A product design framework for a circular economy

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Abstract: The paper provides a circular economy framework from a product design perspective with tools to aid product designers in applying circular product design in practice. Design research for circular economy has so far mainly been limited to referring to existing fields of research such as design for disassembly, remanufacturing and recycling. The implications of combining these fields in the context of circular economy from a product design perspective however have remained largely unexplored. Furthermore, available aids for product designers are limited. A critical review of current 'circular economy' terminology led to the (re)definition the five most design-relevant topics: future proof design, and design for disassembly, maintenance, remake and recycling. With this an adapted circular economy model was proposed. Next, several tools were developed to aid a designer with the application of circular product design. The tools were tested and validated with Philips designers and engineers. A Philips case study was used in the development and application of the tools.

Introduction

Circular Economy (CE) describes a model of closing material loops in an economically attractive way to decouple wealth from resource usage. The model addresses the challenges of today where the consumption of a growing population is leading to unsustainable usage of finite resources with increased price volatility and higher prices (Ellen MacArthur Foundation, 2012). CE is based on five principles, inspired by natural systems: design out waste, build resilience through diversity, shift to renewable energy sources, think in systems and think in cascades (Ellen MacArthur Foundation, 2013). In the case of products changes can be made by business strategies (e.g. leasing products) and product design (e.g. longer lasting products).

The concept of CE is certainly not new as it is derived from several schools of thought such as biomimicry, cradle-to-cradle, the blue economy, industrial ecology and the performance economy. So what exactly is circular product design? There are only a few definitions presented in literature:

> *"Circular design, i.e. the improvements in material selection and product design (standardisation and modularisation of components, purer material flows, and design for easier disassembly)"* (Ellen MacArthur Foundation, 2012).

> *"Circular product design: Elevates design to a systems level (1), Strives to maintain product integrity (2), is about cycling at a different pace (3), explores new relationships and experiences with products (4) and is driven by different business models (5)"* (Bakker, Hollander, van Hinte, & Zijlstra, 2014)

These descriptions provide a general overview of what circular product design is but are not clearly related to the CE model and are not part of a framework with more detailed information to aid product designers. Design research for circular economy has so far mainly been limited to referring to existing fields of research such as design for disassembly, remanufacturing and recycling. However, guidelines from different areas of expertise sometimes overlap. Modularity as a design principle is part of the disassembly and remanufacturing literature (Mital, Desai, Subramanian, & Mital, 2008) (Ijomah, McMahon, Hammond, & Newman, 2010) while disassembly as a design principle can be found in the modularity and remanufacturing literature. Of the several Design for Excellence (DfX) methods remanufacturing is the most encompassing, including disassembly, cleaning, reassembly and testing guidelines. Remanufacturing however is approached from a single product view lacking the system approach thinking of CE. The implications of combining these fields in the context of circular economy from a product design perspective however have remained largely unexplored. Some examples exist where guidelines from different DfX disciplines have been combined in a CE context (Poppelaars, 2013) (University of Cambridge, Institute for Manufacturing , 2013), but give mainly a summary of guidelines and lack new insight. Furthermore, available aids for product designers are limited.

Therefore this paper will aim to bring a clear understanding of circular product design and present a framework and aids for product design in a circular economy.

The central research question is: "What is circular product design and how can it be applied in the design process?"

Methodology

The results are based on insights gained during a TU Delft, Faculty of Industrial Design Engineering Master graduation project at Philips in Eindhoven, The Netherlands, in 2014. A literature review led to the development of the guideline overview. Interviews and workshops with experts at Philips and the design of a concept luminaire were used to develop and verify the results. B2B indoor LED lighting was used as a case study for the development and application of the framework. The research approach was taken from product design perspective, leaving out business related aspects and primarily focused on the technological lifecycle to ensure manageability.

Results

Adapted circular economy model

In order to describe a circular product design framework a set of definitions needed to be developed that are all inclusive, fully applicable to product design and with a single interpretation of the terminology used. The currently best known CE model (Ellen MacArthur Foundation, 2013) is not all inclusive (lack of time aspect), not fully applicable to product design (reuse/redistribute circle) and there are multiple interpretations of the terminology used (reuse, refurbish, remanufacture) resulting in misunderstanding and discussion. Therefore, an adapted model is proposed (Figure 1) from a product design perspective, the circular product design model. The five main characteristics will now be explained, from the inner loop to the outer loop.

Future proof

CE addresses the unsustainable resource usage by closing the loop via several circles. This only works if all resources can be fully recycled without loss of quality and the whole system runs on renewable energy sources. Without those conditions a time aspect needs to be included to focus on slowing down the process. This could be done by reducing the need for new products, for instance by making longer lasting (functional) products that will be used longer (desirability), i.e. future proof.

Disassembly

Disassembly is the first step in most actions performed to the product in order to either extend its lifetime or to give a new life to the materials. Optimizing product disassembly can best be done at the design stage where 80-90% of disassembly gains are determined (Desai & Mital, 2003) in contrast to optimization of the disassembly processes. For maintenance and remake non-destructive disassembly should be prioritized, destructive disassembly is more appropriate for recycling (Peeters, Vanegas, Dewulf, & Duflou, 2012). To avoid overlap between the circles and its importance to the design process disassembly is mentioned as a separate topic. Disassembly can be subdivided into connections and product architecture. While the literature mostly discusses fasteners (Peeters, Vanegas, Dewulf, & Duflou, 2012) (Mital, Desai, Subramanian, & Mital, 2008) the word connections removes the restriction in limiting thinking to fasteners. Connections can also be made without fasteners, e.g. by a form fit or welding. The product architecture facilitates the ease and speed of disconnecting those connections.

Maintenance

Maintenance is the prolonged use of products and consists of all aspects related to delivering performance for as long as possible in the use phase. This includes cleaning, repair, upgrade and lifetime prognostics. From a design perspective, optimal maintenance also includes designing a product with lifetime prognostics, which allows predicting the future performance of a product. Such predictive tools can include tracking of use conditions and can be a strong enabler for service-based business.

Remake

Remake is the prolonged use of components and consists of all actions performed when a product returns back from the customer.
Remake is used as an umbrella term for refurbishment, remanufacturing and reconditioning since they are interpreted different per industrial sector (Parker, 2007). Modularity is of key importance: modules should be defined to allow effective repair and upgrading, which also implies that common interfaces between modules are desired. Also in this stage lifetime prognostics, i.e. assessment of the remaining reliability is of importance. Reverse logistics whereby additional transportation changes the economics can influence design decisions on the product (e.g. improved stackability) and location (e.g. local production).

Recycling

Recycling consists of material recovery at end-of-life and is the last option to recover any remaining value that a product or component has. This means that, in contrast to all previous aspects, recycling in CE is a mandatory requirement for every product. In recycling disassembly for low-value products is often destructive. Partial non-destructive manual disassembly can be used to achieve higher economic yields due to better material separation. Recyclability is determined primarily by the choice of materials (although this also depends on developments in the recycling industry) and the extent to which they

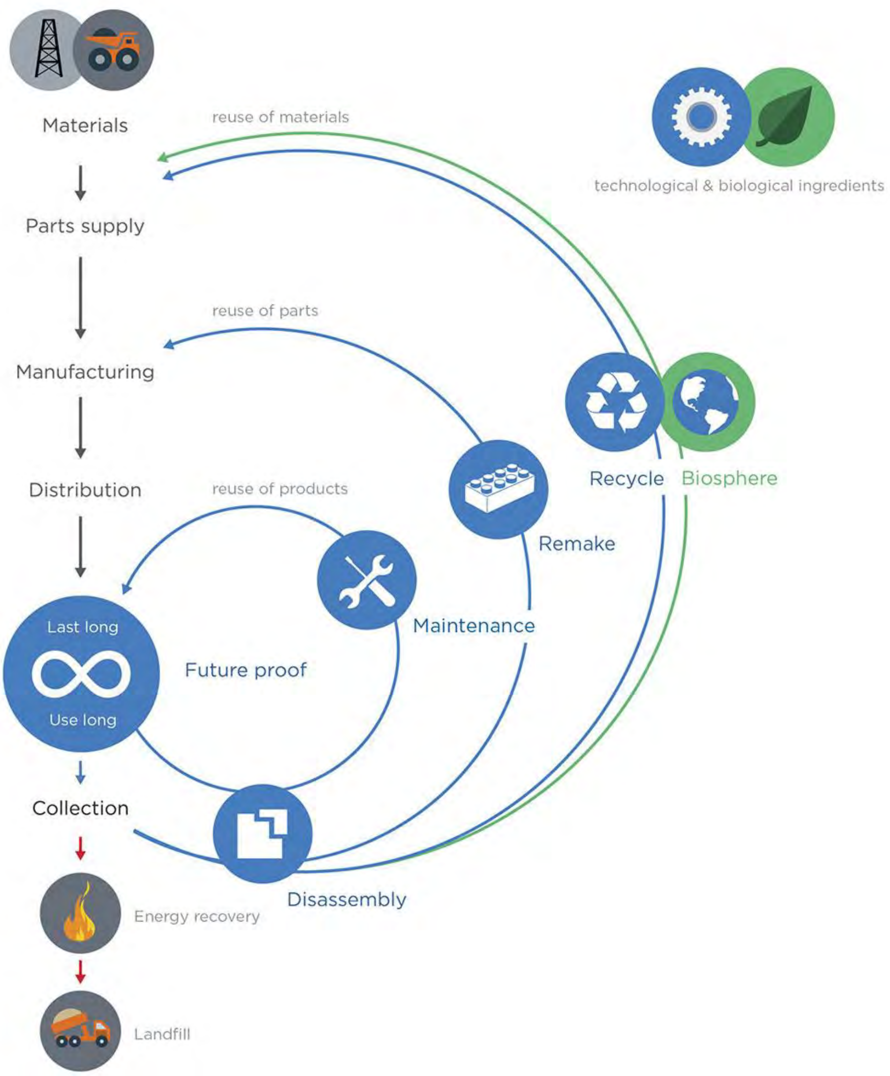

Figure 1. Circular product design model.

can be separated from each other. Electronic boards, given their high complexity and high materials value, pose a special case and should preferably be retrieved as an entity from the device.
The bio cycle with biological ingredients is simplified and placed next to the recycling circle. From a design perspective the ability to separate and recover materials is important.

Reuse is ill-defined, easily misunderstood and is therefore not used in the circular product design model. A recycling company and a second-hand shop both can talk about reuse, but will use the word in a completely different way. In the CE model every circle returns to an earlier point in the product life cycle, which is effectively the reuse of a product, component or material. Direct reuse by reselling/redistributing where a product is used for the same purpose without any changes is part of a business model and not that of product design, although such a business model will make longevity of products more attractive.

With the circular economy model adapted for product design and the derived five main topics a better understanding of criteria important to circular product design is obtained. Circular product design enables products that are future proof (last long and use long) and that can be disassembled, maintained (products), remade (components) and recycled (materials).

Vision

The circular product design vision (Figure 2) presents a quick overview of the five topics in their context. The tool could be used as a quick introduction, a discussion tool, a tool used in a workshop for a short design exercise or as a memory aid during the design process.

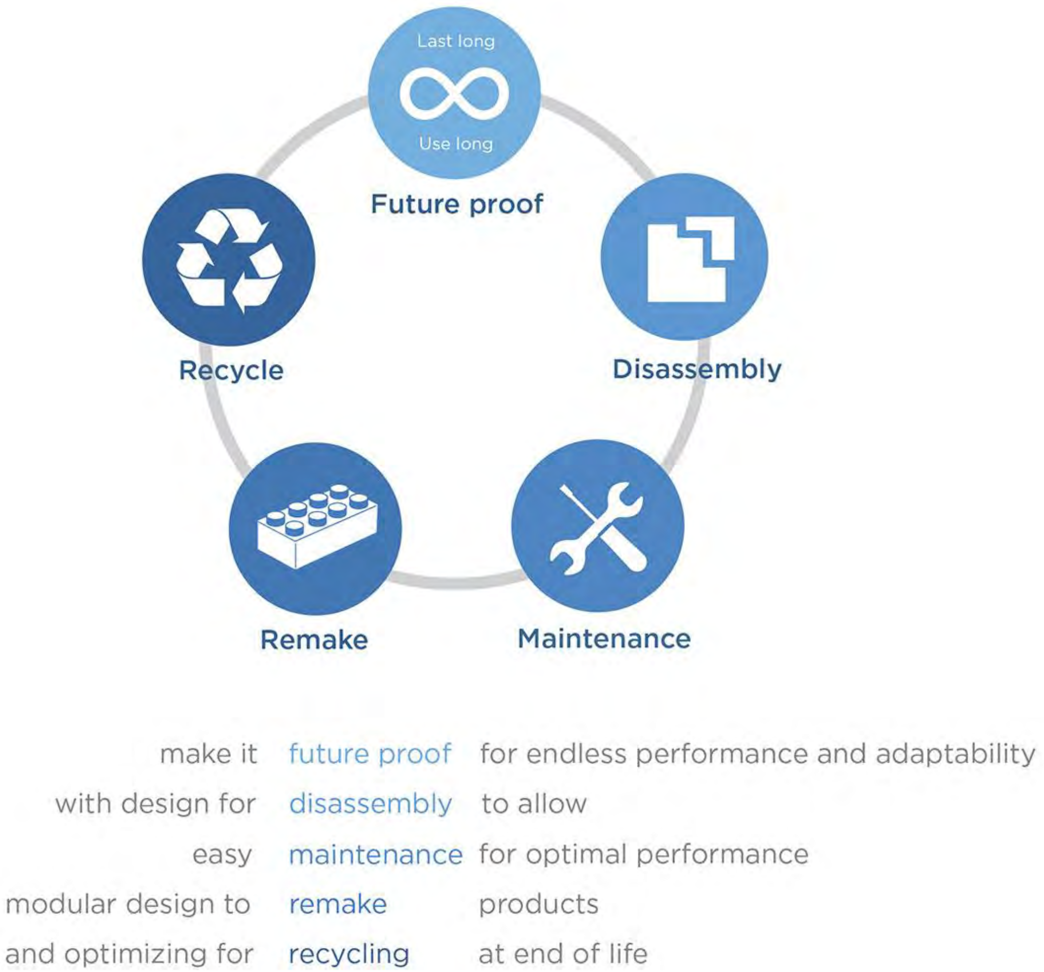

Figure 2. Circular product design vision.

Guidelines

The guideline list overview (Figure 3) groups and orders all relevant topics for circular product design. The extended list with guidelines from literature (Balkenende, Aerst, Occhionorelli, & van Meensel, 2011) (Desai & Mital, 2003) (Hata, Kato, & Kimura, 2001) (Hultgren, 2012) (Ijomah, McMahon, Hammond, & Newman, 2010) (Mital, Desai, Subramanian, & Mital, 2008) (Peeters, Vanegas, Dewulf, & Duflou, 2012) (Peeters & Dewulf, 2012) (Sundin, 2004) (Mulder, Basten, Jauregui Becker, Blok, Hoekstra, & Kokkeler, 2014) can be found in Appendix A. Disassembly is part of every circle and thus represented by a line on the left side extended downwards, divided in non-destructive and destructive disassembly. With the system approach of the CE model additional guidelines are included that are not part of DfX literature. Anticipating legislation could reduce the risk of not being allowed to use certain components or materials in the future. For example, legislation might be introduced to restrict the use of brominated flame retardants (Burridge, 2015) or to remove the PCB from

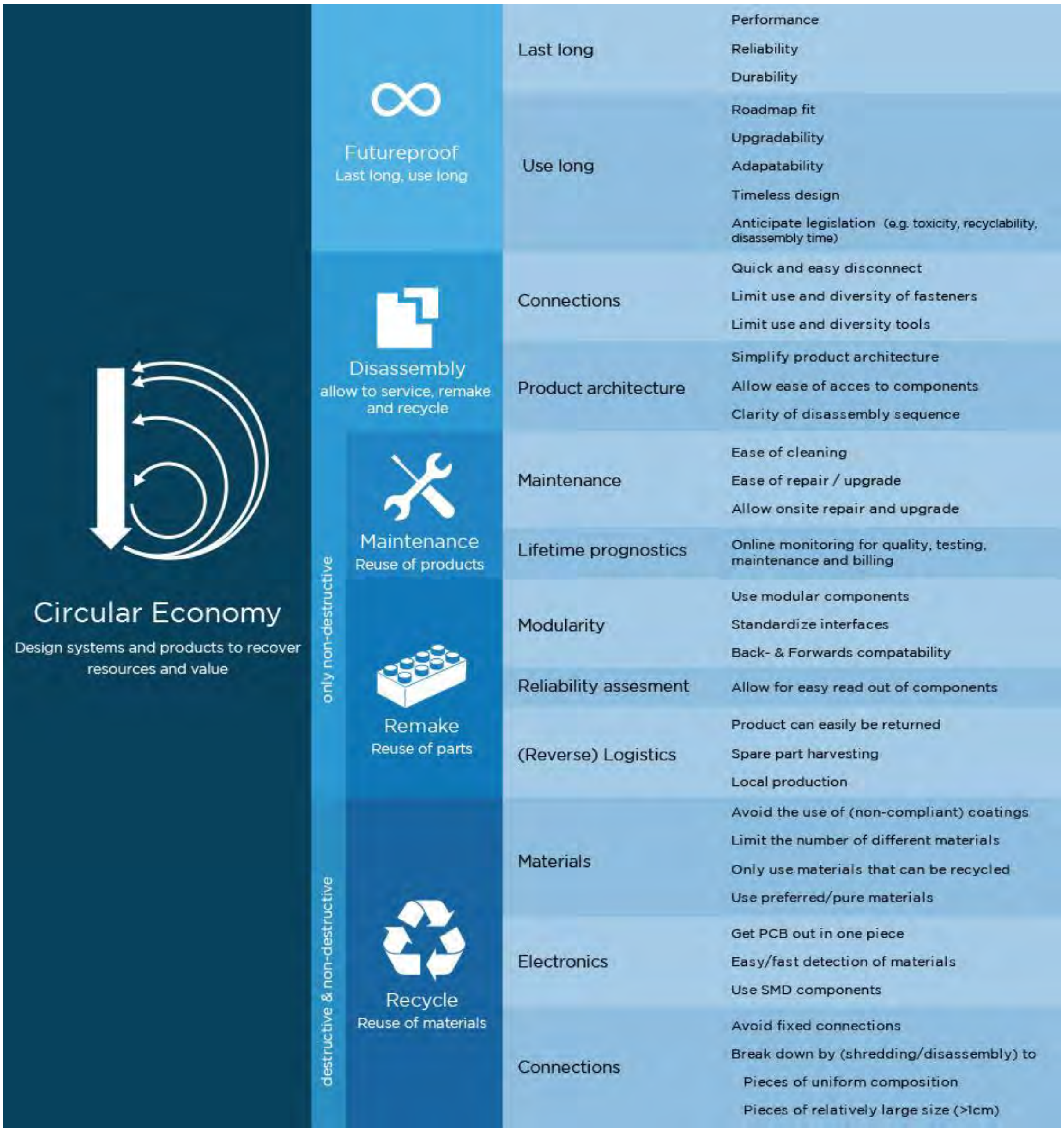

Figure3. Guideline list overview.

televisions by manual disassembly within 180 seconds (European Commission, 2012). The five main topics are further separated in sub-categories and sub-sub categories with respective guidelines.

Spider map

The guidelines can be translated into a spider map (Figure 4) for a more detailed tool to use in the design process. Words are placed along the axes to show an increase of circularity, i.e. describing aspects that are likely to aid in optimal resource usage and recovery. The tool can be used in the first phases of the design process when no detailed information is available yet. The spider map was tested in a workshop and design meeting with Philips employees (consisting of 3 product designers, 4 managers and 4 engineers, with different levels of CE knowledge). The Spider Map enabled the discussion of the ambitions for a new project, to show a way towards circular product design, to agree on terminology and to compare with other products. For example, the spider map was projected by a beamer and regularly referenced to during the workshop to discuss on which areas the product needs to be improved upon and to what degree. In contrast to a similar earlier workshop without the spider map there was more structure in the discussion and less time spent on defining the aspects that need to be taken into account for CE.

Concept design

The circular product design approach has been applied to the concept design of a B2B indoor luminaire (Figure 5 and 7). As a design exercise for testing and validating the framework the design goal was to design a luminaire that is optimally suited for a CE. The LEDs and driver are quick and easy to disassemble and accessible from underneath. This addresses one of the major limitations of

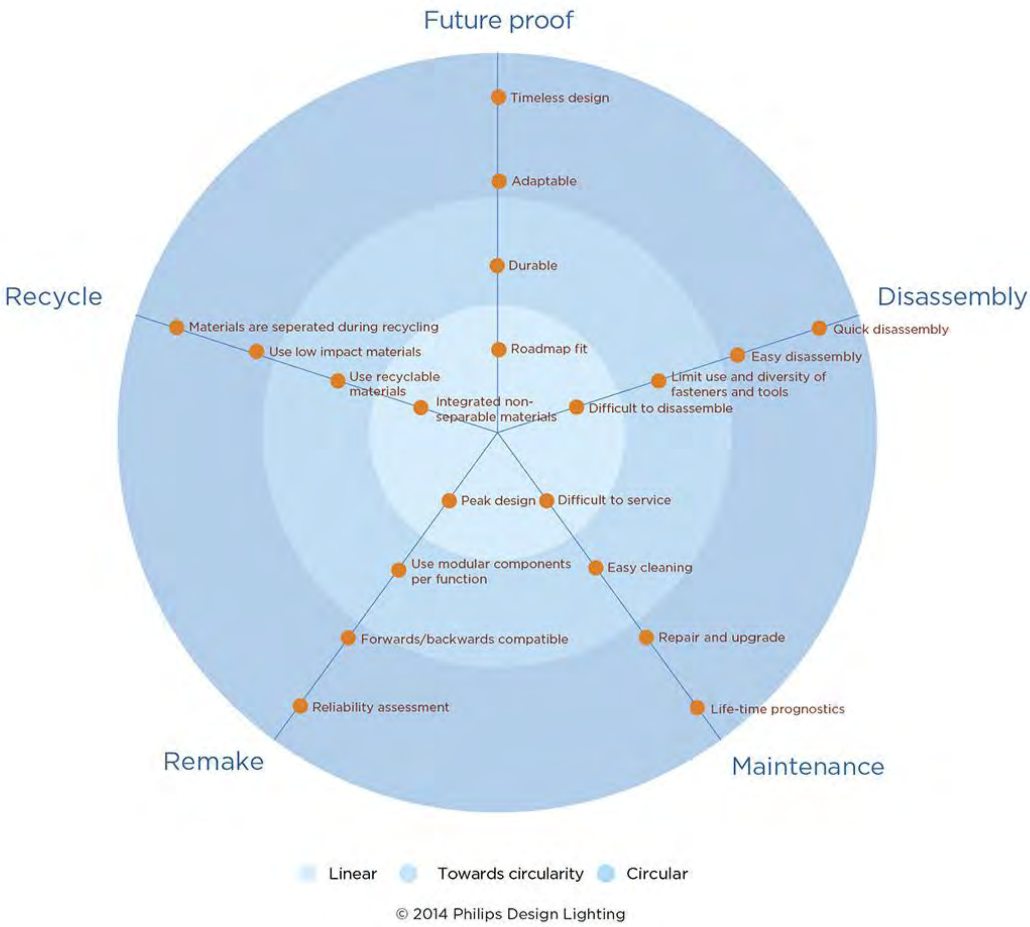

Figure 4. Spider map.

most B2B luminaires where LEDs are either non-replaceable or not in a cost-effective way. The driver includes power over Ethernet for life time prognostics. Both allow for improved maintenance. The modular approach benefits remake with the ease of access to all modules and allowing for easy reliability assessment. For recycling the same type of material is chosen for the backbone and housing, preferably aluminium for its high recyclability and, based on a quick estimation, relatively low impact. The electronics are easily separated by hand.

Initially, in the ideation phase, several product types were explored by going through each topic of Figure 2 while keeping in mind their relationship to each other by reading the sentences. Figure 1 continued to remind that towards the inner circle the most value is retained. For the highest chance of optimal resource use it made sense to take a systems approach by using a modular platform allowing a wide range of configurations and applications including retail, office and industry. This was mainly driven by Future Proof: what can increase the survival chance of a luminaire to be used long the most? This would need a shift from product to part obsolescence. The guideline list was primarily used after the ideation phase to see which guidelines could be further applied. The spider map has been used to verify the concept design was indeed better suited for a CE than several reference luminaires (Figure 6).

Conclusions

In this paper we outlined the exploration of circular economy from a product design perspective. A new understanding of circular design is presented, consisting of the following five main topics: future proof, disassembly, maintenance, remake and recycling. Three tools have been presented that aid the product designer in different ways. The circular design vision can be used for a quick-scan approach, the guidelines for detailed design and the spider map for comparing products and as a discussion tool with experts from other areas.

It should be noted, however, that the guideline list is not a list of independent parameters. For instance, an aspect like modularity is not only important to allow for remake, but also is enabling adaptability and upgradability (future proof) and maintenance. Furthermore, this research has focussed on the technological nutrient cycle and greatly simplified the biological cycle. Design guidelines for biological materials, if applicable, therefore are currently not present. In addition, note that these guidelines are not meant to be exhaustive.

The framework does not include renewable energy use. Product designers usually have no control over the choice of energy source (except for e.g. a built-in solar panel). The energy efficiency can be influenced, although that might be better suited as part of an ecodesign approach.

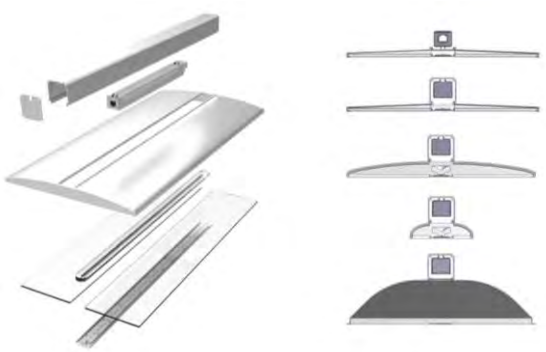

Figure 5. Concept luminaire.

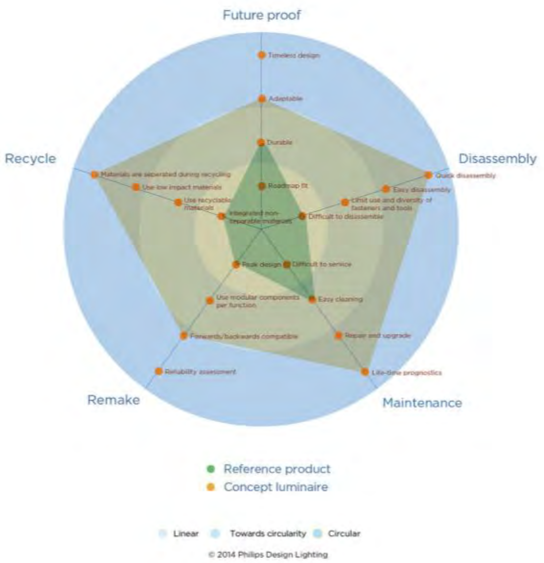

Figure 6. Score for concept luminaire and reference luminaire.

The spider map works well as a tool to show the degree of circularity and to compare between products. However, in the framework it gives the impression that all topics are

Figure 7. Application in office & industry

equally weighted and independent which is not entirely true. Recycling is the last option to recover any remaining value that a product or component has. This means that, in contrast to the other topics, recyclability is a mandatory requirement for every product. Placing recycling at top, using a different color or adding a subtitle might give recycling added importance. Further research and more case studies will be necessary for further testing and validation of the tools.

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Appendix A – Full guideline list

Category	Sub-category	Goal	Means	Source
Futureproof last long and use long	Long lasting	Performance		
		Reliability	Design out moving parts	(Mulder, et al. 2014)
			Design for under stressed use	(Mulder, et al. 2014)
			Provide redundancy	(Mulder, et al. 2014)
			Over dimension critical components	(Mulder, et al. 2014)
		Durability	Wear resistance	(Sundin, 2004)
			Use assembly methods that allow disassembly without damage to (reusable) components.	(Ijomah, et al., 2010)
			Do not use coated, painted or plated components	(Mulder, et al. 2014)
			Prevent discolouring	
			Ensure that fasteners' material are similar or compatible to that of base material thus limiting opportunity of damage to parts during disassembly.	(Ijomah, et al., 2010)
			Aging and corrosive material combinations need to be avoided, since disassembling them cleanly and efficiently (due to their tendency to corrode, spread corrosion, and break off inside the product) often is difficult.	(Mital, et al., 2008)
			Protect subassemblies from corrosion, the reasons being the same	(Mital, et al., 2008)
	Long in use	Roadmap fit	Ensure a long -term roadmap is available	
		Upgradability	Use materials and assembly methods that do not prevent upgrade and rebuilding of the product.	(Ijomah, et al., 2010)
			Structure to facilitate ease of upgrade of product.	

		Adaptability	Ensure a long -term roadmap is available	(Ijomah, et al., 2010)			
			Prevent product obsolescence (user needs)	van den Berg			
		Timeless design	Emotional durable design (user desire)				
		Anticipate legislation	(e.g. toxicity, recyclability, disassembly time)				
Disassembly non-destructive	Connections	Quick and easy disconnect	Use easy to disassemble connections				
			Apply loose fits for internal components	(Peeters, et al., 2012)			
			Avoid welding and adhesive between sub-assemblies	(Ijomah, et al., 2010)			
			Use joining methods that allow disassembly at least to the point that internal components and subsystems requiring it can be accessed for testing before and after refurbishment.	(Ijomah, et al., 2010)			
		Limit use and diversity of fasteners	Minimize the number of fasteners used in an assembly	(Mital, et al., 2008)	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)
			Minimize the types of fasteners used in an assembly and standardize the fasteners used	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)	
			Fasteners need to be easy to remove or destroy.	(Mital, et al., 2008)			
			Allow easy access and identification of the fasteners	(Mital, et al., 2008)	(Sundin, 2004)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)
			Consider the use of fasteners incorporating an active disassembly or embedded disassembly functionality.	(Balkenende, et al., 2011)			
		Limit use and diversity of tools	Limit the number of tools needed and tool changes	(Balkenende, et al., 2011)			
			Make it possible to use simple tools for disassembly	(Balkenende, et al., 2011)			
	Product architecture	Simplify product architecture	Minimize the complexity of the product structure	(Desai & Mital, 2003)	(Ijomah, et al., 2010)		
			Select a product structure which allows a sequence independent disassembly	(Balkenende, et al., 2011)			
			Minimize the number of components used in an assembly	(Mital, et al., 2008)	(Desai & Mital, 2003)	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)

			Optimizing the spatial alignment between various components to facilitate disassembly without jeopardizing assemblability,	(Desai & Mital, 2003)		
			At least one surface needs to be left available for grasping.	(Mital, et al., 2008)	(Sundin, 2004)	
			Simplify and standardize component fits	(Ijomah, et al., 2010)		
		Ease of access to components	Arrange components for ease of disassembly	(Ijomah, et al., 2010)	(Balkenende, et al., 2011)	
			Consider making the plane of access to components the same for all components	(Mital, et al., 2008)	(Sundin, 2004)	(Balkenende, et al., 2011)
			Avoid the need to turn the product in the disassembly process	(Mital, et al., 2008)	(Sundin, 2004)	(Balkenende, et al., 2011)
			Metal inserts in plastic parts should be avoided, since this increases material variety and part complexity and necessitates multiple directions and complex movements in disassembly. Applicable if meant for over moulding	(Mital, et al., 2008)		
			Use assembly methods that would allow disassembly at least to the point that internal components and subsystems requiring work can be accessed.	(Ijomah, et al., 2010)		
		Clarity of disassembly sequence	Identify components assembly sequence.	(Ijomah, et al., 2010)	(Sundin, 2004)	
			Identify components requiring similar assembly tools and techniques.	(Ijomah, et al., 2010)	(Sundin, 2004)	
			Reduce complexity of reassembly	(Ijomah, et al., 2010)		
Maintenanc	Maintenance	Ease of cleaning	Ensure product surfaces are smooth and wear resistant.	(Ijomah, et al., 2010)		
			Ensure that all parts to be cleaned are easily accessed.	(Ijomah, et al., 2010)	(Peeters, et al., 2012)	(Sundin, 2004)
			Use material that would survive cleaning process e.g. ensure that material melting	(Ijomah, et al., 2010)		

	e Reuse of products			point is higher than clean process temperature.			
				Limit the number of material types per part.	(Ijomah, et al., 2010)		
				Identify components requiring similar cleaning procedures and cleaning agents.	(Ijomah, et al., 2010)	(Sundin, 2004)	
			Ease of repair	Allow for easy and quick access to parts prone to failure	(Peeters, et al., 2012)	(Ijomah, et al., 2010)	(Sundin, 2004)
				Avoid assembling components with a different life duration	(Balkenende, et al., 2011)		
			Allow onsite repair and upgrade	Allow on-site maintenance			
		Lifetime prognostics	(Online) monitoring for quality, testing, maintenance and billing				
non-destructive	 **Remake** Reuse of components	Modularity	Use modular components	Use modular structure so that obsolescence occurs with components rather than with entire product.	(Ijomah, et al., 2010)	(Mital, et al., 2008)	(Ijomah, et al., 2010)
				Do not combine components that have different physical life.	(Hata, et al., 2001)		
				Do not combine components that have different intervals for maintenance and upgrade.	(Hata, et al., 2001)		
				Group components in sub-assemblies according to reuse, reconditioning or remanufacturing potential	(Balkenende, et al., 2011)		
				Concentrate compatible material groups in separate subassemblies of a product	(Mital, et al., 2008)	(Balkenende, et al., 2011)	(Hata, et al., 2001)
				Allow customization by grouping components in liberally	(Balkenende, et al., 2011)		
				Combinable subassemblies	(Balkenende, et al., 2011)		
			Use standard interfaces	Standardize parts	(Ijomah, et al., 2010)		
				Standardize interfaces	Maarten		

			Back- & forwards compatibility		Nestor Palma		
		Reliability assessment	Allow for easy testing of components	Standardize test procedures	(Ijomah, et al., 2010)		
				Structure for ease in determining component condition	(Ijomah, et al., 2010)	(Sundin, 2004)	
				Structure so testing is sequential, mirroring reassembly order	(Ijomah, et al., 2010)		
				Minimize the disassembly level required to effectively test components	(Ijomah, et al., 2010)		
				Clearly identify component load limits, tolerances and adjustments	(Ijomah, et al., 2010)	(Sundin, 2004)	
		(Reverse) logistics	Product can easily be returned	Ensure products can be stacked			
				Ensure products can safely be transported			
				Minimize product volume			
			Allow for spare part harvesting				
			Local production				
non-destructive & destructive	**Recycling** Reuse of material	Materials	Avoid the use of (non-compliant) coatings	Any secondary coating processes, such as painting, are to be avoided, since they inhibit access to and removal of components	(Balkenende, et al., 2011)	(Mital, et al., 2008)	(Hultgren, 2012)
			Limit the number of different materials	Minimize the number of material types used in an assembly	(Balkenende, et al., 2011)	(Ijomah, et al., 2010)	(Hultgren, 2012)
			Only use recyclable materials		(Balkenende, et al., 2011)	(Hultgren, 2012)	
			Use preferred/pure materials	Increase the use of common materials	(Balkenende, et al., 2011)	(Desai & Mital, 2003)	
			Allow material separability	Consider the material compatibilities to eliminate the need of separation for recycling	(Balkenende, et al., 2011)		
				Allow easy material identification	(Balkenende, et al., 2011)	(Mital, et al., 2008)	(Sundin, 2004)
				Add non-contamination markings for the ease of sorting and recycling	(Balkenende, et al., 2011)	(Mital, et al., 2008)	

				Any harmful materials, if functionally important, should be grouped together into subassemblies for fast disposal.	(Balkenende, et al., 2011)	(Mital, et al., 2008)
				Do not use fasteners that are not compatible with the connecting components. Fasteners are recycled together with the host component; therefore choose plastic fasteners for plastic and metal fasteners for metal to avoid polluting other material streams or end up in the waste fraction	(Hultgren, 2012)	
		Electronics	Get PCB out in one piece		(Balkenende, et al., 2011)	
			Easy/fast detection of materials		(Balkenende, et al., 2011)	
			Use SMD components		(Balkenende, et al., 2011)	
		Connections	Avoid fixed connections	Prefer snap-fits for plastic components (particularly housing), to allow easy liberation of materials	(Balkenende, et al., 2011)	(Hultgren, 2012)
				Use a detachable power cord instead of a permanently fixed one	(Hultgren, 2012)	
			Break down by (shredding/disassembly) to	If connections are applied that enclose materials permanently, apply gaps and or break-lines to the enclosing material to enable liberation during shredding	(Balkenende, et al., 2011)	(Hultgren, 2012)
			Pieces of uniform composition		(Balkenende, et al., 2011)	
			Pieces of relatively large size (>1cm)		(Balkenende, et al., 2011)	