Supplementary Materials

Supplementary S1

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.
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.

Supplementary S2

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

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

Supplementary S3

Semi-structured interview setup

Design strategies for composites in a Circular Economy

Contact details

Researcher:
Jelle Joustra

Participant:

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?

Supplementary S4

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

Filename: sustainability-1757884-supplementary.docx
Directory: E:\6.30\materials-1770924
Template: C:\Users\jellejoustra\Documents\Documentation\Templates\sustainability-template.dot
Title:
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Comments:
Creation Date: 6/29/2022 11:18:00 PM
Change Number: 4
Last Saved On: 6/30/2022 10:40:00 AM
Last Saved By: MDPI
Total Editing Time: 4 Minutes
Last Printed On: 6/30/2022 4:53:00 PM
As of Last Complete Printing
Number of Pages: 6
Number of Words: 1,170 (approx.)
Number of Characters: 7,643 (approx.)