU Delft. Display of Ecobulk project posters and prototypes.
3. Ecobulk demonstrator activities

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1. Linares, I. (2021). CWA 17806:2021; CEN/WS 113 “Framework linking dismantled parts with new design components for the automotive industry in a circular economy model.” Brussels.
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Contributions

While the articles have been primarily written by myself, I wish to acknowledge the following persons for their contribution. With reference to the chapter number:

2. Joustra, J. J., Flipsen, S. F., & Balkenende, A. R. (2021). Circular Design of Composite Products : A Framework Based on Insights from Literature and Industry. *Sustainability*, *13*(The Sustainability Challenges in Polymer Composite Materials: Bio-Based Materials, Recycling, and Life Cycle), 7223. https://doi.org/10.3390/su13137223
   The design framework in chapter 2 is based on a literature study executed by myself and focus group sessions within project Ecobulk. I prepared the session materials by myself and the moderated the group discussions together with Bram van der Grinten, Ruud Balkenende and Ecobulk project partner company Itene. The responses were processed by myself and Itene. Preliminary results were published in Ecobulk project report D2.4 and at the PLATE conference (Berlin, 2019).
3. Joustra, J., Bessai, R., Bakker, C., & Balkenende, R. (2022). Circular composites by design: testing a design method in industry. Sustainability, 14(13 (Product Eco-Design in the Era of Circular Economy)), 7993. https://doi.org/10.3390/su14137993
   The design framework was tested in design case studies with Ecobulk partners, they redesigned and prototyped the case products, and participated in interviews to reflect on the design process, which were prepared and executed by myself, assisted by Riel Bessai. The preliminary results were reported in Ecobulk report D2.2 (final version, 2021). This was then elaborated into a full article by myself, supported in writing and summarising the case studies by Riel Bessai. Conny Bakker and Ruud Balkenende supervised the case evaluation and article revision process.
4. Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural Reuse of High End Composite Products: a Design Case Study on Wind Turbine Blades. *Resources, Conservation and Recycling*, (167). https://doi.org/10.1016/j.resconrec.2020.105393
   The design case study on wind turbine blades was done by myself. Exhibition at the Dutch Design Week was organised in cooperation with design agency van Berlo. Stijn Speksnijder, Tjits Tuinhof, Isabelle Laros, Esra Polat and Ruud Balkenende assisted with the audience interaction. The article on this design case study were written by myself under supervision of my promotors.

5. Joustra, J., Flipsen, B., & Balkenende, R. (2021). Structural reuse of wind turbine blades through segmentation. *Composites Part C*, *5*(100137). https://doi.org/10.1016/j.jcomc.2021.100137

   The research on segmentation, structural analysis and design for structural reuse was done by myself. Carlo Valk programmed the segmentation procedure in Python. The article was written by myself, under supervision of my promotors.

Acknowledgements

A PhD is a wonderful personal journey but such a dissertation comes about with the help of many. I have listed the contributions for each individual study in the corresponding chapter, here I would like to shed light on those who were with me along the way. Looking back on these past couple of years I will follow a kind of anti-chronological line.

I would like to thank the members of the doctoral committee for lending me their critical eye on my research and their part in concluding this PhD. Ruud and Bas, my promotor and co-promotor, thank you for your supervision in this quest for knowledge and skills. Ruud, thanks for encouraging to keep an eye out for the bigger picture while minding the crucial details. Bas, thanks for engraining me with your approach of delineating design spaces using facts and figures.

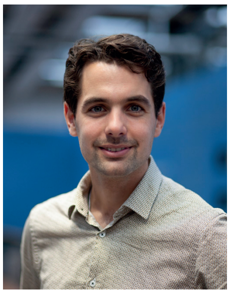
Project Ecobulk funded my research through the EU H2020 program and added an important connection to industry practice. I would like to thank the project partners for their kind cooperation, and especially like to acknowledge the case holders, Markku, Giovanni, John, James, Enrico and Mario, whom I challenged on the implementation of circular product design aspects. Also, Bram for joining in as researcher in Ecobulk and acting with me as client in the IDE Bachelor End Project.

All colleagues at TU Delft, researchers, teachers and support staff alike, it was and still is a pleasure working with you. I especially want to acknowledge all my colleagues in the fourth floor PhD community who walked this path with me. We really created our own world and enjoyed PhD life together. I also want to mention the students who helped me to explore the fringes of my research area in their graduation, BEP and research projects.

Off course I want to thank myfriends and family for their love and support. My parents for providing me with a solid base on which I could always build with creativity and an eye for sustainability. Nynke, thank you for exposing me some much-needed culture. Irene, our paths crossed at the same time I started this, and while the PhD journey ends, I can’t wait to see where ours will take us. Dear Sverre, I hope this work will contribute to a sustainable future for you.

Lastly, I want to acknowledge David, Nick, Richard and Roger, as well as Geddy, Alex and Neil, Bruce, and Arjen for the soundtrack to which this dissertation was written, it still echoes in my mind.

Curriculum vitae



Jelle Jouke Joustra was born on April 16th, 1986 in Zutphen, the Netherlands. From 2004, following his interest in making and finding out how things worked, he studied Industrial Design Engineering at Delft University of Technology. During his studies, he sailed and restored the classic fishing boat BU130 “Trui”. After his bachelor, he joined the Nuon Solar Team to design, build and race solar car Nuna5 in the 2009 World Solar Challenge in Australia and the 2010 Suzuka Dream Cup, Japan. This project brought together design, solar energy and composite materials. In 2012, he finished his master thesis on the design of thermally optimised and adaptive sailing gear for dinghy sailors.

Jelle gained professional experience at Hukseflux Thermal Sensors, where he also had a part-time job during his study. He designed sensor equipment for measuring solar power, including the highest performing solar radiation sensors available. After 5 years at Hukseflux he decided to deepen his knowledge on implementing sustainability by design.

He started his PhD research on design strategies for composite products in a Circular Economy in October 2017. The research was embedded in project Ecobulk, an Horizon2020 project which brought together partners from industry and academia to close the resource loop for composite materials. During the PhD, he published four journal articles, presented at international conferences and supervised students in courses and graduation projects. His design case studies delivered rich insights in circular product development. The resulting prototypes were presented at the Dutch Design Week 2019. Next to his PhD, he built a 12 foot skin-on-frame kayak and a 14 foot wooden skiff which he enjoys sailing on the local waters.

Propositions accompanying the dissertation

Circular Composites

Design strategies for products containing composite materials in a circular economy

By Ir. J. J. Joustra

1. The perspective of composite product development as combination of materials, shape and process (Mallick, 2007) does not suffice for realising a sustainable product. Recovery should be added.
2. Structural reuse, sometimes referred to as “structural recycling”, is a promising end-of-use solution for composite products.
   This proposition pertains to the contents of this thesis.
3. Wind turbine blades make for good construction elements.
   This proposition pertains to the contents of this thesis.
4. Circular design is currently limited by linear constraints.
   Building on Eames, C., Eames, R., & Ostroff, D. (2015).
5. Upcycling does not exist.
6. Prototyping, especially when carried out by the researcher him/herself, is a powerful tool to uncover and demonstrate (un)imaginable insights.
7. It takes dirty hands to create a clean and circular economy.
8. There is no design without research, and no research without design.
   Inspired by Peart, N., Lifeson, A., & Lee, G. (1985).
9. Simple solutions outperform smart technologies.
10. Boatbuilding supports thesis writing.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors prof. dr. A. R. Balkenende and dr. ir. S.F.J. Flipsen