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A design case study on wind turbine blades**

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Full length article

Structural reuse of high end composite products: A design case study on wind turbine blades

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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.

1. Introduction

Composites, specifically fibre reinforced polymers, provide many advantageous properties to use in product design (Yang et al., 2012). 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 (Mangino et al., 2007). 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 (Mallick, 2007; Papadakis et al., 2009; Teuwen, 2011).

Design of composite products is currently optimised for mechanical performance in the use phase (Perry et al., 2012). This focus, combined with the complex and heterogeneous nature of the materials, leads to problematic end-of-life (EoL) processing (Naqvi et al., 2018; Yang et al., 2012). In particular for Glass Fibre Reinforced Plastics (GFRP), which dominates the composites market, no clear recycling route is available even though various options exist (Job, 2014; Liu et al., 2019).

Composite materials can be recycled using mechanical, thermal or chemical processes (Chen et al., 2019; Oliveux et al., 2015; Yang et al.,

2012). 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 recycle value does not offset the costs (Oliveux et al., 2015; UBA, 2019). Consequently, the majority of composite waste is landfilled or incinerated (Jensen, 2019; Mativenga et al., 2017; Ratner et al., 2020).

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 (Cherrington et al., 2012). This option is not further considered in recovery frameworks, such as 9R (van Buren et al., 2016). Incineration recovers energy, but presents additional problems with release of toxic gases, fly-ash and the need to process the solid residue (Chen et al., 2019; Jensen, 2019). To prevent such treatments, we need reprocessing options that are efficient, cost-effective and have minimum environmental impact (Chen et al., 2019; Psomopoulos et al., 2019).

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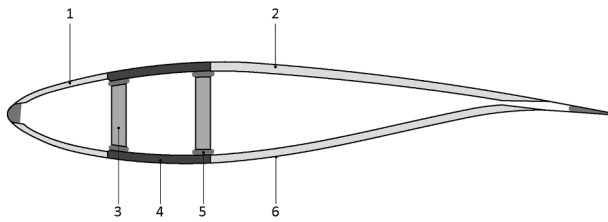


Fig. 1. Sections in a blade cross-section: 1) leading edge, 2) trailing edge, 3) shear webs, 4) spar caps, 5) adhesive bonds, 6) coating.

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 (Ellen MacArthur Foundation, 2013). Most value is preserved when the product or material remains close to its original state; preserving its integrity (Bakker et al., 2019). Recycling is eventually necessary to prevent loss of materials, but is also the least preferred loop, as the effort invested in manufacturing is lost (Balkenende et al., 2017). This is especially relevant for composites, which derive their high quality mechanical properties from a specific combination of materials, manufacturing process and design (Beukers and van Hinte, 2005).

Structural reuse, sometimes referred to as “structural recycling”, presents a promising alternative EoL solution for composite products (Asmatulu et al., 2014; Bank et al., 2019; Beauson and Brøndsted, 2016; Jensen and Skelton, 2018; Joustra et al., 2019). The process reuses the material as large parts or construction elements. Such reuse or “repurposing” of (partial) components is preferred over recycling (Allwood et al., 2011; van Buren et al., 2016). 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 (Beauson and Brøndsted, 2016). 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 (Jensen and Skelton, 2018). Also, design aspects that facilitate structural reuse are addressed in the Circular Product Design framework for composites, but received little input from design practice (Joustra et al., 2019). 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 (Joustra et al., 2019). 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 (Jensen and Skelton, 2018; Liu et al., 2019).

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 (Mishnaevsky et al., 2017; Resor, 2013). 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 (Fig. 1). The spar caps (4) have a monolithic layout 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.

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 (Siemens, 2012). LM introduced a two-piece blade design to reduce transport cost and increase configuration options (LM Windpower, n.d.) and more developments are expected in this field (Peeters et al., 2017). While predominantly made of GFRP, blades over 50 m in length also use carbon fibre (Bank et al., 2018), as unidirectional reinforcements in spar caps or hybrid weaves for the shells (Mishnaevsky et al., 2017).

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 (Nijssen and Brøndsted, 2013). Design and certification guidelines stipulate a design life of 20 to 25 years (Germanischer Lloyd, 2010; WindEurope, 2017). But, decommissioning is often primarily an economic decision (Tazi et al., 2019). 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 (Ciang et al., 2008; Rubiella et al., 2018). Measurements on a decommissioned blade showed the material retained its original stiffness and strength (Beauson and Brøndsted, 2016), 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 (Witten et al., 2017). Considering market growth, the annual decommissioning of wind turbine blades is expected to reach 2 Megatons by 2050 (Liu and Barlow, 2017). 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 (Cherrington et al., 2012; Teuwen, 2011), recovery is currently lacking in the design and certification guidelines for wind turbine blades (DNV-GL, 2015; Germanischer Lloyd, 2010).

Recent publications show a range of blade repurpose concepts, mainly in one-off applications: housing (Bank et al., 2018), power transmission line poles (Alshannaq et al., 2019) and bridges (Jensen and Skelton, 2018; Speksnijder, 2018). 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.

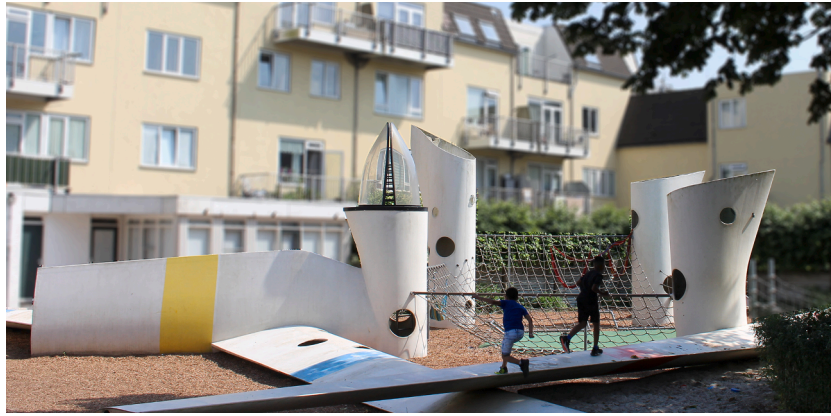


Fig. 2. Wikado playground Rotterdam, photo by J. Joustra.

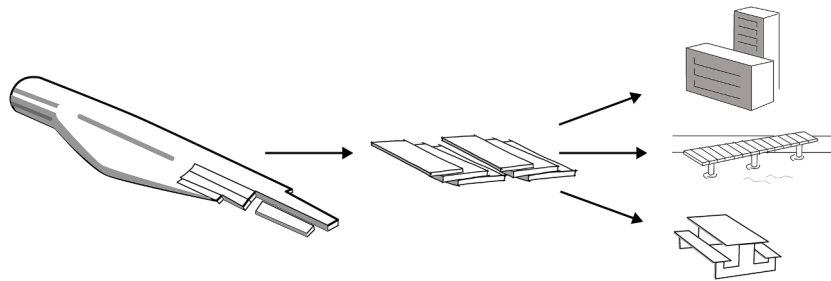


Fig. 3. Structural reuse of a wind turbine blade: segmentation into construction elements, reuse in diverse applications. Building on (Beauson and Brøndsted, 2016; Jensen and Skelton, 2018).

A well-known example of repurposing large parts is the Wikado playground in Rotterdam (Fig. 2) (Beauson and Brøndsted, 2016; Peeren et al., 2012). The blades are generally considered safe to use in such a different application (Jensen and Skelton, 2018). 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 (Medici et al., 2020). Such applications are, however, challenging to upscale. Beauson and Brøndsted (2016) 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 (Liu and Barlow, 2017; Papadakis et al., 2010).

Beauson and Brøndsted (2016) expect that cutting large blades into practically usable construction elements will diversify the potential applications (Fig. 3). 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 (Beauson and Brøndsted, 2016; Jensen and Skelton, 2018). 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.

2.3. Relating circular strategies to design aspects

To analyse 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 (Joustra et al., 2019). 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 (Stappers and Giaccardi, 2017). 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 (Horvath, 2008; Stappers et al., 2019). 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 (Stappers and Giaccardi, 2017). 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 (Stappers et al., 2019). 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 $0.3 \times 0.5 \text{ m}^2$ up to $6 \times 2 \text{ m}^2$ using a portable waterjet cutter. In these segments, we distinguish between panels and beams. Where, following the definitions of Ashby (2011) and Mallick (2007), 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 (Beauson and Brøndsted, 2016). Moreover, it has the additional advantage of being recognisable to a broad audience, enabling discussions on the acceptance 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 (Sumter et al., 2020). 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 (NEN-ISO, 1990), a common standard for design drawings and component specifications.

The process was documented according to the critical journaling guidelines for Research through Design projects (Sadokierski, 2019). 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 (Saldaña, 2009), using codes derived from the Circular Product Design framework for composites (Joustra et al., 2019).

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 (Patton, 2002) 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. 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).

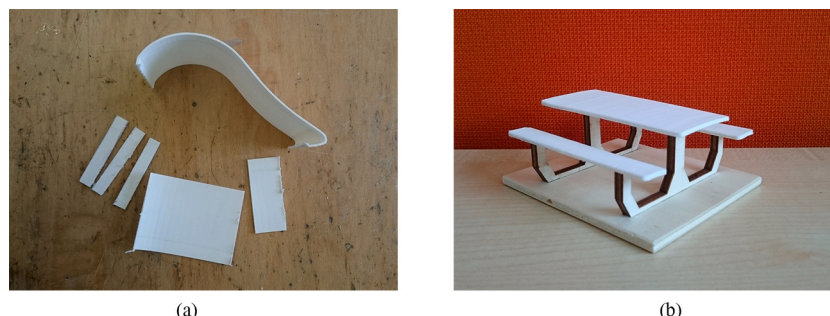


Fig. 4. Segments cut from a 1:20 scale blade(a) and used in a model (b).

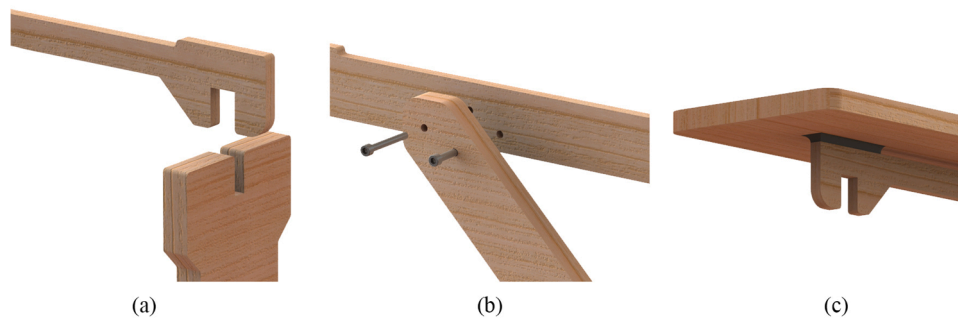


Fig. 5. Connection types used in the table design. Form fits (a), fasteners (b), adhesive bonds (c).

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 (Bank et al., 2018; Jensen and Skelton, 2018).

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 $0.3 \times 0.7 \text{ m}^2$ up to $2.5 \times 1 \text{ m}^2$. 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 (Fig. 4). On scale, 0.3 m wide leading edge segments were used for the seats, a 0.8 m 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 5 mm 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.

Three connection types were investigated in the table: form fits, fasteners and adhesive bonding (Fig. 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



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

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.

4.1.2. Prototype manufacturing

A full scale prototype was made to test the material in manufacturing and use (Fig. 6). 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 through-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.

Waterjet cutting delivered high sectioning accuracy but inflicted minor damage to the core material. In general, the linear dimensions

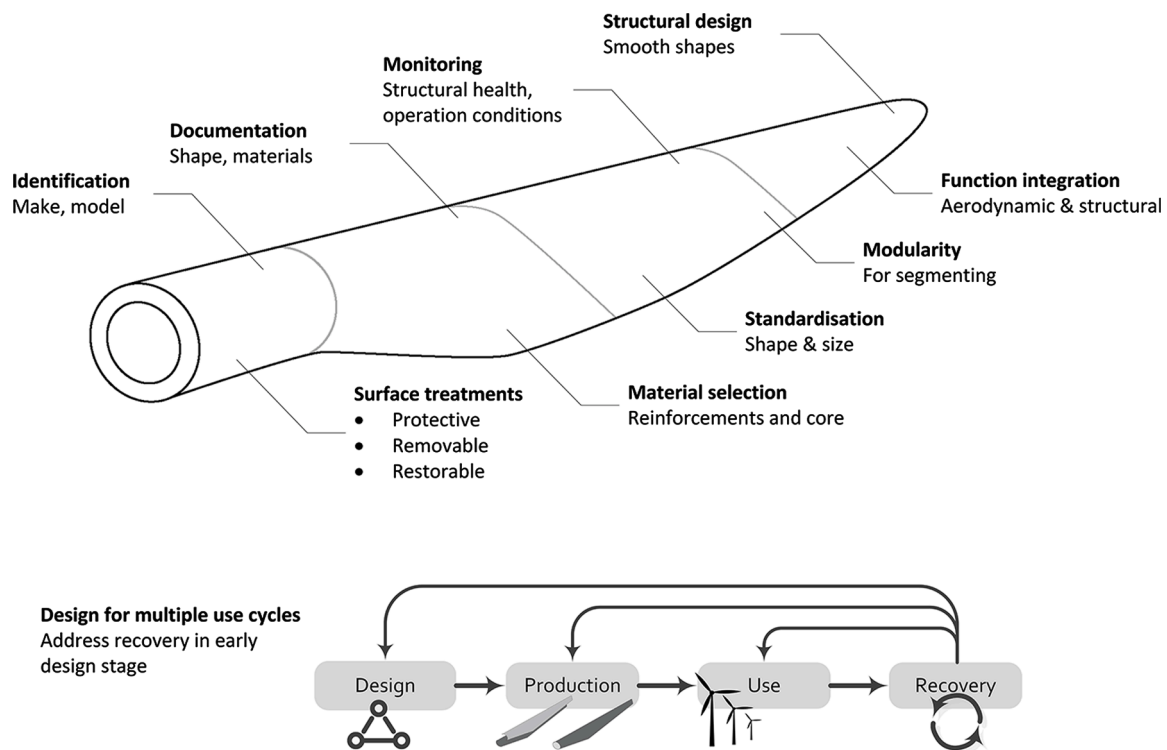


Fig. 7. Blade annotated with *Design for Structural Reuse* aspects.

remained within 0.5 mm of the design specifications, and as such complied to tolerance class ISO 2768-m (NEN-ISO, 1990). 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 (Joustra et al., 2019). 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 (Fig. 7), which served to trigger discussion with experts.

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.

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 (Joustra et al., 2019), 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

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)		
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.
Standardisation	Standardisation of curvature, dimensions, laminate layups and tolerances, construction materials will make construction elements less dependant 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 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.

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 (DNV-GL, 2015), 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 (Sayer et al., 2009; Tasistro-Hart et al., 2019).

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 (Peeters et al., 2017). 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 be used 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 (Balkenende et al., 2017; Pahl and Beitz, 2013; Peeters et al., 2017). 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 (Mallick, 2007).

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 (Ellen MacArthur Foundation, 2013). Both have been identified as core competencies and major challenges for designers in a Circular Economy (Sumter et al., 2020). Unfortunately, experts and literature note that the full product lifecycle is difficult to grasp for designers (Perry et al., 2014). 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 (Bakker et al., 2018). 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 thus far 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 (Cherrington et al., 2012; WindEurope et al., 2020).

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 (Joustra et al., 2020).

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 is 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.

CRedit authorship contribution statement

Jelle Joustra: Conceptualization, Investigation, Writing - original draft, Visualization. **Bas Flipsen:** Writing - review & editing, Supervision. **Ruud Balkenende:** Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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Appendix A. Design aspects and their descriptions

Table 2

Aspects for design of composite products in a Circular Economy (Joustra et al., 2019).

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

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