Circular Approach for Eco-Composite Bulky Product

GA NUMBER: 730456

D2.2: Report on design strategies and tools, version 1
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<table>
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<th>Version</th>
<th>Date</th>
<th>Author</th>
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**Glossary of key terms:**

The table below gives an overview of the key concepts and terminology used in this report. These definitions build on reports issued by the Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2013a, 2013b, 2014) and work in the field of Circular Product Design (Balkenende et al., 2017; Bocken et al., 2016; den Hollander et al., 2017).

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Business model</td>
<td>Describes the way an organisation delivers and reclaims its products and services to &amp; from the market, creating and capturing value over a product lifetime.</td>
</tr>
<tr>
<td>Circular economy</td>
<td>A circular economy entails decoupling economic activity from the consumption of finite resource and designing waste and pollution out of the system. It aims to keep products and materials in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life. A circular economy should build economic and social capital and regenerate natural systems.</td>
</tr>
<tr>
<td>Design principle</td>
<td>Technological aspects applicable to a product design, described as high level principles to allow for use on different product categories and in specific contexts.</td>
</tr>
<tr>
<td>Design strategy</td>
<td>Describes design considerations and choices for a particular design direction, aimed at enabling a particular property or activity. For example, how a product could be designed for long use.</td>
</tr>
<tr>
<td>Downcycling</td>
<td>Recycling materials into new materials with lower performance or functionality.</td>
</tr>
<tr>
<td>Lifecycle</td>
<td>The functional life of a product; starts when released for use and ends when definitively disposed or dismantled. Lifecycles of individual components can continue in new products.</td>
</tr>
<tr>
<td>Use cycle</td>
<td>Starts when released for use and ends when the user of the product changes or when the lifecycle ends. A single product lifecycle can consist of multiple usecycles, for example through sharing, resale or remanufacturing.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Regular inspection and servicing tasks to keep the product in good functional and/or cosmetic condition.</td>
</tr>
<tr>
<td>Part</td>
<td>Single element used in the manufacturing of components or products.</td>
</tr>
<tr>
<td>Product</td>
<td>From a product construction perspective the top level assembly of components. Can be anything that is manufactured and offered to customers for use, including services.</td>
</tr>
<tr>
<td>Recovery</td>
<td>On the level of products: returning a product to usable (functional) condition through for example reuse, repair, refurbishment or remanufacturing actions. On the level of parts: Parts harvesting On the level of materials: recycling (which might be upcycling or downcycling) In the Waste Framework often used to describe energy recovery (through incineration) of materials. Energy recovery is explicitly considered not to be a Circular way of handling resources as it incurs complete loss of materials.</td>
</tr>
<tr>
<td>Refurbish</td>
<td>Returning a product to good working condition by (preventive) replacement of components by OEM or third parties, usually the start of a new product use cycle. (limited) warranties on product functionality may be given.</td>
</tr>
<tr>
<td>Remanufacture</td>
<td>Disassembly, cleaning, testing and reassembly of a product resulting in a</td>
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1 Adopted from [The Ellen Macarthur Foundation](https://www.ellenmacarthurfoundation.org) and the [UKs Waste Resources Action Programme](https://www.gov.uk)
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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<tbody>
<tr>
<td>Parts harvesting</td>
<td>Disassembly, cleaning, testing and stocking of product components to prepare them for a next use cycle, often as spare component in another product.</td>
</tr>
<tr>
<td>Repair</td>
<td>Correcting specific faults to restore the product to satisfactory working condition. Also referred to as corrective maintenance.</td>
</tr>
<tr>
<td>Repurposing</td>
<td>Utilizing a product or its components in another function than in its original use. Might be taken into account in the initial design.</td>
</tr>
<tr>
<td>Reuse</td>
<td>All actions where a product are used again, with the same purpose or little changes to the original.</td>
</tr>
<tr>
<td>Recycling</td>
<td>Preparing materials for a next lifecycle through reprocessing. See also: upcycling and downcycling.</td>
</tr>
<tr>
<td>Upcycling</td>
<td>Recycling materials into new materials with higher performance or functionality.</td>
</tr>
<tr>
<td>Upgrading</td>
<td>Extending a product’s original properties to offer improved performance.</td>
</tr>
<tr>
<td>Adapting</td>
<td>Adjustments to a product to meet changing use conditions and demands, without adding new functions.</td>
</tr>
<tr>
<td>Composite</td>
<td>An assembly of two or more materials with dissimilar chemical structure: a matrix and a fibrous or particulate fraction. Also referred to as hybrid material.</td>
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Table 1-1 Glossary
1 Summary

Deliverable report 2.2 sets out a framework of design strategies to use when developing composite products for a circular economy and describes the initial outcomes of the task 2.2 “Development of design strategies & tools” of the EcoBulk project.

Circular product design includes both design for product integrity and design for recycling:

*Designers in a circular economy should first aim to prevent a product from becoming obsolete and, second, make sure that materials can be recovered with the highest level of integrity. These two goals can be pursued at the level of products and components or at the level of materials.*

(adapted from den Hollander, 2018)

Longevity of products & components is the goal of design for product integrity, compromising three design approaches: a long product lifetime, product life extension or recovery of the product at the end of its use cycle (den Hollander, 2018). Closing material loops is the domain of design for recycling, where materials are reprocessed from obsolete products into raw materials ready for a next lifecycle.

*Long lifetime* is enabled by design for long use and reuse. For long use, the product life cycle is as long as the use cycle. Reuse aims to increase the number of use cycles within a single product lifecycle, for example by sharing.

*Extended use* is enabled by actions prolonging the product life, like maintenance, repair and upgrading. Addressing these in the initial design makes the operations later in the lifecycle easier and cost effective.

*Product recovery* returns obsolete products or parts thereof to working condition, returning products that risk to be lost to the economy.

*Recycling* recovers resources at a material level, thereby closing the loop. When the product or its components cannot be recovered anymore, recycling can return the materials to resources for new products. As all products will become obsolete one day, design for recycling is considered essential for all products.

<table>
<thead>
<tr>
<th>Circular product design</th>
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</table>
| Design for product integrity | Design for recycling  
| Products and components | Materials  
| Long lifetime | Extended use | Product recovery | Recycling  
| Long use | Maintenance & repair | Refurbishment | Composite recycling  
| Reuse | Upgrading | Remanufacturing | Materials recycling  

Table 7-1 Circular product design strategies and approaches.
Tools are developed to apply the framework methodology in design practice. The framework and tools are evaluated in workshops with and design done by Ecobulk project partners. This report is complementary with D2.4, which describes the results of design activities and workshop.

2 Introduction

2.1 Description of document and purpose
This report is part of Ecobulk Work Package 2 “Design framework for thee Circular product sectors” and more specifically task 2.2 “Design Circular: strategies and tools”. Task 2.2 focuses on searching for strategies, methods and tools that fit the requirements of a circular economy.

T2.2 receives input from T2.4 “Design circular validation-from conceptual design to prototyping” and WP8 “Circular business models”. In T2.4, Ecobulk reference products are redesigned to fit within a circular economy setting. To operate in this context, new business models are developed in WP8. Observations from prototype and business model development are used to develop design strategies in T2.2.

This report, delivered in M18, describes the first version of circular design strategies resulting from the work in T2.2 and T2.4. The strategies are structured in a framework built on recent literature in the field of circular product design. As ECOBULK progresses, the task will be completed by further detailing the design strategies and tools. The final version of the report will be delivered in M42.

2.2 Reading guide
Composites have some very distinct properties which have to be taken into account in the design. Chapter 3 provides an introduction to the design approach, manufacturing and recycling. And sets out a categorisation of composite materials, used to classify Ecobulk reference products. Insights from Circular Product Design and composite materials are used to propose an initial set of design strategies for composites in a Circular Economy. The framework and design strategies described in chapter 4 have been evaluated through interaction with the Ecobulk consortium. First, a workshop was done to verify the identified design approaches and to elicit potential challenges and solutions. These observations were used to detail the design principles in chapter 5. The principles were applied to the redesign of reference products. Chapter 6 describes tools developed to use in the workshops and at various stages of product development. Application of the design tools and results from workshops & redesign with Ecobulk partners is further described in report D2.4 “Design circular validation-from conceptual design to prototyping”. Chapter 7 reviews how emerging technologies like Internet of Things and Additive Manufacturing can contribute to a Circular Economy with composites. A more elaborate explanation of design principles can be found in the attachments, chapter 8.

2.3 Relevance
Composites are an attractive materials choice, as they combine high modulus materials with freedom of form, resulting in lightweight mechanical structures (Mishnaevsky et al., 2017; Perry et al., 2012). Lightweighting of constructions is a beneficial approach to reduce resources needed for construction of the product and energy usage over its lifetime, especially in transport applications (Allwood et al.,
A composite, also called hybrid material, is a combination of two materials. Endless combinations are possible, allowing for material properties unachievable with mono materials. However, this combination of materials does cause problems with recycling, in particular for thermoset-based composites (M. F. Ashby, 2005; Yang et al., 2012).

The added value of design and manufacturing is typically lost in a recycling process, it therefore makes economic sense to focus on product and component level strategies to keep the material longer in the system (Bocken et al., 2016). This can be done by designing the product for a long service life, lifetime extension or recovery. Material properties such as fatigue and corrosion resistance make composites very suitable for long life applications. But more attention is needed to enable lifetime extension and recovery of products and components. Also, in the field of recycling, more attention is needed to make the products suitable for recycling while preserving as much value as possible.

2.4 Scope

The properties of a composite are determined by materials selection, design and manufacturing method (Beukers & van Hinten, 2005). The initial design of a product determines its properties in terms of function, maintenance, recycling, disposal and more (Pahl & Beitz, 2013). However, how circular product design and composite design strategies can be used to contribute to the performance of composite products in a circular economy is still relatively unexplored. This report presents a set of design strategies for composite products in a Circular Economy. The focus is on the recovery of the materials, as this is the major addition to longer existing sustainable design strategies. So the strategy will (have to be) combined with a broader perspective on design for sustainability, e.g. ecodesign, to achieve the full sustainable potential of composite materials.
3 Composites

3.1 Design
Composites owe their characteristics to the combination of design, manufacturing and choice of materials (Beukers & van Hinte, 2005). Design of composite products is a complex task, where shape, process and materials are optimised for mechanical characteristics, aiming for lightweight structures. These factors interact: Manufacturing processes, material selection and design put limits on each other. For example, manufacturing technologies limit the types of materials and shapes to be used and influence the structural properties of the final product. Conversely, materials selection and shape of the product influence the choice of manufacturing process. Often, the decision for manufacturing process or materials is used as the starting point.

To achieve structural lightweight products, the design should adhere to the following rules (Beukers & van Hinte, 2005):

- Load materials as equally as possible
- Understand the load path – a short path is preferred
- Use low density material, optimise for minimum mass
- Select materials with high mechanical properties

The advantage of composites in the manufacturing and use stages comes to their disadvantage at end of life: composite products are difficult to reuse on a functional level because they are tailor-made for a specific use case. Recycling is complicated by the composition of the material: the heterogeneous nature makes it difficult to separate the constituent materials for further reprocessing. An important role is reserved for the designer: “Designers determine the properties of every product in terms of function, safety, ergonomics, production, transport, operation, maintenance, recycling and disposal.” (Pahl & Beitz, 2013).

Material properties such as fatigue and corrosion resistance make composites very suitable for long life applications. But more attention is needed to enable lifetime extension and recovery of products and components. Also in the field of recycling, more attention is needed to make the products suitable for recycling while preserving as much value as possible.

3.2 Material types
A composite is an assembly of two or more materials with dissimilar chemical structure: a matrix and a fibrous or particulate fraction. Additives, in the broadest sense, are added to the matrix to make a composite material. Colouring pigments and simple inexpensive particles used to lower the material cost are referred to as fillers (Carter, Giles F. Paul, 1991). Reinforcements come in the shape of
particles and fibres ranging from short and randomly ordered to continuous, unidirectional applications (Ashby, 2005). Although referred to as “reinforcements”, the fibre and particle fractions can serve to optimise various functions of the material, like thermal or electrical conductivity. The resulting mechanical properties depend on materials, mixture ratio, bonding properties and reinforcement structure (orientation & size).

Three types of reinforcement structure are distinguished: ‘Particles’ having similar dimensions along each axis, ‘Fibres’ having a large length-to-diameter ratio and ‘Structural’, a combination of homogeneous and composite materials (Callister & Rethwisch, 2007), e.g. sandwich structures. In large particle and fibre reinforced composites, the forces exerted on the composite material are transferred from matrix to reinforcement. Bonding between matrix and reinforcement is important and a minimum fibre length can be calculated from the material properties. For glass & carbon fibres the minimal length is about 1 mm. (Callister & Rethwisch, 2007).

For the matrices, ceramic, organic and metal are commonly used, where organic includes polymer matrices, by far the largest group encountered in composites. Within polymer matrices thermostets (mainly epoxides) and thermoplastic can be distinguished. The former remain solid until they decompose above their decomposition temperature, while the latter exhibit melting behaviour when their melting point is exceeded. The share of thermoplastic composites, relative to thermostet-based, has increased. In 2012, a share of about 1/3 for thermoplastics was reported, which has grown to about half in 2017 (Witten et al., 2017; Yang et al., 2012). Thermoplastics are used for large series as injection- or bulk moulding compounds.
3.3 Manufacturing & structure

Manufacturing of thermoset composites is typically characterised by small series and open mould techniques like Resin Transfer Moulding (rather than an enclosed mould for e.g. injection moulding). It allows for the use of long fibres and sandwich constructions to produce components with a high stiffness to weight ratio. Fibre content by weight is about 30% for glass fibres and 60% for carbon fibres. However, an average manufacturing process generates about 10% of material waste, due to off cuts and trimming (Mativenga et al., 2017; Papadakis et al., 2009). Production cycle times are long, owing to the build and curing time. Advancements in materials, manufacturing and calculation methods have led to increasing part size, as illustrated by the growth of wind turbine blades.

![Figure 3-1 Representative turbine architecture from 1980 to 2010 (Lantz et al., 2011)](image)

Thermoplastic composites are more suitable for smaller sized products, large series or mass production. Tooling costs are relatively high compared to the value of a single product. Production techniques like injection moulding and extrusion can handle short fibre reinforcements. Fibres are aligned parallel to the materials flow in the mould cavity. Typical applications, like power tool housings and automotive components add in up to 20% (by weight) of short glass fibres with polymers like PP, ABS or nylon to improve strength and stiffness properties. Thermoplastic composites do not lend themselves for sandwich constructions due to the high processing temperatures and manufacturing techniques used.

Use of fibre reinforced materials is explored in the domain of additive manufacturing (AM). Incorporating fibre reinforcements in the thermoplastic matrix bears can potentially enable AM of complex end products, rather than have it restricted to prototypes (Sher, 2017).

Wood based composites harness the quality of natural fibres. In plywood, multiple sheets of wood are stacked and bonded together in a laminate structure. Fibre alignment is chosen such to form a panel with more uniform load bearing properties compared to solid wood (Matweb, 2018). The same principle is used by bonding large wood flakes for OSB or small wood chips for particle board. The fibre content of the panels is high: usually about 95%.

3.4 Classification of reference products

The table below shows the Ecobulk reference products mapped according to their composition. Wood-based composites, e.g. particle board and OSB, are mapped in the “other” matrices, as the
binder agent used is in fact a polymer, yet represents a different group of materials than the thermoset or thermoplastic matrices. The empty boxes are less favourable for the material combination shown.

<table>
<thead>
<tr>
<th></th>
<th>Thermoplastic</th>
<th>Thermoset</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural</td>
<td></td>
<td>Wind turbine blades</td>
<td>Plywood structural panel</td>
</tr>
<tr>
<td>Fibrous</td>
<td>Safety belt brackets</td>
<td></td>
<td>Non-woven, insulation</td>
</tr>
<tr>
<td></td>
<td>Solid panel/plank</td>
<td></td>
<td>Non-woven, floor carpets</td>
</tr>
<tr>
<td></td>
<td>Post/pillar</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulate</td>
<td>Fascia central console</td>
<td></td>
<td>Bookcase</td>
</tr>
<tr>
<td></td>
<td>4WD control frame</td>
<td></td>
<td>Upholstered bed</td>
</tr>
<tr>
<td></td>
<td>Centre console cowlings</td>
<td></td>
<td>OSB structural panel</td>
</tr>
<tr>
<td></td>
<td>Wheel arcs</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Interior panels</td>
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</tr>
</tbody>
</table>
### 3.5 Recycling of composites

In a Circular Economy, building on the material recovery & chemical foundations of Cradle to Cradle, two recovery cycles are distinguished: the biological and the technological cycle. The bio-cycle ideally handles consumables; food, but also consumables like lubrication and cleaning agents are preferably part of this cycle to prevent pollution. Materials that are to be returned to (soil) nutrients through the bio-cycle have to be fully biodegradable and non-toxic.

In the techno-cycle, two levels of resource recovery can be identified: products and materials. Energy recovery is not regarded a circular strategy as it involves complete loss of the materials. On a product level, it is desirable to keep products and components in use as long as possible. This can be done by enabling a long product lifetime, where no interventions are needed to keep it in active service. Or extend the lifetime with small interventions to keep the product functioning and desirable for multiple use cycles. Products that have become obsolete may be recovered into active service through refurbishment or remanufacturing.

It is important not to mix materials from these two cycles: biological materials in the techno-cycle risk being lost or contaminating the process, while technological materials in the bio-cycle risk being unrecoverable.

Composites are mostly found in the technological cycles. When bio-based materials are used, for example wood or flax fibres, these are processed with technological resins, creating a hybrid product that cannot be entrusted to the biological recovery loop.

The composite recycling process is mostly determined by the matrix material. Thermoplastic matrix composites can be thermally recycled (remoulded) into new products. For thermosets, recycling usually means dissolving the matrix and recovering the fibre; thus, the matrix determines the process, the fibre the recyclate value (Job et al., 2016). In addition, generic recycling problems apply as well for collection, identification, separation and concentration (sorting) of the material and contamination in the reprocessing stage (Pickering, 2006).

#### 3.5.1 Thermoset matrix

The main drawback of thermosets in the recycling process is that they cannot be remoulded. Depending on the application, various additives and reinforcements can be added to the matrix. There are few standardised formulations as for most applications the composite is tailor made. Sometimes additional materials are used, like foam or wood cores and metal inserts. This adds to the number of materials, all bonded together using the matrix or an additional adhesive, complicating the separation (Pickering, 2006). For thermoset matrix composites, the most important methods are mechanical, thermal and chemical reprocessing (Yang et al., 2012).

**Mechanical recycling** means physically breaking down the product into smaller pieces through shredding or grinding. The processing cost is relatively low, but so is the value of the resulting materials; the shape and much of the value is lost:

- Long fibers are shortened
- Poor bonding to new matrix material due to bonds with old matrix & loss of fibre sizing
- Variation in particle size due to shredding process
- Mixed materials; fibre, matrix, adhesives, core material
Adhesive bonds will not separate completely. The particle size tends to increase with increasing tensile strength of the material and brittle materials result into smaller pieces than more ductile materials (Knight & Sodhi, 2000), which may fold rather than break.

**Thermal** recycling or pyrolysis heats composite material to temperatures around 500°C in a controlled (inert) environment to liberate the fibres and inserts. Sometimes the chemical constituents of the matrix can be recovered in the form of gas and oil fractions, but mostly the matrix is incinerated with energy recovery. Glass fibre is severely degraded after pyrolysis, but carbon fibre can retain about 85% of its original strength & stiffness (Job et al., 2016). Variants of the process enable long fibre recovery and involve conveyors or a fluidized bed (where heated sand is used to effectively apply heat and abrasion).

**Chemical** recycling or solvolysis processes use solvents like supercritical water to dissolve the matrix. The dissolved matrix has potential for monomer recovery but is, as with pyrolysis, usually burnt to recover energy and sustain the process. The operating temperature is lower and the reclaimed fibres are less degraded, but the used chemicals pose a potential health and disposal risk.

### 3.5.2 Thermoplastic matrix

Thermoplastic matrix composites can be reshaped by applying heat, as opposed to thermoset matrices. The most straightforward technique is to shred the plastic composite and to use the granules in the original manufacturing process. Full recovery of material properties has been shown at lab scale. But in practice, reprocessed materials show reduced properties including visual appearance (Mangino et al., 2007). Rendering the use predominantly to non-visual components, for example those where now talc and glass reinforced PP are used. The process is energy and cost intensive due to the high temperatures and pressure needed to reshape thermoplastic matrices, which has hindered further market development. (Yang et al., 2012)

#### 3.5.2.1 Concluding remarks on recycling

Through exposure to environmental conditions in the use phase and processing conditions in the recycling stage, the quality of both matrix and fibres degrade. Recycling processes for thermoset composite materials generally imply loss of the matrix and recovery of the fibre fraction. Use of recycled materials in new products is limited due to the low material properties and uncompetitive price (compared to virgin materials).

Most literature describes processes for fibre recovery as economically barely viable. Due to the aggressive nature of the processes (pyrolysis, fluidised bed, chemical or supercritical fluids), the matrices are usually lost for further application and the fibre quality is reduced. Glass fibres suffer larger reduction in quality (strength, sizing & adhesion properties) than carbon fibres.

The relatively high recycling quality of carbon fibres combined with their high material price and price volatility makes them more interesting for recycling than glass fibre: Recycling technology is available, the market is driven by carbon fibres scarcity, driving prices high. But logistics and material identification have to be developed further. Both are easier for primary scrap than for secondary scrap (Perry et al., 2012).
4 Circular product design strategies

4.1 Design approaches

Three approaches can be identified to reduce the input (resources) and output (waste & emission) of a system: narrowing, slowing or closing the flow of resources through the system. Narrowing refers to using less materials, which is commonplace in product design as it results in direct cost reduction. The aforementioned Lightweight design approach reduces both materials in the manufacturing stage and fuel consumption in the use phase, especially in transport applications. Slowing down the flow refers to keeping products in use for longer. Longevity of products & components is the goal of design for product integrity, compromising three design approaches: a long product lifetime, product life extension or recovery of the product at the end of its use cycle (den Hollander, 2018). Closing resource loops is the domain of recycling, where materials are reprocessed from obsolete products into raw materials ready for a next lifecycle.

**Long lifetime** is enabled by design for long use and reuse. For long use, the product life cycle is as long as the use cycle. Reuse aims to increase the number of use cycles within a single product lifecycle, for example by sharing.

**Extended use** is enabled by actions prolonging the product life, like maintenance, repair and upgrading. Addressing these in the initial design makes the operations later in the lifecycle easier and cost effective.

**Product recovery** returns obsolete products or parts thereof to working condition, returning products that risk to be lost to the economy.

**Recycling** recovers resources at a material level, thereby closing the loop. When the product or its components cannot be recovered anymore, recycling can return the materials to resources for new products. As all products will become obsolete one day, design for recycling is considered essential for all products.

<table>
<thead>
<tr>
<th>Circular product design</th>
<th>Design for product integrity</th>
<th>Design for recycling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>Products and components</td>
<td>Materials</td>
</tr>
<tr>
<td>Approach</td>
<td>Long lifetime</td>
<td>Extended use</td>
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<tr>
<td>Strategies</td>
<td>Long use</td>
<td>Maintenance &amp; repair</td>
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<td></td>
<td>Reuse</td>
<td>Upgrading</td>
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*Table 4-1 Design approaches and strategies categorisation, based on (den Hollander et al., 2017)*

It is important to realise that these strategies do not work isolated, the system in which they are applied has to be regarded as well. A design strategy in itself will not make recovery happen. For example, refurbishment implies a long product (or component) lifetime which must be addressed; refurbishment is not interesting if the resulting product does not comply to new technical or functional demands.

Design strategies can pose multiple and sometimes conflicting demands on the product design. Therefore, it is important to consider the desired recovery process and stakeholder in the design stage. As well as developing scenarios to anticipate future changes. The measures taken to increase a product’s durability or other adjustments made must be weighed against the envisioned benefits.
Additional resources used in the initial production must be worth the additional lifetime, use, recovery and recycling benefits.

4.2 Long lifetime

Product and component recovery of composites is the most valuable approach, as most of the embedded value is retained. For composites, this value is typically high, because composite product design is complex and manufacturing resource-intensive in terms of time and cost of labour and materials.

However, to increase durability a product needs to be built more robust. Cleaning and transport may be needed to prepare the product for the next use cycle. The positive and negative impacts have to be evaluated when selecting the appropriate design strategy.

4.2.1 Design for long use

The goal of long use is to enable a long product lifetime without the need for interventions to the product during that lifetime. The lifetime of a product is not just limited by its physical durability, as it can enter its end of life stage for various reasons. A product lifetime can be defined as the shortest of either of these lifetimes (M. Ashby, 2009). When either one of these lifetimes end, the product is regarded as obsolete and likely to be replaced. Design for long use will make the product resist becoming obsolete by addressing these reasons.

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Life ends when...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Breakage beyond economic repair</td>
</tr>
<tr>
<td>Functional</td>
<td>Need for product ceases to exist</td>
</tr>
<tr>
<td>Technical</td>
<td>Technological developments make the product outdated, while still functional</td>
</tr>
<tr>
<td>Economic</td>
<td>Newer products are more economic in use</td>
</tr>
<tr>
<td>Legal</td>
<td>The product no longer complies to new regulations</td>
</tr>
<tr>
<td>Desired</td>
<td>The product is rendered old-fashioned by changes in style etc.</td>
</tr>
</tbody>
</table>

Table 4-2 Description of product lifetime

The list above relates to the lifetimes of complete products; it is important to realise the same reasoning goes for the parts they’re assembled of. For example, a long-lasting card dashboard piece will not drastically prolong the lifetime of the complete car when engine mileage is the governing lifespan. However, a rapid degrading part may decrease the desirability and thereby the complete product lifetime. When a component is still usable after the product has become obsolete, it may be recovered through e.g. remanufacturing or refurbishment, described in the respective paragraphs.

The physical durability of a part reflects its ability to withstand the conditions in the use phase and to prevent breakdown beyond economic repair. Degradation mechanisms and failure modes causing the breakdowns are often well known and can be addressed in the design of the product and its components (Allwood et al., 2011). For example by selecting movements, connection and assembly types and production methods that increase the overall resistance to wear and stress (den Hollander, 2018).

Degradation of the top coating exposes the composite to environmental conditions such as UV radiation and rain. Water ingress, especially in polyester matrix composites, is known to cause osmosis: a process wherein small water pockets expand under the formation of acids, damaging the laminate. Careful selection of materials and surface treatments may help to prevent these failures.
and prolong the product lifetime. Structural failure can happen through breaking of fibres or cracking of the matrix material. When a fibre fails, the load is redistributed to nearby fibres, preventing catastrophic, immediate, failure of the complete structure. The risk of load failures is increased at local stress concentrations, which should therefore generally be avoided by careful application of geometry changes and inserts.

Functional, technical, economic and legal lifespans, are as much dependent on external factors as the design of the product itself. However, developments in these fields can be anticipated and included in the design. When interventions are expected to be needed to keep the product in use for longer, *Design for updating and adapting* may be considered.

The desired life, or emotional durability, reflects how long the product remains relevant for, and desired by the user. Reasons to fall out of grace include changes in fashion and personal preferences or the visual ageing of a product. On the other hand, the same mechanisms may be used to prolong the product life. A product can be designed to be less fashion sensitive and the selection of materials and surface treatments can influence the visual ageing. Ageing is not necessarily a bad thing, as it can give personality to a product and become a fashion statement in itself.

### 4.2.2 Design for Reuse

The goal of reuse is to enable a long product or component lifetime and increasing the number of use cycles within one product lifecycle. It is up to the business model to determine how the product is reused and what the length of the use cycles will be. The use cycle may be very short when the product is only used for a short time before it is made available for the next user. Examples are deposit systems where products are returned and reused or sharing of products. In the latter case, product use is intensified.

On the other hand, the use cycle may be long and instead of ending product life at the end of the use cycle, another is added for example by reselling used products. The next use cycle can be in a different context than the product was originally designed for. In general, no interventions larger than cleaning and superficial inspection are needed for reuse.

Product use intensification requires the product to be robust and easy to maintain & repair for the owner, which is further elaborated in chapter 4.3.1. Ownership usually resides with an operating company, providing access to the product as a service.

Reselling may be direct or through a facilitating company or service. Reselling products builds on trust: the buyer must trust the value of the product on offer (M. F. Ashby, 2016, p. 226). This implies a link to business models related to price transparency, trust in the reseller and, on product level, quality assurance.

Assessing the structural quality of a used composite product can be difficult. Guidelines exist to estimate the number of load cycles, which can be used together with in-use monitoring to determine residual value. Design guidelines to enable structural evaluation are further discussed in chapter 4.3.1 design for *maintenance and repair*. 
Reuse can involve transport and (de)construction activities between the subsequent product use cycles, which can be made easier by making a modular design and design for dis- and re-assembly as well as providing documentation with the product parts and (dis)assembly instructions.

4.3 Extended use

Not all products can function without or with limited interventions throughout their lifetime. Interventions like maintenance can help prolong the functional life of a product and even be part of a business strategy where customer relations are kept through a service system and regular check-ups. In addition, upgrading may prolong the desired life, by having the product grow with the user (even in the most literal sense) and adapt it to changing needs.

4.3.1 Design for maintenance & repair

Maintenance is the checking (testing) of a product and taking preventive (maintenance) or corrective (repair) action to keep/restore it in using condition. The process can be done by a company or by the user. Maintenance and repair can be a valuable business case by providing (qualified) services to the user and sale of materials & spare parts. In general, a repairable product benefits from easy access to parts, a simple modular structure and ensuring no unsafe conditions appear during the process. Both maintenance and repair benefit from status indicators on, or embedded in, the material.

A repair or maintenance task should not pose a risk to the person performing the task. Selection of materials and connections, as well as developing a clear procedure for dis- and reassembly actions are recommended.

Composites are generally damage tolerant materials. Local fibre failure will not immediately result in catastrophic failure of the component (complete breakdown) due to load redistribution in the composite. External, the impact absorption characteristics of the material enable shape recovery after an incident. Which could be beneficial for superficial repairs, but a drawback when attempting to assess the extent of structural damage.

Load cases during product life may lead to damage like delamination, adhesive bond or core material failure and cracking of coatings or matrix material. Delamination, when layers within the composite separate, is difficult to observe from the outside but is audible when tapping the material. The extent of delamination can be measured using ultrasound equipment (Otheguy et al., 2010).

Typical repair of a composite part consists of: removal of damaged material, cleaning and surface preparation (sanding, degreasing), application of new fibre & matrix, curing and finishing. Filler and coatings are used to restore the outer protective layer and visual quality. For the difference of processing, it is useful to distinguish between thermoset and thermoplastic composites.

4.3.1.1 Thermosets

Basic repairs can be done by users. Knowledge and materials are widely available and a typical repair task needs basic safety precautions and tools. For high end and complicated repairs, specialised equipment and knowledge is needed and company repair makes more sense. Composites have seen a steady growth since the 1950’s and their omnipresence has given rise to specialised repair shops, for example in the marine and automotive industry.
Often, the repair can be done in situ, without the need for a fully equipped workshop or controlled environmental conditions. If needed, localised heat can be applied to aid the curing process using a small heater or heating blanket. The materials, skill and process used determine the structural and visual quality of the repair. Skilful composite repairs can be done without leaving any visual trace, however the original strength may not be restored (R.P.L.Nijssen, 2015).

4.3.1.2 Thermoplastic
Thermoplastic components can be repaired using fusion bonding. Using fusion bonding, pieces of a damaged laminate or severed parts can be replaced, creating a strong and durable repair. However, the application of heat may also affect other nearby parts of the product and leave residual stress in the material when the bond has cured. The process is relatively simple and quick compared to thermoset composite repairs: no resins or adhesives are needed, omitting long curing time and avoiding problems with the shelf life of materials (Otheguy et al., 2010; Welder et al., 1986).

4.3.2 Design for upgrading & adapting
The goal of upgrading and adapting is to keep the product relevant for the users for a long time. External changes like technological developments can make the product uneconomic or otherwise unsatisfactory to use. In this case the product can be upgraded to enhance its functionality or adapted to adjust its functions compared to its initial specifications. In contrast to maintenance, which is a regular activity, an upgrade is done typically only once during the product’s lifetime (den Hollander, 2018).

Upgrades are often offered to the user as part of a service operation, like refurbishment, repair or maintenance. For example, increasing the battery capacity of a phone during refurbishing. Also, companies, both OEMs and third parties, support upgrading by individual customers by providing instructions and parts.

Composite material properties are tailored to the specific application during the manufacturing process, through design and material selection. Later in the product lifecycle, the mechanical properties can be changed by adding additional layers to the original structure. This practice is already applied to reinforced concrete where modern standards in building regulations put higher demands on the structures. Fibre reinforced plastics are used to increasing its strength or stiffness characteristics where needed, while requiring relatively little construction effort (Prota et al., 2001). In operations like these, the materials selection must be carefully considered to enable recovery at the end of life. The example of FRP applied to concrete has the drawback of materials mixing, but illustrates how composites are used to adapt a construction to changing demands.

While described extensively in literature governing lifetime extension of products in a circular economy, little is written about the upgrading or adaptation of composite structures. However, it is expected that for composites, increasingly used for infrastructural applications, upgrading and adapting could be a viable, life-extending strategy.

Upgrading is regarded as an extension of maintenance and the same design principles apply. As upgrading often involves replacement of components, modularity and accessibility have to be included in the design.
As upgrading and adapting is meant to respond to changing future demands, it is worthwhile to prepare a future outlook for the product. Time and planning of the intended upgrades are important, as is determining who will perform the upgrades and what expected functionality they will affect.

An approach to incorporate upgradability in the design is to write scenarios based on expected future developments in use, technology and trends. Experience with similar products, for example from repairs or maintenance contracts, can provide useful insights. Some functions of the product will be affected quickly and others slowly, these insights can be used to compile modules and making material choices.

4.4 Recovery of products

Products can become obsolete for a number of reasons, listed in section 4.2.1. The goal of recovery is to reverse product obsolescence (den Hollander et al., 2017) and enable another product use cycle. Recovery actions include inspection, cleaning and replacement to return a product to an as-new condition. Or even better than new, when upgrades are included. When opting for product recovery business models, it is important to consider the environmental impacts of for example logistics and production of spare parts (Bakker et al., 2014).

Parts harvesting is when parts and modules are taken from obsolete products to serve as spares for upgrades and repair of other products. It is not included as a separate design strategy as it relates closely to remanufacturing and refurbishment and most of the same design principles apply (Bakker et al., 2018).

4.4.1 Design for refurbishment

The goal of refurbishing is to extend a product life, by restoring its condition at one or more moments during its lifetime. It is defined as to “return a used product to a satisfactory working condition by rebuilding or repairing major components that are close to failure, even where there are no reported or apparent faults in those components,” (Bakker et al., 2014)

It includes the cosmetic as well as the functional condition, the result is usually of lower specification compared to the original –new- state, as is the warranty given on the product. Refurbishment needs products to be collected, disassembled, evaluated, cleaned and reassembled while replacing components or modules. Resurfacing can be done to improve the aesthetic appearance as well as the wear resistivity. When the replacements provide improvements compared to the original specifications, these are considered upgrades.

Refurbishment has proven to be viable for composite components like wind turbine blades. After the initial use cycle of about 20 years, the blades are tested, repaired and resurfaced. Due to logistical challenges, refurbishment seems viable for small size turbines (Beauson & Brøndsted, 2016).

Important when designing for refurbishment is to envision the necessary actions and timing thereof. Choosing the appropriate business model ensure products return in time for refurbishment. For example lease constructions with refurbishment in between contract periods. (Bakker et al., 2014)

Factors playing a role in determining a components’ lifespan are the functional, emotional, aesthetic and economic performance & degradation. Also mentioned in the strategy design for long life. User acceptance is important for the success of refurbished products. Increasing acceptance start with
reducing the perceived risk through providing information and emphasizing the benefits (Balkenende et al., 2017). In the case of the refurbished wind turbines for example, these are access to a range of used models, reduced costs and lead time. (Beauson & Brøndsted, 2016)

In general, refurbishable products benefit from accessibility and modularity, enabling quick & easy replacement of components. Surface treatments and materials have to meet the proposed refurbishment processing like repair or restoration of surface quality.

4.4.2 Design for remanufacturing

Remanufacturing takes place at the product and component level, more thoroughly than Refurbishing: Remanufacturing is to “return a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product” (Bakker et al., 2014). The goal is to recover complete subassemblies or components from a used product which can be reused after cleaning and inspection. Reuse can be in as-new products or as spare parts. In the automotive industry, it is not uncommon to do repairs using remanufactured parts.

A completely remanufactured product can be better than the original product, when the remanufacturing action is used to implement upgrades. Such upgrades need careful planning and development of the product platform in the initial design stage.

Remanufacturing or parts harvesting actions are usually executed by OEMs or related parties (e.g. licensees), which enables the OEM to retain control of the parts quality and market. Using remanufacturing in a business strategy is profitable: each remanufacture cycle generates profit for little investment of energy and material resources. However, a supply chain, inspection procedures etc. must be established and remanufacturing has the potential drawback of cannibalising on sales of new products.

Remanufacturing works best with settled technology, for example automotive engine components. Standardisation is key and parts can be kept on stock for extended time to serve as replacements for existing products, or to build new products. Considering this, rapid changing technologies are unfit for remanufacturing based business models.

The product lifetime should be dominated by the functional and physical lifespan of its constituent components rather than external factors like the economic life, which is an important consideration in the structural design and selection of materials and surface treatments. Attention must be given to the selection of fasteners and connection methods. Inserts, fasteners integrated in the component structure, provide an effective way of transferring loads, but cannot easily be replaced. Depending on the anticipated recovery operations, inserts can be selected to enable quick disassembly of components.

Disassembly, cleaning and fault isolation has to be time-efficient to make component recovery economically worthwhile. These actions can be aided by developing diagnostic tools, documentation and identification systems. An embedded monitoring system can help estimate the condition and residual value. No unsafe conditions should appear during the process, so safe tooling and materials have to be used.
To prepare for future upgrades, a life cycle perspective has to be included, which is further described in section 4.3.2 Design for upgrading & adapting.

4.5 Recycling of materials

Where the EoL scenarios above consider integrated products or parts, recycling is focused on recovery of materials. Recycling is both the last resort and a prerequisite. The last resort, because all product integrity and material structure are lost. A prerequisite, since all products, even after having served multiple use cycles, will become obsolete beyond product recovery. At that moment the resource loop should be closed by recollecting the products and reprocess them into material feedstock for new products & components. For product design this means that recycling should always be anticipated for in the design stage. The very integrated nature and materials used for composites however, make recycling difficult.

Recycling is categorised in four levels:

<table>
<thead>
<tr>
<th>Recycling level</th>
<th>Material description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary, or: upcycling</td>
<td>Recycled materials properties are equivalent to original</td>
</tr>
<tr>
<td>Secondary, or: downcycling</td>
<td>Recycled materials are of lower quality</td>
</tr>
<tr>
<td>Tertiary</td>
<td>Recovery of chemical feedstock</td>
</tr>
<tr>
<td>Quarternary</td>
<td>Recovery of energy (not further considered: complete loss of materials)</td>
</tr>
</tbody>
</table>

Upcycling is a popular term, awarded to many recyclate products. From the perspective that waste is transformed into usable materials, indeed economic value is added. However, closer inspection of materials quality shows reprocessing typically incurs material degradation. E.g. through shortening of polymer chains or decreased purity of metals. Usually the loss in quality is compensated by adding virgin material to the recycled content.

Using the recycled materials is as important as recycling them in the first place (Liu et al., 2017). Use creates a market and value for the recyclate, adding to the economic viability next to the environmental gains. Environmental gains are found in the reduced need for virgin materials and energy needed to process them, as well as in the end of life situation of undesired landfilling (Halliwell, 2006).

Design for recycling guidelines are found by considering the process steps: collection, liberation, concentration and reprocessing. For collection a suitable supply (chain) of recyclable feedstock is needed. This implies use of recyclable materials and incorporation of business models that serve to return materials at a specific rate. Liberation, the (mechanical) separation of parts, needs processable connection types. Concentration of the materials, e.g. automated sorting techniques, benefit from less variety in materials used, including the fasteners.

4.5.1 Composite recycling

As described in chapter 3.5, recycling of thermoset matrix composites has a severely degrading effect on fibre and matrix value. It therefore makes more economic and environmental sense to strive for functional reuse. However, if this proves to be unfeasible, reuse of structural elements can be investigated. Using integrated composites retains the value embedded by manufacturing, which in the case of thermoset composites is significant compared to the energy embedded in the materials.
This approach is strongly related to parts harvesting and can also be described as repurposing of functional elements, as the elements are not necessarily used in applications similar to the original one.

Composites, with their favourable structural properties and resistance to fatigue, could very well be structurally repurposed. This has been demonstrated with EoL wind turbine blades, being repurposed to design a bridge or outdoor furniture (Beauson & Brøndsted, 2016). For such applications, information about the material or product at hand is vital. Structural and dimensional details are needed to design the new object and to model mechanical structure. Data on initial use conditions and load cycles are used to determine residual quality.

This does not necessarily imply that the complete component is used, segments and parts fulfilling the desired functional specifications may be demounted from the original component. Adhesive bonding, often applied in composite structures, make such recovery difficult. Fastener & connection selection in the initial design may be used to anticipate for future deconstruction of the components.

### 4.5.2 Constituent material recycling

For composites, no cases have been found for primary recycling, even if the recovery process resulted in fibres with mechanical properties similar to virgin fibres. Reason is that the fibre value depends on material properties as well as on fibre length and orientation (Oliveux et al., 2015).

For thermoset composites, high temperatures and aggressive chemical treatments are necessary to dissolve the matrix. Typically, value is recovered from the fibre fraction, the resin fraction is reduced to fuel. Recycling has proven to be viable in the case of carbon fibres, which withstand the processing conditions better than glass fibres and have a higher raw material price. Thermoplastic composites have a potential for remoulding, which has been demonstrated at lab scale. In practice, materials degradation following from exposure to environmental conditions in the use phase impedes high quality recycling (Mangino et al., 2007).

Both reprocessing of thermoset and thermoplastic matrix composites benefit from uniformity in materials selection, including fasteners and other joining techniques. Owing to the range in resins and fibres used, classification to those qualities may be necessary to enable reprocessing and valuable reuse of the recovered material (Oliveux et al., 2015). This could already be implemented in the design stage by reducing the variety of materials and fibre grades.

Degradation of materials during reprocessing shows the need for less aggressive methods, both in terms of temperature and chemicals used, as well as matrices that need less aggressive conditions to dissolve. Connora for example, has developed an epoxy resin that can be recycled into a reusable thermoplastic resin and keeps fibres at near-virgin quality using their proprietary, low-energy solvolysis process. (Connora, 2018)

The case for recycling of composites could be further enhanced by generating a market demand. When primary recycling is unachievable, the materials can be appointed to less (structural) demanding applications. Use of short carbon fibres in thermoplastic composites, recycled from long fibre thermoset composites, has been demonstrated (Perry et al., 2012). Such a cascading approach prolongs material life and brings value to the recyclate. The goal must always be to find applications at the highest value level, using recycled carbon fibres in downcycled or even unreinforced materials may lead to higher cost and a lower environmental efficiency (Oliveux et al., 2015).
5 Composite design strategy framework

5.1 Framework setup

Product design integrates requirements from (circular) business models and technological design aspects. The business model directs the product lifecycle; what kind of interventions will be done. When and which incentives are in place. A design strategy serves to bridge the gap to product design.

During its lifetime, a product encounters many processes and stakeholders. In a circular economy, the number is likely to grow. It is important to gather knowledge about these processes and stakeholders and to translate these into technological aspects to include in the product design.

For example, a product fitting the business model of Classic long life can be designed using the design strategies for long use or reuse. Technical aspects like materials selected for durability and a sound structural design enable product longevity.

As specific technicalities are product context specific, providing universal technological guidelines is impossible. Therefore, this chapter provides a summary of generic design principles. Summarising has the benefit of widening applicability to a large group of products and identifying similarities between technological design aspects. The design principles can be used to derive product specific design guidelines.

<table>
<thead>
<tr>
<th>Business models</th>
<th>Design strategies</th>
<th>Technological design aspects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classic long life</td>
<td>Long use</td>
<td>Material choices</td>
</tr>
<tr>
<td>Access and performance</td>
<td>Upgrading</td>
<td>Modularity</td>
</tr>
<tr>
<td>Exploiting residual product value</td>
<td>Repair</td>
<td>Accessibility</td>
</tr>
<tr>
<td>Gap exploiter</td>
<td>Refurbishment</td>
<td>Dis- &amp; Reassembly</td>
</tr>
<tr>
<td>Renew resource functionality</td>
<td>Remanufacturing</td>
<td></td>
</tr>
<tr>
<td>Renew resource value</td>
<td>Recycling</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1 Business models, design strategies and Technological design aspects. Adapted from (Balkenende et al., 2017)

The set of principles proposed here builds on the circular product design framework (den Hollander, 2018). All design principles support multiple design strategies and are often interconnected. Therefore, this chapter starts with an overview table showing the relations between design strategies and design principles. Followed by a short description of the design principles.
5.2 Design strategy framework

The table below shows the relations between the design strategies listed horizontally and design principles listed vertically. The table shows considerable overlap: all design principles support multiple design strategies. This might give the impression that all design will provide similar results, since they are all built using near identical sets of design principles. However, the implementation of the principles in product design is very context dependent. Business models determine the operation of a product during the use and end-of-use stages, including the stakeholders and processes involved. This poses specific demands on the design, e.g. type of identification will be different for a recycling process, compared to remanufacturing. However, applying a certain design principle will usually affect multiple design strategies; materials selection for long life will also have an effect on recyclability. Both effects can be negotiated by careful planning and including business models in the initial design.

<table>
<thead>
<tr>
<th>Design strategies→</th>
<th>Long use</th>
<th>Reuse</th>
<th>Maintenance &amp; repair</th>
<th>Upgrade &amp; adapt</th>
<th>Refurbish</th>
<th>Remanufacture</th>
<th>Recycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dis-&amp;re-assembly</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Modularity</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Identification</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interchangeability</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Accessibility</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material selection</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Surface treatment</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Separation (Mechanical)</td>
<td></td>
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</tr>
<tr>
<td>Resilience</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Malfunction annunciation</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural design</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>Fastener &amp; connection</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Documentation</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Simplification</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
5.3 Design principles

The selection of design principles builds on *design for product integrity* (den Hollander, 2018), developed for consumer products. For composites in a circular economy, *design for recycling* and approaches for large structures beyond the scope of consumer products are included.

<table>
<thead>
<tr>
<th>Design principle</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dis- &amp; reassembly</td>
<td>Facilitate demounting of components in a non-destructive way</td>
</tr>
<tr>
<td>Modularity</td>
<td>The product is subdivided in functional units which operate largely independent from each other. Use of (functional) modules within a larger frame provides benefits in all lifecycle stages</td>
</tr>
<tr>
<td>Identification</td>
<td>Applying recognizable features to products &amp; components to enable quick recognition when serviced, exchanged or reprocessed.</td>
</tr>
<tr>
<td>Interchangeability</td>
<td>Enables easy exchange of components within an assembly. A feature that greatly benefits efficient lifetime extension and product recovery interventions.</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Ensuring (internal) parts can be reached and/or demounted from a product.</td>
</tr>
<tr>
<td>Material Selection</td>
<td>Selecting the material that is best suited to the design requirements (including EoL treatments) of the product under consideration</td>
</tr>
<tr>
<td>Surface treatment selection</td>
<td>Selection of the outer layer to be applied to a component, depending on the desired functionality.</td>
</tr>
<tr>
<td>Malfunction indication</td>
<td>Measures taken in the design to facilitate evaluation of product (structural) quality and fault isolation</td>
</tr>
<tr>
<td>Structural design</td>
<td>Utilizes the freedom of fibre composition and orientation within the material, having an effect on all lifecycle stages. A physically durable structure is able to withstand the degrading effects of use and environment, while remaining functional for a long time.</td>
</tr>
<tr>
<td>Separation</td>
<td>To facilitate liberation and concentration in the recycling procedure, notably in mechanical processing</td>
</tr>
<tr>
<td>Resilience</td>
<td>“Providing an excess of functionality and/or material in products or parts, for example to allow for normal wear or removal of material as part of a recovery intervention or to prevent interruptions in the functioning of a product.” (Keoleian &amp; Menerey, 1993; Kuo et al., 2001)</td>
</tr>
<tr>
<td>Fastener &amp; connection selection</td>
<td>Selection taking the envisioned lifetime extension and product recovery as well as material recycling processes into account</td>
</tr>
<tr>
<td>Documentation</td>
<td>Information about the design, materials, dimensions etc. enables multiple use cycles and proper end of life processing.</td>
</tr>
<tr>
<td>Planning</td>
<td>Planning is an important activity in the design of circular products. Timing, operations and incentives for future product interventions can be evaluated and anticipated for in the design.</td>
</tr>
<tr>
<td>Simplify</td>
<td>Reducing number and complexity of the product and its parts as well as its visual appearance</td>
</tr>
</tbody>
</table>
6 Design tools

The previous chapters set the framework of design strategies for composite products. This chapter proposes a set of tools to use in various stages of the design process, the goal of these tools is to transform theory into actionable strategies for product design. These tools are developed to be used in the context of Ecobulk and applicable to various stages of the design process.

The design process starts with definitions of the product and its lifecycle through exploring the value chain and reasons for end of life. These tools assist in selecting the design approach to use for further development. By detailing the specific recovery processes and resource circulation, challenges and opportunities as well as criteria for the design can be found. The design for reuse method uses the design principles described in chapter 5 to address the main challenges. Product integrity mapping is then used to build and evaluate potential reuse and recovery scenarios.

These tools can be used iteratively to improve the product. At the beginning of the product development process there is still room to make major changes and to determine how the strategies must be applied. The methods can be further detailed as more information becomes available as the design progresses. Selection and implementation of product lifetime extension approaches will be different per product type and tailored approaches may be needed. Lifespan and reason for end of life are important in the selection, yet other conditions should not be neglected, such as technology and business perspectives (Bakker et al., 2014). The latter implies that the design strategies here are preferably combined with the business model tools that are also developed as part of Ecobulk.
Figure 6.1 Design tools connected to stages in the product development process. Process adapted from (Roozenburg & Eekels, 1998)
6.1 End of life mechanisms

On the level of products & components it is important to realise their respective lifespans may differ; components can be replaced during refurbishment actions. Or components are reused through remanufacturing, thus outliving their initial product assembly. Evaluating reasons for End of life of the product and its constituent components reveals relations and assists in selection of design strategies. This tool serves to estimate lifespans and evaluate which design approaches to apply to the redesign. It is best used at the start of a design process, to select initial focus areas and can later be refined when more information is available. It helps to check assumptions and effect of design choices.

6.1.1 Method

Lifetimes are estimated using the definitions mentioned in chapter 4.2. This exercise will show the limiting factors for product life by evaluating End of Life information in a structured way. Opportunities for circular redesign of the product & component are explored using the design strategies described in chapter 4.

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Life ends when...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td>Breakage beyond economic repair</td>
</tr>
<tr>
<td>Functional</td>
<td>Need for product ceases to exist</td>
</tr>
<tr>
<td>Technical</td>
<td>Technological developments make the product outdated, while still functional</td>
</tr>
<tr>
<td>Economic</td>
<td>Newer products are more economic in use</td>
</tr>
<tr>
<td>Legal</td>
<td>The product no longer complies to new regulations</td>
</tr>
<tr>
<td>Desired</td>
<td>The product is rendered old-fashioned by changes in style etc.</td>
</tr>
</tbody>
</table>

Table 6-1 Reasons for end of life

6.1.2 Tool

The tool is presented as an A4 worksheet, guiding the designer through the process. The full worksheet and working method are described in appendix 9.1. First, the designer is asked to define the product & component at hand. In this way, the designer has to clearly distinguish between the estimated lifespans of product & component.

Then, the designer should estimate the respective lifespans of product & component for the lifetimes listed above. The mechanism for EoL is noted. From this exercise, two main insights will become apparent:

1. Mechanisms limiting product life, which can come from both component of product EoL
2. Mechanisms limiting component life

The mechanisms of the four shortest lifespans are further explored using the design strategies. This will reveal options to extend product or component life, bearing in mind that component life may surpass product life, for example through remanufacturing.

6.1.3 Initial results

This tool was applied to the Ecobulk reference product “car dashboard”. It was expected that the lifespan of the car would be shorter than the functional lifespan of the component. For further development, it is therefore recommended to investigate opportunities for component reuse.
6.2 Product and lifecycle exploration
Design for a circular economy requires planning of the product lifecycle and collaboration of stakeholders in the value chain. The goals of this tool are to gain insight in the current (linear) value chain, connect stakeholders and explore opportunities for design & recovery.

6.2.1 Method
This tool builds on the schematic product value chain often used to describe the flow of goods and resources through the economy (Ellen MacArthur Foundation, 2013b). The setup implies a closed loop, closed source scenario, where resources are circulated within a single value chain (Bakker et al., 2018). At the end of the initial product life, the resource flow is closed through a recovery operation. Each operation results in specific components or materials returning to one of the stakeholders.

6.2.2 Tool
The tool is presented as a workshop, where stakeholders form the value chain collaborate to explore new circular value chains of a reference product. The manufacturer prepares for the group session by filling out the value chain for the reference product. Stakeholders and goods moving through the value chain are identified. In the group session, additional return flows are explored with the stakeholders. The full working method and worksheet are included in appendix 9.2.

6.2.3 Initial results
This workshop was held at the Ecobulk M12 General Assembly in Koblenz in June 2018. Three sessions were held, corresponding to the three Ecobulk industry sectors. In each session, groups were made representing stakeholders from the reference product value chain. So each table would have representatives from e.g. manufacturing, materials supply and EoL facilitators. Manufacturers were asked to draw their product lifecycles beforehand and to present these shortly. In the groups, this value chain was used to explore recovery operations. The resulting remarks were used as input for the next tool: “Exploring circular challenges & opportunities”.

6.3 Recovery & design exploration
Recovery of products, components and materials brings in new demands to the product design. Now that the reference product and lifecycle are known, and some ideas for the new circular value chain have been explored, it is time to have a look at the design challenges and opportunities. The goals of this tool are to explore opportunities for product design & recovery and to identify the next steps in product development.

6.3.1 Method
This tool connects the resource flows and recovery actions identified in the “Product and lifecycle exploration” to the design strategies described in chapter 4. This is done by explicitly formulating the foreseen challenges of the recovery actions, followed by exploring design solutions that could be applied. It results in specific challenges and opportunities for the redesign of demonstrator products, as well as insight into which types of challenges and design solutions are described most often across all cases.

6.3.2 Tool
The tool is presented as a workshop, where stakeholders form the value chain collaborate to explore challenges and solutions to the previously identified recovery actions. As such, “Recovery and design
“exploration” builds on the results of the Product & lifecycle exploration tool. With representatives from the value chain brought together in one group, the participants are able to immediately discuss specific product features. The workflow and worksheet are further explained in Appendix 9.3.

6.3.3 Initial results
This tool was used at the M12 General Assembly in Koblenz and follows the same format as the “Product and lifecycle exploration”. The workshop showed were the most challenges and opportunities were identified for development of the Ecobulk demonstrator products. Detailed results from the workshop on Recovery & Design exploration can be found in Ecobulk report D2.4.

6.4 Design & business model strategies
The process of considering how products can be designed to be more circular is underway for Ecobulk. Here we consider how business strategies can support a move towards a more circular economy and consider if any change to business strategy will influence design. This tool aims to:

- Clarify what is currently done, why and why it is or is not circular
- Consider what CE objectives can be applicable to the product
- Explore more deeply how objectives could be met through redesign and business strategies

6.4.1 Method
The product is evaluated using three circular economy principles:

1. Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
2. Optimise resource yields by circulating products, components and materials in use at the highest functionality at all times
3. Foster system effectiveness by revealing and designing out negative externalities

6.4.2 Tool
The tool is presented as a semi-structured interview with the product developer. Using questions derived from the circular economy principles mentioned above, the circularity of the redesigned reference product is evaluated. A strategy overview is presented to stimulate discussion on how to achieve high value recovery of materials & products. Building on the product developer’s expertise, (new) technologies and opportunities for design and business models are explored. The connection between design and business models is highlighted to broaden the scope and emphasize that these can be developed in parallel in the product development stage.

6.4.3 Initial results
This tool was used in a series of semi-structured interviews with Ecobulk manufacturing and design partners. Through evaluation of the current designs in relation to circular economy strategies, blockers and opportunities for product development within and external to Ecobulk were identified. Using the circular economy principles and strategies proved to be an effective approach to explicitly evaluate potential resource flows.
6.5 Design for Reuse
The Design for Circularity workshops in Koblenz explored the circular recovery options for Ecobulk reference products. It was found that there are opportunities for reusing the products through remanufacturing or refurbishment. Also, challenges were identified which have to be addressed in the design of the product. As a follow-up, manufacturers are asked to start working on the found design challenges, using a set of proposed design principles. In a Circular Economy, we want to focus on the recovery of products as this preserves most of the original product value. Especially in the case of composite materials, where material integrity is mostly lost during the recycling process. However, after the product has been reused for multiple life cycles, the materials should be recyclable. Therefore, design for recycling is regarded as a mandatory requirement for all products, in this assignment participants are asked to focus on the design for recovery of products & components. This tool aims to improve circular redesign of the reference product through applying a selection of design principles.

6.5.1 Method
This tool builds on the design principles for circular product design (den Hollander, 2018). The framework lists a set of design principles that support one or more circular strategies. When a specific strategy is selected, these principles can be used to redesign the product. In this stage, no cost restriction apply to the design. In a later stage initial investments and manufacturing costs, as well as the total cost of ownership will be looked into. This may change considerably if the product can be used for multiple lifecycles.

6.5.2 Tool
The tool uses the results from the “Recovery & Design Exploration” workshops. These workshops have shown which recovery strategies are considered most relevant for a reference product. With this input, a selection of design principles relevant to the product design challenge is made. Product developers are then asked to redesign their product using these principles. The workflow and materials are described in more detail in appendix chapter 9.5.

6.5.3 Results
This design method was used by manufacturing partners in August and September 2018. The results of the redesign efforts are further described in Ecobulk report D2.4.

6.6 Product and material integrity mapping
The lifecycle of a product or component starts at the moment it is first produced and ready for service, the lifecycle ends when it cannot be used functional anymore. Products can be used multiple times within a single lifespan by facilitating multiple use cycles within a single product lifecycle.

6.6.1 Method
This tool connects the circular product design strategies to composite material structures. Structural state of the composite material is regarded as a measure of value: long and unidirectional fibre packages represent a higher value than short & random oriented. Plotting successive use cycles in a table cross-referencing materials and product integrity visualises the flow of materials and recaptured value. For a circular economy, the product should be kept as much as possible in the upper left corner: where product and material integrity are high.
6.6.2 Tool
The tool, in the form of a worksheet for designers, was developed for the Ecobulk project. An example of its application is shown in appendix chapter 9.6.
7 Emerging technologies for composites in a Circular Economy

This chapter describes the opportunities for emerging technologies in improving the circular use of composites.

7.1 Additive manufacturing

Additive Manufacturing (AM), also known as 3D printing, is an emerging technology that can be used for production of composite components. Within the domain of AM, various processing techniques and materials are found and more are currently being developed. Despite their differences, these technologies share some very distinct properties that set them apart from conventional manufacturing techniques. These characteristics can have both positive and negative effects on establishing a Circular Economy with composite materials.

<table>
<thead>
<tr>
<th>AM Characteristic</th>
<th>Enabling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digital production</td>
<td>Individual adjustment of components</td>
</tr>
<tr>
<td>On demand production</td>
<td>Smaller stock of components needed</td>
</tr>
<tr>
<td>Small scale feasibility</td>
<td>Distributed and local manufacturing</td>
</tr>
<tr>
<td>Rapid response to demand</td>
<td>Quick design iterations &amp; component availability</td>
</tr>
<tr>
<td>Large design freedom</td>
<td>Optimised structures &amp; shapes</td>
</tr>
<tr>
<td>Highly automated workflow</td>
<td>Cost efficient production</td>
</tr>
<tr>
<td>Tool-less production</td>
<td>Flexibility to design adjustments</td>
</tr>
<tr>
<td>Additive process</td>
<td>Topology optimisation, new forms and lightweight structures</td>
</tr>
</tbody>
</table>

Table 7-1 AM characteristics, from interview with M. Sauerwein, 2018

7.1.1 Trends

AM is viewed as to streamline the manufacturing process without sacrificing benefits of fibre reinforced plastics in terms of weight optimisation & strength. Materials science, especially regarding composite materials, is expected to be a large factor in the development of AM. Extrusion processes allow for long (~3 mm) up to continuous fibres, while powder based processes need small (particle) fillers (Sher, 2017).

AM has been demonstrated on a small scale and for prototypes, but effects like “smaller stock” have to be proven on a large scale. Even though it is regarded as an enabling technology to establish a Circular Economy and is often described as sustainable, no consensus has been reached on how sustainable it actually is. Convincing LCAs taking a systemic perspective on AM do not yet exist.

7.1.2 Effect of AM on Circular strategies

The expected effects of AM on composites in a Circular Economy are mapped using the Design strategy framework presented in Chapter 4.

AM, as digital manufacturing technology, allows for adjustment and personalisation of individual components. Personalisation is expected to increase product attachment and thereby long use.

Use of multiple materials and structures within a single component allows for function integration. Integration reduces the number of components in product assembly and potentially reduces the risk of failure, as less connections are needed.

Function integration has a negative effect on the upgrade- and reparability, as it makes replacement of individual parts more difficult or even impossible.

AM can be used to produce spare parts. The spare can be tailored to exactly fit to a broken component or even add functionality.
Product recovery

Quality is expected to be the limiting factor for recovery of AM products, which depends largely on materials & manufacturing. Distributed and hence locally available (re-)manufacturing facilities, enabled by AM’s small-scale feasibility may benefit product recovery.

Materials Recycling

AM products face to a large extent the same challenges as conventional manufactured products. Functional & material integration provide great benefits in initial production & use, but limit EoL possibilities. Separation of binder and filler is challenging.

7.2 Internet of Things

Internet of Things (IoT) is an umbrella term for many applications of embedded electronics, which have sensing and connectivity in common. Connectivity can be to the greater network, the internet, or to local networks to exchange information between nodes. In general, IoT is a great technological opportunity to fill information gaps. As indicated in various design strategies, most stakeholders and processes in a product lifecycle would benefit from available and accurate information on the product.

This immediately introduces the question of who should have access to which data. Privacy and Intellectual Property are reasons to restrict data flowing between stakeholders. Currently, most IoT applications related to sustainability and Circular Economy are found the field of energy efficiency. Sensing and control networks are used to optimise power plans, for example for buildings. IoT’s capabilities could support Circular Economy in a number of ways.

<table>
<thead>
<tr>
<th>IoT Characteristic</th>
<th>Enabling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>(embedded) availability of information on product specifications</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Gathering of data during and about the use of the product</td>
</tr>
<tr>
<td>Control</td>
<td>Remote or internally programmed response</td>
</tr>
<tr>
<td>Using the characteristics above</td>
<td></td>
</tr>
<tr>
<td>Optimisation</td>
<td>Optimal functioning, usage and service provision</td>
</tr>
<tr>
<td>Design Evolution</td>
<td>Improvements based on (usage, environmental, etc.) data analytics</td>
</tr>
</tbody>
</table>

Table 7-2 IoT characteristics, from interview with E. Ingemarsdotter, 2018

For composite products, especially tracking and monitoring functions could be useful. Tracking, including identification, to make information on material composition and other specifications available. And monitoring to evaluate the functional and structural quality based on use-phase data. Number of use cycles, age and environmental conditions can give insight to the current state of the product.

7.2.1 Trends

IoT can be used to optimise maintenance, the extent to which it is applied and maturity of technology depend on industry sectors. Typical applications are high value products with costly downtimes, although it has been observed to trickle down into more common and ubiquitous available products. Material passports, capturing information on material composition and processing, is spurred by EU policy and are enabled by embedded identification systems.
Digitisation is also used to servitize products and set up Product Service Systems (PSS). PSS like maintenance contracts help to optimise product life and usage, as well as generate additional company revenue and connection to the user. However, the trend of functionality extension by adding digital measurements and other IoT solutions has to be regarded with care. Embedded electronics make a product more complex to repair and recycle. And, as illustrated by smartphones, risk the by-effect of introducing fast-paced obsolescence.

### 7.2.2 Effect of IoT on Circular strategies

The expected effects of IoT on composites in a Circular Economy are mapped using the Design strategy framework presented in Chapter 4.

<table>
<thead>
<tr>
<th>Products and components</th>
<th>Long lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuse, through sharing systems, is enabled through availability of information about the availability, functional state and through access control.</td>
<td></td>
</tr>
<tr>
<td>Caution: adding IoT functions can unintentionally shorten product lifetime.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Extended use</th>
</tr>
</thead>
<tbody>
<tr>
<td>IoT has great potential to optimise maintenance operations using monitoring and control. Monitoring allows to keep track of the state of a product whilst used in the field.</td>
</tr>
<tr>
<td>Control, response to sensed input, can be used to prevent consequential failures. For example, a wind turbine can be shut down when an imbalance is suspected to prevent damage to other components in the system.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Product recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Remanufacturing operations benefit from information on when the product will be available and the state it is expected to be in. Tracking and monitoring systems can help manufacturers plan and prepare for remanufacturing actions.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycling</td>
</tr>
<tr>
<td>IoT can serve to track materials streams for recycling, so the relevant stakeholder can know where to tap in to their desired resource flows. This could include product-tracking as well as monitoring collection points.</td>
</tr>
<tr>
<td>Identification and/or embedded information can provide the recycler with information on the material composition, suggested handling and potential health hazards of the product.</td>
</tr>
<tr>
<td>However, embedded electronics risk to make recycling more difficult, as it adds more and complex materials to a product.</td>
</tr>
</tbody>
</table>
Appendix 1: Design principles

The selection of design principles builds on design for product integrity (den Hollander, 2018), developed for consumer products. For composites in a circular economy, design for recycling and approaches for large structures beyond the scope of consumer products are included.

8.1 Dis-&re-assembly

Design for dis- and reassembly facilitates demounting of components in a non-destructive way. The goal is to minimise complexity, cost, downtime & resources. These are interconnected; a complicated disassembly will require more time and resources, for example skilled personnel (M. den Hollander, 2018). The benefits of dis- and reassembly are noticeable in practically all product recovery and some material recycling processes, although the latter usually work with mechanical separation processes which are discussed in section 8.9. Disassembly is especially relevant for the reuse of large structures. Transport, for example may be limited to certain size.

Manual assembly will happen if this it is required to meet regulations (e.g. separation of harmful substances) or if the part is significantly valuable, where value is determined by functionality or material (weight).

8.2 Modularity

Modular design is referred to in circularity strategies repair, upgrade and remanufacture. The product is subdivided in functional units which operate largely independent from each other. The use of (functional) modules within a larger frame provides benefits in all lifecycle stages (Baldwin & Clark, 1999):

- **Design**
  - Parallel development of multiple modules
  - Increase of manageable complexity by limiting the scope of interaction between tasks
  - Accomodation of uncertainty (a “black box” module)
- **Production**
  - Scale & scope advantages: shared parts allow for larger production volume
  - Mass customisation (pick&place components)
- **Use**
  - Replacement of modules for upgrading, repair, etc.
- **End of Life**
  - Remanufacturing or refurbishment of modules

Modules can be composed according to different conditions like transport; grouping according to weight and size, lifetime; grouping parts to be replaced at the same time, assembly; enabling preparation or dismounting of subassemblies, and recycling; assigning similar materials to one module to aid separation of material streams, grouping inserts within one module, to reduce the number of materials used within other modules.
8.3 Identification

“Identification utilizes engraving, labelling or marking for quick location of parts or assemblies upon which preventive or corrective maintenance may have to be performed.” (Moss, 1985).

On product & component level, identification tags are placed on parts, assemblies & modules to be replaced or stocked to aid location and logistics. Repair, maintenance and remanufacturing activities use identification to select fault isolation and recovery procedures when processing an end-of-use product.

Recycling benefits from classification according to matrix type (determining the recycling process) and recovered fibre type as well as grade (representing value) (Oliveux et al., 2015). Thermoplastic composites with a matrix density <1 are discernible from their uncompounded counterparts by sink-swim separation, sinking materials with > 3wt.% of glass fibre content. In this case, presence of the fibres itself provides an identification method.

8.4 Interchangeability

Interchangeability summarizes the definitions of interchangeability, keying and standardisation as described by (Moss, 1985) and (Kuo et al., 2001). The principle enables easy exchange of components within an assembly. A feature that greatly benefits efficient lifetime extension and product recovery interventions. Within composite components, the high level of (functional as well as structural) integration and preference for permanent connection methods (adhesive bonding) conflicts with easy exchange. Something which could be further explored through application of the design principles “modularisation” and “dis- and reassembly”.

Interchangeability is “Controlling dimensional and functional tolerances of manufactured parts and assemblies to assure that [a part that is expected to fail or has failed] soon can be replaced in the field with no physical rework required for achieving a physical fit, and with a minimum of adjustments needed for achieving proper functioning” (Moss, 1985).

Keying enables replacement of components by “Utilizing matching geometric features (e.g., matching sizes and shapes like holes and pins to ensuring correct positioning of connectors, components and parts. (Kuo et al., 2001)

Standardisation assures compatibility (with i.e. mating parts and tooling) and minimises the number of spares that must be kept on stock through enforcing “the conformance of commonly used parts and assemblies ... to generally accepted design standards for configuration, dimensional tolerances, performance ratings and other functional design attributes” (Moss, 1985).

8.5 Accessibility

Accessibility refers to making the product’s components and modules available for lifetime extension and product recovery interventions. These are addressed in the design phase by making “the spatial arrangements of parts and assemblies within a [product] so that each of these items is readily accessible for replacement or repair in-place” (Moss, 1985).

For large structural components, manholes or inspection hatches may be necessary to provide access to the interior. Anticipated adaptations and upgrades to the product structure can be enabled by making the desired functional parts accessible & not interfering with prospective functions.
Accessibility coincides with dis- and reassembly and interchangeability to enable efficient mounting and demounting of components.

External accessibility, making the product available for multiple users, is excluded from this definition. Access and ownership models for circular products are further explored in Ecobulk Workpackage 8: Circular Business Models.

### 8.6 Malfunction indication
Comprises both the definitions of malfunction annunciation as fault isolation, as described by Moss:
- Malfunction annunciation is providing means “for indicating to the operator that the equipment is malfunctioning, in those cases where a malfunction is not readily evident” (Moss, 1985, p. 37).
- Fault isolation is assuring “that an [approaching] equipment malfunction can be traced to the part of the assembly requiring replacement” (Moss, 1985)

Measures to evaluate the quality of a composite component can be included in the design. Several options are available to assess the structural quality of composite components during and after use. Monitoring can be used to evaluate the state, prevent failure, estimate residual value and provide insight for future designs. For some products, specific guidelines are in place to estimate material quality after a number of use cycles (Germanischer Lloyd, 2005). Both signalling the need for documentation on the product’s usage history. Embedded sensing, ie. Fibre bragg grating, can be used to monitor load cases.

Damage evaluation from the surface is difficult as shape recovery of a part after impact makes it difficult to assess the extent of damage. Mostly, inspection starts with a visual check, aided by reference material from previous inspections. Yet evaluation of composites can be difficult as damages within the material, potentially even caused during production, like fibre misalignment, may not be visible on the surface (Mishnaevsky et al., 2017). Ultrasound testing can be used to assess the internal structure but is time consuming.

### 8.7 Material selection
Materials selection is defined as “Selecting the material that is best suited to the design requirements of the product under consideration.” (den Hollander, 2018). The materials selection should reflect the expected lifespan and use cases of the product or component. A number of suggestions a given for circular design approaches.

Products designed for a long lifetime should use a material that is durable enough to withstand multiple use cycles. For example: In a product, the internal structure and demands to its mechanical performance often rarely change, so materials with a long life expectancy can be used here. Shortlived and disposable products are best made of biodegradable materials.

Products, or parts thereof, intended to be recovered should prevent materials and constructions that pose a danger to health & environment. Examples are outgassing of toxics, like styrene from polyester, or dust when cutting. Fast changing parts should be made of easy recoverable or recyclable materials.
In general, recycling processes benefit from uniformity of the input material, in the case of composites regarding both matrix and reinforcement fractions.

8.8 **Surface treatment selection**

A surface treatment must be selected such, that it is “best suited to the design requirements of the product under consideration” (den Hollander, 2018). Requirements come from e.g. material selection, use context and (future) processing. The type of treatment depends on the surface it has to be applied to, usually predominantly matrix material if the fibres are properly embedded and include painting, plating & coating.

Surface treatments alter the appearance of the part, as well as its longevity; the composite material underneath is protected from detrimental environmental conditions like UV exposure and humidity. Prospective processing can be included in treatment selection. Repair, for example, may need removal or a polishable coating. Whereas recycling needs a coating that does not interfere with thermal or chemical reprocessing.

8.9 **Separation**

Separation is to facilitate liberation and concentration in the recycling procedure. The goal is to enable efficient separation of materials before they enter the reprocessing stage of the recycling process.

Liberation, the (mechanical) separation of parts, needs processable connection types. Fasteners or mechanical interlocking (snapfits) techniques are preferred over adhesive bonding. Concentration of the materials, e.g. automated sorting techniques, benefit from less variety in materials used, including the fasteners.

Design for separation is especially relevant for composite products for their integrated nature, both in material composition and integrated functions. For example fasteners, sandwich materials and inserts. Considering separation in the design process prevents loss and contamination of valuable materials.

8.10 **Resilience**

Resilience builds on the principles of redundancy and sacrificial elements as described by (den Hollander, 2018), the effective implementation in composite structures is similar. Redundancy is “Providing an excess of functionality and/or material in products or parts, for example to allow for normal wear or removal of material as part of a recovery intervention (Keoleian & Menery, 1993) or to prevent interruptions in the functioning of a product (Kuo et al., 2001).

Sacrificial elements work by “Introducing an inexpensive and easy to replace part that is “designed to be used up or destroyed in fulfilling a purpose or function” (Oxford, 2017), such as protecting more expensive and difficult to replace parts” (den Hollander, 2018).

8.11 **Structural design**

Long lifespans and intensified use strategies result in increased wear and stress on products in a circular economy. A physically durable structure is able to “withstand wear, stress, and environmental degradation and remain able to fulfil all physical functions for which it was designed
over a long period of time” (den Hollander, 2018). Physical durability can be achieved by over dimensioning, but this conflicts with the starting point of many composite designs: minimisation of mass (material volume) to be used. Lightweight design and evaluation of functional fulfilment can be exercised to reduce wear and prevent failure.

Lightweight design aims to distribute stresses evenly over the materials, thus optimising material use and preventing stress concentrations. Stress concentrations at inserts, changes in layup and geometry (e.g. sharp edges) should be avoided as these can cause local failure which, if left unattended, can result in complete failure of the product.

In addition, the basic working principles of the product could be designed to minimize wear & stress. For example by comparing different types of movement, joining or production methods and selecting those that introduce the least amount of wear & stress. The load cases in normal use conditions should never exceed the material limits (den Hollander, 2018).

Structural design also affects material recycling processes and the resulting material value. Both benefit from uniformity in supplied materials, which can be achieved by restricting the variation in layup and fibre types (e.g. grades and orientation in the composite structure).

8.12 Documentation
Much of a product’s value is determined by what is known about it. Information about the design, materials, dimensions etc. enables multiple use cycles and proper end of life processing (recycling). Documentation in many forms can be used to provide stakeholders along the value chain with necessary information.

The manufacturer can provide instructions for product life extension and recovery operations. For example, to provide instructions for dis- and reassembly, maintenance, fault isolation, baseline measurements & testing procedures as well as safety and environmental considerations.

In the use phase, documentation on use, environmental conditions and repairs can be used to monitor the product (Germanischer Lloyd, 2005). Such a status report can be used to estimate the residual value and need for preventive maintenance.

8.13 Planning
Planning is an important activity in the design of circular products. Timing, operations and incentives for future product interventions can be evaluated and anticipated for in the design. Scenarios can be used to explore future developments and actions that can be taken to keep the product relevant to the user. When no interventions are needed in use, a product can be designed for long use or reuse. When interventions are needed, extended use and product recovery strategies may be considered. Scenarios also help to evaluate the relation to an existing product line and sales, to plan the availability of spares, successive models, recollection systems and stock.

Planning could include a Life Cycle Analysis, although the extensiveness and complexity of such assessment makes it unpractical to use in the early stages of a design process. Instead, expert consultation often reveals quickly what environmental impacts may be expected.
8.14 Simplify
Simplification is recognised as making a product less sensitive to changes in fashion, often advocated by the term “less is more”. Simplification serves many more goals, as explained by (Keoleian & Menerey, 1993): “Parts reduction and simplified design can increase both reliability and manufacturability. Simpler designs may also be easier to service” and “simplification and parts consolidation can also make products easier to recycle”.

In the design of a product, “Given the choice between functionally equivalent designs, the simplest design should be selected” (Lidwell et al., 2003).

8.15 Connection & fastener selection
Fastener and connection selection strongly relates to design principles like dis- and reassembly, separation and structural design. Selection should take the envisioned lifetime extension and product recovery as well as material recycling processes into account. Selection criteria have to be established based on e.g. manufacturing, use, product recovery and material recycling operations. General requirements include:

- Use reversible & reusable connection methods.
- Inserts are hard to replace, so think of adaptation beforehand
- allow for quick & easy disassembly & reassembly: minimise the number of fasteners and preferably use mechanical fittings.
- Select inserts that are recoverable in the recycling process: collection, liberation (will it be separated from the composite?), concentration (picked out by sorting), or processable in the same recycling process?
- Mechanical interlockings can be preferable to completely rule out the need for additional materials.
- Metals are usually valuable and identifiable (magnetic separation) so provide an economic incentive to recycle.

Bootroyd provides a calculation method to evaluate (dis) assembly time depending on fastener type (Boothroyd & Alting, 1992). Such calculations are useful to balance (additional) cost of the fastener with prospective time benefits when reprocessing the product.

The fastener toolbox, developed in Ecobulk Deliverable D2.5, enables multi-criteria fastener selection. The toolbox contains a large database of fastener types currently available.
9 Appendix 3: Design tools

9.1 End of Life mechanisms, workflow

First, the product and component are defined and assigned a colour. The colour is used to distinguish between their respective lifetimes when sketching those on a bar graph. Then the lifetimes are estimated using the definitions mentioned in chapter 4.2. This exercise will show the limiting factors for product life.

The bottom half of the worksheet is then used to explore which design approaches can be used to prevent early end of life. The design strategy framework, presented in chapter 5 can be used to find principles to apply to the product design.

1. Define the product & component(s) to evaluate
   a. Sketch the product & component, assign a color to each
2. Estimate lifespans of product & component, drawing a bar-graph in their respective colors
3. Describe the dominant end of life mechanisms (eg. Change in fashion)
4. Select driving End of Life reasons
   a. Identify which lifespans are shortest
   b. Copy EoL reasons & mechanisms to the bottom table
5. Explore design approaches
   a. Determine which approach may be used to increase the lifespan
   b. Use the framework to identify design principles that can help
6. Evaluate the findings
<table>
<thead>
<tr>
<th>Desired</th>
<th>Life</th>
<th>Functional</th>
<th>Physical</th>
<th>Technical</th>
<th>Economic</th>
<th>Legal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product &amp; component description</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long life</td>
<td>Extended life</td>
<td>Product/component recovery</td>
<td>Recycling</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EoL 1</td>
<td>EoL 2</td>
<td>EoL 3</td>
<td>EoL 4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 9-1 EoL reasons and design approach selection worksheet
9.2 Product & lifecycle definition

Preparation

1. By manufacturer / designer, write on the Stakeholder & lifecycle sheet:
   a. Describe the product with a sketch or photo, name, material & manufacturer
   b. Identify the stakeholders for each lifecycle stage
   c. Draw the current (linear) lifecycle of the product at the bottom of the sheet (trace dotted line)
   d. Note processes & actions in the current lifecycle

2. By Workshop facilitator:
   a. Print out the Stakeholder & lifecycle worksheet, A1 will do for small groups (2-3 persons). A0 is recommended for a large group.
   b. Bring post-its & pens
      assigning a post-it colour to each participant helps to trace input afterwards
   c. Form groups, where each participant represents a stakeholder in the value chain

During workshop

3. Start with short presentation
   a. Workshop setup & goals (Facilitator)
   b. Product & lifecycle introduction (Manufacturer)

4. Discuss the product value chain (in groups)
   a. Explore circular strategies. For each strategy, note using post-its:
      i. Processes and actions
      ii. Products, components and materials that can be recovered
      iii. Add additional stakeholders where needed
   b. If additional product requirements emerge, make a note for the next workshop:
      Exploring circular challenges and opportunities
Figure 9-2 Example of Stakeholders & lifecycle worksheet, filled out for a wind turbine blade
9.3 Exploring Circular challenges & opportunities

Preparation

1. By workshop facilitator:
   a. Print out the Recovery & design worksheet, A1 will do for small groups (2-3 persons). A0 is recommended for a large group.
   b. Bring post-its & pens
      assigning a post-it colour to each participant helps to trace input afterwards
   c. Form groups, where each participant represents a stakeholder in the value chain

Workflow

1. Explore circular strategies shown in the columns:
   a. Describe the recovery actions and process (eg. Disassembly, stocking, etc)
   b. What challenges are encountered in the recovery process?
   c. What product requirements & design ideas are found?
2. Go back & forth between this worksheet and the “Product and lifecycle definition sheet” to identify stakeholders, recovery & design ideas
3. The exploration can be done for the current linear lifecycle and future circular lifecycles
4. Present: every group presents their results

To assist the exploration of recovery options, the following questions can be used:

- Resource perspective:
  - What material or product is recovered here?
  - What is the quality of the recovered resource and how can it be used?
  - What is needed of the product design for successful (valuable) recovery?
- Stakeholder perspective:
  - To which stakeholder is the material/product delivered?
  - What requirements would he ask for?
- Business perspective:
  - What is the value proposition of this recovery?
9.4 Design & business model strategies

**Preparation**

1. Prepare presentation to guide the discussion (facilitator)
   a. Summarize current position of manufacturer in project

**Workflow**

In the conference call, the facilitator will guide the participants through the discussion:

2. Identify why baseline product is not circular
   a. Discussion on current product design, value chain and proposed actions

3. High level assessment of relevant CE objectives. For each CE principle, describe
   a. Current product related activities and performance
   b. Potential for exploration within Ecobulk

4. Review of possible design & business strategies to achieve CE product objectives
   a. Design: what are the goals & what is needed to proceed making it circular?
   b. Business: what business models would fit and which consumer behaviour is desired?

5. Decision making for pilot product
   a. What CE objectives will be further developed?
   b. How will this affect design & business?
   c. Which project partners are involved & how?
9.5 Design for Reuse

Preparation

1. By facilitator
   a. Evaluate workshop results to identify main design challenges and recovery opportunities for the reference product
   b. Assemble a basic design brief using requirements from the Baseline report & workshops
   c. Identify which design principles are most promising to use in the redesign
   d. Combine the above in the Design for Reuse template
   e. Send to manufacturers:
      i. Design for reuse worksheet for the specific product
      ii. A product redesign example
      iii. A list of connection methods and their applicability for dismantling

Workflow

2. Detail the design brief (manufacturers)
   a. Problems found for the circular redesign
3. Redesign the product (manufacturers)
   a. Application: attempt to solve the challenges by using the principles
   b. Effects: Evaluate the redesign results
4. Discuss the results (facilitator & manufacturer)
Figure 9.4 Design for Reuse method, completed with the example of a Fairphone.

**Principles**
- The product is designed for disassembly and incremental improvements.
- The product is designed for repair, maintenance, and easy replacement of parts.
- The product is designed for easy access to internal components.
- The product is designed for easy removal of materials.

**Application**
- The principles are applied to the design of the Fairphone.
- The Fairphone is designed for easy disassembly and repair.

**Effects**
- The Fairphone is designed for easy repair and maintenance.
- The Fairphone is designed for easy removal of materials.

**Challenges**
- The Fairphone is designed for easy disassembly and repair.
- The Fairphone is designed for easy removal of materials.
- The Fairphone is designed for easy access to internal components.

**Problems**
- The Fairphone is designed for easy disassembly and repair.
- The Fairphone is designed for easy removal of materials.
- The Fairphone is designed for easy access to internal components.
9.6  Product & material integrity mapping

9.6.1  Example

Here plotted the successive use cycles of a wind turbine blade and the design strategies employed to enable those, based on design studies performed at Delft University of Technology.

First, the blades serve a 20 to 25 year life using their full functional capabilities. Even though the blades are design for long use, intermediate maintenance is needed to keep the blade in active service. Design strategies employed are design for long life and design for maintenance and repair.

Decommissioned blades are then used to construct a slow-traffic bridge, harnessing the residual structural capabilities of the blade. Other functions, like aerodynamic shape, are not employed in the new application. For installation, the blade tips are removed, but the majority of the initial blade structure remains intact.

![Circular product design approaches diagram](image)

After an estimated lifespan of 50 years, the bridge is deconstructed and structural members are cut into sizeable pieces to be used for other infrastructural or building purposes. Most of the initial

Figure 9-5 Product & material integrity mapping of a wind turbine blade

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product value and functionality is lost. Fibre length and structural integrity are decreased. After an estimated 20 years, the composite elements are removed and shredded. Product integrity is completely lost and material integrity is reduced from structural level to individual fibre fragments, mixed with fractions of core and matrix materials. This fibre mixture is encapsulated in a thermoplastic matrix to extrude beams and boards. Such extrusion elements are used for e.g. decking and fencing. Recycling of the thermoplastic profiles through shredding and re-extrusion, prepares the material for new products, yet decreases fibre length.

The scenario illustrates how a material can run through multiple successive product and material loops. Degradation in use and reprocessing leads to decreasing material integrity. Design measures preventing or abating degradation mechanisms help to prolong material life and can thereby slow down resource consumption.
10 References


Composites in Civil Engineering (pp. 919–926). Hong Kong: Elsevier Ltd.  

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