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A Preliminary Framework Based on Insights from Literature and Industry

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Publication date
2021

Document Version
Final published version

Published in
PLATE – Product lifetimes and the environment

3[rd] PLATE 2019 Conference
Berlin, Germany, 18-20 September 2019

PLATE
Product Lifetimes And The Environment

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

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Keywords: Design; Circular Economy; Composite Products.

Abstract: Composite materials are an attractive material choice as they enable lightweight, low maintenance products with a long lifespan. But closing the loop for these materials in a Circular Economy (CE) is challenging, especially for thermoset composites. In a CE, products should be designed for minimal impact while preserving their environmental and economic value for as long as possible. However, design strategies for composite products in a CE are currently largely unexplored.
Insights from literature on design for a CE as well as on composites recovery are combined to create a set of design principles for composites in a CE. In addition to well-known long life, lifetime extension and product recovery approaches, literature indicates the potential value of structural recycling. Structural recycling preserves most of the functional value of the product, which is largely lost in materials recycling. Experts from composites industry were interviewed in focus groups to further explore CE strategies and design principles for a set of reference products, such as car interior components. The resulting framework connects Circular strategies to design principles for composite products and supports design of new composite products for use, reuse and recycling in a CE.

Introduction

The current rate of consumption puts dangerous pressure on our global ecosystems, depleting resources and generating waste. The Circular Economy (CE) offers a promising alternative to lower the environmental burden. The CE aims to prevent waste by design and to preserve economic and environmental value (Balkenende et al., 2017). Products, components and technical materials are kept in the system by repairing, refurbishing, remanufacturing and recycling. Potential value gains are largest when the product remains as close as possible to its original state. This retains most of the energy, material, labour and capital that are embedded in the product (Bakker et al., 2018).
In a CE, products have to be designed for a low environmental impact, long lifetime, and recovery of products, parts or materials at the end of life. Composites (fibre reinforced polymers, (FRP)) are an attractive materials choice for designers, as they enable lightweight structures with a long lifespan (Yang et al., 2012). Yet, these materials present opportunities as well as challenges for use in a CE. Composite materials can reduce impact during the use phase (Mangino et al., 2007), enable long product lifetime (Jensen & Skelton, 2018; Job et al., 2016; Yang et al., 2012) and provide opportunities for lifetime extension (Beauson & Brøndsted, 2016; Nijssen, 2015). However, closing the loop remains challenging (Job et al., 2016; Yang et al., 2012).
Composites reaching their End of Life (EoL) are a growing concern for industry and policy makers. Approximately 12 million tons of composites were produced in 2017. Annual production rates increased by 5% (glass fibre composites) up to 10% (carbon fibre composites) (Effing, 2018). No clear solution has yet been found for the increasing volume of composite waste; all recovery processes severely degrade materials, making recycling economically barely viable (Job et al., 2016). Thus, the majority of composite material is landfilled or incinerated, losing material properties and the potential for reuse (Mativenga et al., 2017).
Opportunities for recovery and reuse of composites, key aspects of the CE, will increase when addressed in the initial design stage (Jensen & Skelton, 2018; Perry et al., 2012; Yang et al., 2012), and new policies are expected to stimulate this (Cherrington et al., 2012). Still, design of composite products for a CE remains largely unexplored. Although examples of composite product reuse can be

found (Beauson & Brøndsted, 2016; Jensen & Skelton, 2018), this is generally not addressed in the initial design. It needs to be investigated to what extent CE strategies are applicable to composites, and how circular design principles can address the challenges found when developing composite products for a CE.

Approach

The focus of this research is on design strategies that enable long life, lifetime extension and closing the loop for composite products, specifically for FRP. As shown in figure 1, first the design framework for preserving product integrity (Den Hollander, 2018) is adapted to designing composites in a CE. Literature from the field of design for a CE as well as composites recovery is studied to identify strategies and design principles that prolong the product life or facilitate recovery of composite materials in a CE. Then, these strategies and principles are further explored by interviewing experts from companies using composites in a focus group setting. Finally, the paper concludes by proposing a design strategy framework which connects CE strategies to actionable design principles applicable to composite products.

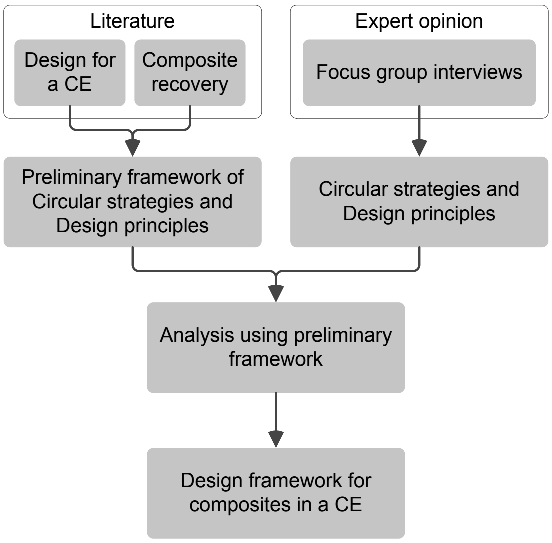

Figure 1. Research approach.

Literature background

Product integrity is a key concept in the circular economy. Maintaining product functionality has preference over materials recovery (Den Hollander, 2018). Product value can be preserved through long life, lifetime extension and product recovery approaches. Material value can be preserved through recycling.

In the case of composites this scheme can largely be followed as far as product integrity is involved. However, recycling routes for composite materials show some distinct aspects (Yang et al., 2012).

Composite materials can only be recycled to a limited extent by mechanical (shredding), thermal and chemical processing. Thermoplastic composites can also be remoulded (Yang et al., 2012). Thermal processes range from oxygen-rich combustion, recovering energy and ash (e.g. by co-processing in a cement kiln), to pyrolysis in an inert environment, recovering (damaged) fibres and generating fuel or organic feedstock. Chemical recycling, solvolysis, aims for full recovery of fibres and chemicals from the matrix, but still has not passed pilot scale (Job et al., 2016). In all cases the loss of material functionality and the deterioration of material properties is considerable.

More interesting, and specific to composites, is structural recycling. This preserves material quality with relatively little effort (Asmatulu et al., 2014), 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 (Jensen & Skelton, 2018). This is considered a promising approach to preserve value for relatively little investment of energy and resources, and has been demonstrated on a small scale (Beauson & Brøndsted, 2016; Jensen & Skelton, 2018).

To generate a framework for actionable design guidelines, the CE strategies have to be connected to design principles and the business context wherein the product operates. Design principles address product realisation and for example include modularity and disassembly, which are directly related to choices with respect to materials and connections (Balkenende et al., 2017). A generic framework for CE strategies and design principles was derived by Den Hollander (2018).

Expert opinion

Experts were interviewed in focus groups to explore circular strategies and design principles for products containing composites. This study was done in the context of the H2020 project Ecobulk, a large scale demonstration project for composites in a CE. Ten groups of 6 to 8 participants were asked to explore opportunities for circular redesign of different products representing various industry sectors: a car interior part (automotive), a bookcase or bed (furniture), and outdoor panels or bars (building), respectively. The participants were stakeholders from the respective product value chains, including material suppliers, Original Equipment Manufacturers (OEMs) and recyclers.

The discussion was guided by a moderator. During the discussion, notes were taken and added to a shared worksheet. Afterwards, the notes were transcribed and categorised using the CE strategies and design principles from literature.

Results

Based on the literature and focus groups, a framework connecting CE strategies (columns) and design principles (rows) for composite products in a Circular Economy was derived. This framework is shown in Table 1. The table fields show where a specific combination of CE strategy and design principle was found: in the studied literature (LIT) or focus groups (FG).

		Design for preserving product integrity			**Design for recycling**	
		Long life	Lifetime extension	Product recovery	Structural recycling	Material recycling
		Reuse Long use Physical durability	Repair Maintenance Upgrade Adapt	Refurbish Remanufacture Parts harvesting	Repurpose Resize	Remould Mechanical Thermal Chemical
Concept design	Accessibility		LIT	LIT		
	Adaptability	LIT, FG	LIT, FG	LIT, FG	FG	
	Dis- and reassembly	FG	LIT, FG	LIT, FG	LIT, FG	LIT, FG
	Fault isolation		LIT	LIT		
	Interchangeability		LIT, FG	LIT, FG		
	Keying		LIT, FG	LIT, FG		
	Modularity		LIT, FG	LIT, FG	LIT	LIT
	Sacrificial elements	FG	LIT	LIT		
	Simplification	LIT	LIT	LIT		FG
	Standardisation		LIT, FG	LIT	LIT	LIT, FG
	Function integration	FG	FG			FG
Embodiment	Material selection	LIT, FG	LIT, FG	LIT, FG	LIT	LIT, FG
	Surface treatment sel.	LIT, FG	LIT, FG	LIT, FG		LIT, FG
	Connection selection	FG	FG	FG	LIT	LIT, FG
	Manufacturing		FG	FG	FG	LIT, FG
	Structural design	LIT, FG	LIT, FG		LIT, FG	LIT, FG
Realisation	Identification	FG	LIT	LIT, FG	LIT	LIT, FG
	Malfunction annunciation	FG	LIT	LIT		
	Documentation	FG	LIT, FG	LIT	LIT	LIT
	Monitoring	LIT, FG				

Table 1. Design strategy framework for composites in a Circular Economy. Showing circular strategies, design principles and where a combination was found: literature (LIT) or Focus group (FG).

Most design principles were identified for long life, lifetime extension and product recovery. Less design principles were found for material recycling, while structural recycling was incidentally encountered. Findings from literature and expert consultation showed considerable overlap.

Literature
Based on insights from literature, the circular design framework proposed by Den Hollander (2018) is adapted to composite product design:

- Structural recycling is added as intermediate strategy between product recovery and material recycling, preserving part of a product's functional value (Asmatulu et al., 2014).
- Five design principles are added, notably 1) manufacturing process selection, 2) structural design, 3) selection of connections 4) documentation of product specifications and 5) in-use monitoring. Manufacturing, structural design and connections determine to a large extent the processability of the product at the end of use (Jensen & Skelton, 2018; Perry et al., 2012; Yang et al., 2012), while documentation and monitoring enable better estimation of residual quality (Jensen & Skelton, 2018).
- Three design principles are omitted: 1) animacy, 2) redundancy and 3) ergonomics. Composites are predominantly used in aerospace, automotive, furniture, construction and wind energy industry for their lightweight properties (Perry et al., 2012; Yang et al., 2012). This type of applications does not call for animacy – making the product behave as if it were alive– or weight increasing features like redundancy. Ergonomics was omitted as this relates to generic product design criteria, but has no special significance in relation to designing for lifetime prolongation or recovery in a CE.
- Two principles were merged: functional packaging and modularity, as both aim to create readily replaceable subassemblies by grouping e.g. parts, functions or materials (Den Hollander, 2018).

Expert opinion
In the focus group sessions materials selection, dis- and reassembly and adaptability were mentioned most, and a new design principle, function integration, was found.

- Material selection was mostly regarded as a means to make the product better recyclable. For example, participants suggested to "Create materials with inherent aesthetic properties", to avoid coatings and thereby material contamination in the recycling process.
- Dis- and reassembly as well as connection selection were discussed for all Circular strategies except long life.
- Adaptability was predominantly recognised for long use and lifetime extension. For example by enabling the user to adapt furniture to changing needs.
- Function integration was suggested as additional design principle, as integrating functions will increase a part's value and mass. The first may provide an incentive for product recovery, and the latter for material recycling. When applied to a car dashboard component, this could incentivise dismounting of the complete component for refurbishment or recycling the materials.

Both literature and expert consultation
EU regulations, product lifecycle planning, repair technology and information exchange in the product value chain were noted in both literature and by experts. However, these are not directly part of the product design process as such, but should be aligned to it to develop a circular product. They are therefore not added to the design strategy framework, but should anyhow be considered in the early stage of new product development.

Discussion
In the framework, design principles are grouped using the stages of the product innovation process (Roozenburg & Eekels, 1998): concept design, embodiment and realisation. Grouping the principles in this way shows how they relate to the design process at large. In the early stage, a product strategy is formulated, addressing EU regulations and the product lifecycle plan. Then, principles like modularity and standardisation are used to find conceptual design solutions. In the next stage, the concepts are embodied to a detailed product design by, for example, material selection and structural design. Finally, documentation and identification provide stakeholders along the value chain with the information needed to use and recover the product according to the product strategy.

In the product innovation process, product design runs parallel to market development, i.e. the product's business and societal context. Thus, it becomes evident that, in addition to design principles, business model development as well as (development of) repair technology play a role in a Circular design process.
Most of the design principles were encountered by both literature and experts. However, two design principles were only encountered in literature: accessibility and fault isolation. Although not mentioned by the experts, both should be considered as an important factor to facilitate lifetime extension and product recovery.
One design principle, function integration, was only mentioned by the experts. Function integration is a new contribution to the field of design of composites for a CE. It serves to increase a part's recovery incentive by expanding its functionality (for parts harvesting and structural recycling) or mass (for material recycling). Function integration seems to conflict with the design principle of dis- and reassembly, which is relevant to all CE approaches. However, it may align with modularity, as function integration can be used to create a single-material module. For example, integrating multiple functions into one car dashboard component reduces the number of parts, connections and materials used. Which facilitates disassembly and avoids material contamination in the recycling process.

Recommendations
The framework is considered as a first step that provides insight in available design strategies and tools, to support designers developing new composite products for a Circular Economy. However, the framework might need further expansion as the selection of focus group participants and design cases was limited. Also, attention should be given to addressing the trade-offs in product design. For example, materials selection for recycling may conflict with materials selection for long product life.
Implementation of the framework in the product development process, as well as alignment with the product's market context has to be further detailed. As shown, the product design process should have a clear and strong connection to its business and societal context to realise a circular product. The relevance and application of design principles and CE strategies depends on this product context like recovery actions and business case.
Further research, building on design studies with composite products, will be carried out to validate and build upon the framework.

Conclusion
This study found that composites provide opportunities for the design of products in a CE. The material is often applied to minimise product weight, thus reducing materials used, and ensure long product lifespans. However, closing the loop remains a challenge and design of composite products for a CE is largely unexplored. This paper set out to explore design strategies for products containing composite materials in a Circular Economy. CE strategies and design principles found in literature and expert interviews were categorised into a framework.

The circular approaches found in CE literature are extended by introducing structural recycling. The approach, positioned between product recovery and materials recycling, has the potential to preserve composite material value for relatively low cost. A new design principle, function integration, was added to the existing body of knowledge and included in the framework. This is expected to increase the recovery value of parts as well as materials. On the other hand, some design principles found in literature were not mentioned by the experts and further expansion of the framework might be needed.
The framework is a first step in the development of strategies and tools, to support design of new composite products for a Circular Economy.

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

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Appendix

Descriptions of design principles

Design principle	Description	Quote
Accessibility	Ensuring (internal) parts can be reached for e.g. maintenance or repair operations.	related to the way in which parts are shaped, grouped and connected [1]
Adaptability	Enabling changes and adjustments to be made to the product during its life.	Changing the furniture to a user's changing needs
Dis- and reassembly	Facilitating (manual or mechanical) disassembly and reassembly of the product.	Design for disassembly by using screws or reversible snap fits
Fault isolation	Facilitating fault finding for e.g. repair.	Assuring that a… malfunction can be traced to the part … requiring replacement [2]
Identification	Using labels, tags etc. to facilitate recognition of the product and/or its specifications	Use markers for materials to facilitate separation
Interchangeability	Making parts or subassemblies of the product readily replaceable	Replaceable panels for damaged sections
Keying	Using product shape to facilitate alignment, e.g. holes and pins	use "slotted assembly" where the product is fixed from the ends into a groove.
Malfunction annunciation	Indicating (imminent) product failure	Inform user of bad use
Material selection	Selecting matrix, reinforcement, connections and other materials	Create materials with inherent aesthetic properties
Modularity	Grouping features within the product to create separable sub-assemblies	modular upgrades … to refresh design with minimal intervention.
Sacrificial elements	Defining replaceable components to take up wear and damage, thus protecting other parts	Grading and categorising parts which are likely to have most wear tear
Simplification	Minimising the complexity of the product, by e.g. appearance, assembly or materials	adopt essential lines and shapes … neutral colours such as scales of white and grey
Standardisation	Using standard components, processes, dimensions etc. in the product design	Same assembly system along time and models
Surface treatments	Selecting coatings and other surface treatments appropriate for the use and recovery of the product.	glass or aluminium replaceable covers in order to protect coatings during the whole life cycle
Connection selection	Selecting connections for the use and recovery actions during product life	use "pane type of roofing" … to avoid unnecessary fasteners nor use of sealants
Documentation	Providing information about the product to stakeholders in the value chain	Make it easy for customers to return at end-of-life --> info attached to product,
Manufacturing	Selecting and optimising the process to meet the material, shape and recovery criteria	… techniques that can at least partially use the recycled fibres instead of only new
Monitoring	Measuring (and storing) product properties while in use.	Lifetime monitoring … necessary to ensure the safety of re-using the blade [3]
Structural design	Optimising the shape to get the best structural quality.	Structure made of linear components like truss structures so [parts] could be re-used
Function integration	Combining multiple functions and (sub)components into one part.	Easier [Dis]assembly … due to the reduction of parts for a multi-functional component.

Table 2. Description and examples of design principles, quote from experts in this study and literature. From [1] (Balkenende et al., 2017); [2] (Den Hollander, 2018); [3] (Jensen & Skelton, 2018).