CIRCULAR DESIGN APPROACH FOR INDUSTRIAL PRODUCTS

Making product designs more circular enables in the implementation of various circular strategies. In this white paper, an approach for the generation of circular design guidelines utilizing circular design principles is presented and how these design guidelines can be used to generate various circular design solutions for automotive wire harness components

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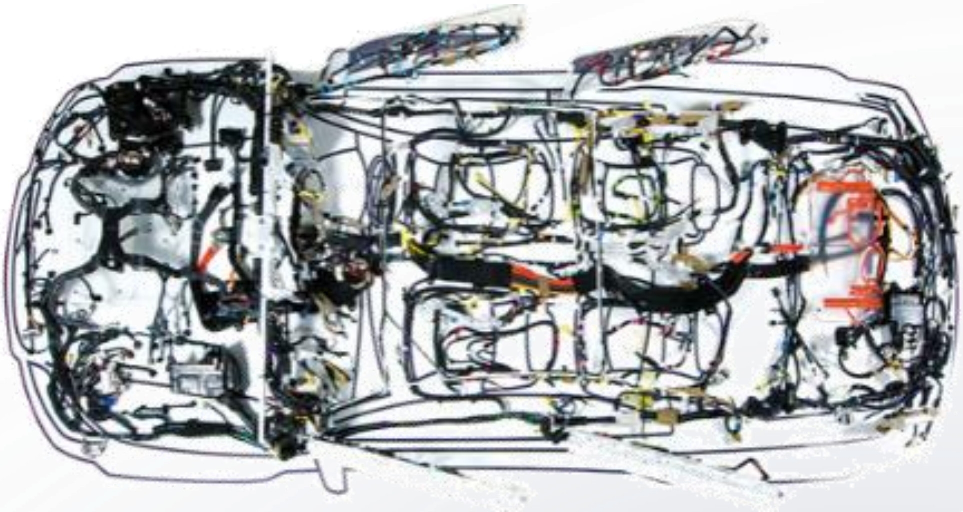

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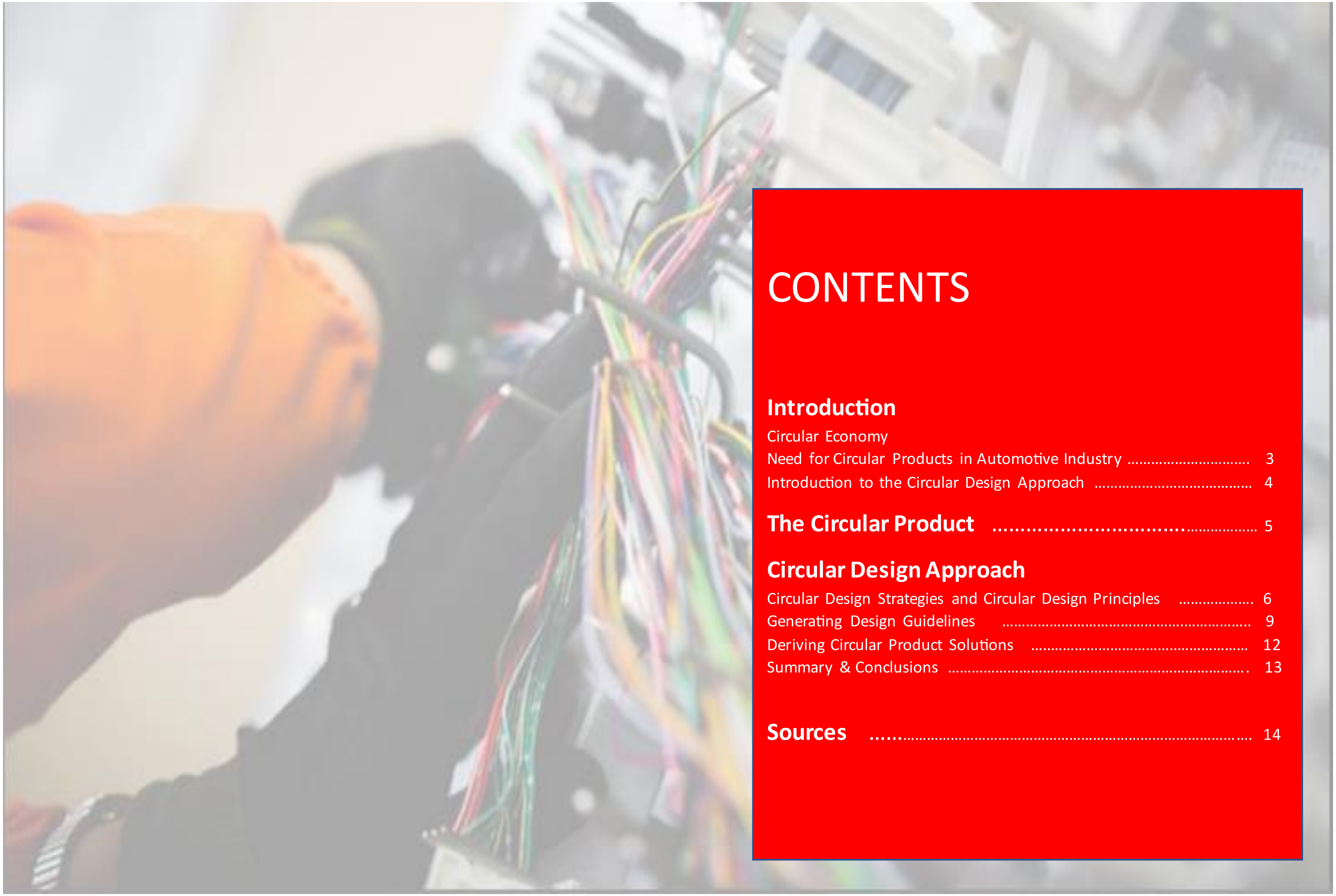

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INTRODUCTION

> **Circular Economy** has gained significance in the last decades in the face of the ever-changing climate conditions, environmental degradation, resource depletion, and increasing demands from legislation via the Circular Economy Action Plan(CEAP) and related policies/directives. In contrast to a Linear Economy where products are manufactured for only a single life and treated as waste after its use, the Circular Economy model emphasizes on slowing, closing, and narrowing material and energy loops to keep resource inputs, emissions, and leakages(wastes) to a bare minimum [7]. As defined by the Ellen Macarthur foundation, the Circular Economy represents an 'industrial economy that is restorative or regenerative by intention and design'. Considering that the annual electrical and electronic wastes generated in 2018 from businesses were more than 80,000 tons in Germany alone, the need for automotive products including EEEDS products to be suited to the Circular Economy model are becoming increasingly important. Although strategies like Recycling, Repair and Reuse have seen a major push following further circular strategies such as Preventive maintenance, Refurbishing, Remanufacturing, Repurposing could bring to the fore cost-effective solutions that can combine resource-efficiencies with optimized time-to-market and environmental benefits for many products. These further circular strategies open up a new paradigm to the Circular Economy model previously defined by the European Commission as they adopted an ambitious Circular Economy Package in 2015. These different circular strategies come into play during the different stages of the product life cycle as shown in the **Fig.1** here. While strategies such as Refuse, Rethink and Reduce play a role during the design phase of the product life cycle, Remanufacturing & Refurbishing involve, to an extent at least, the production stages for the parts manufacturer.

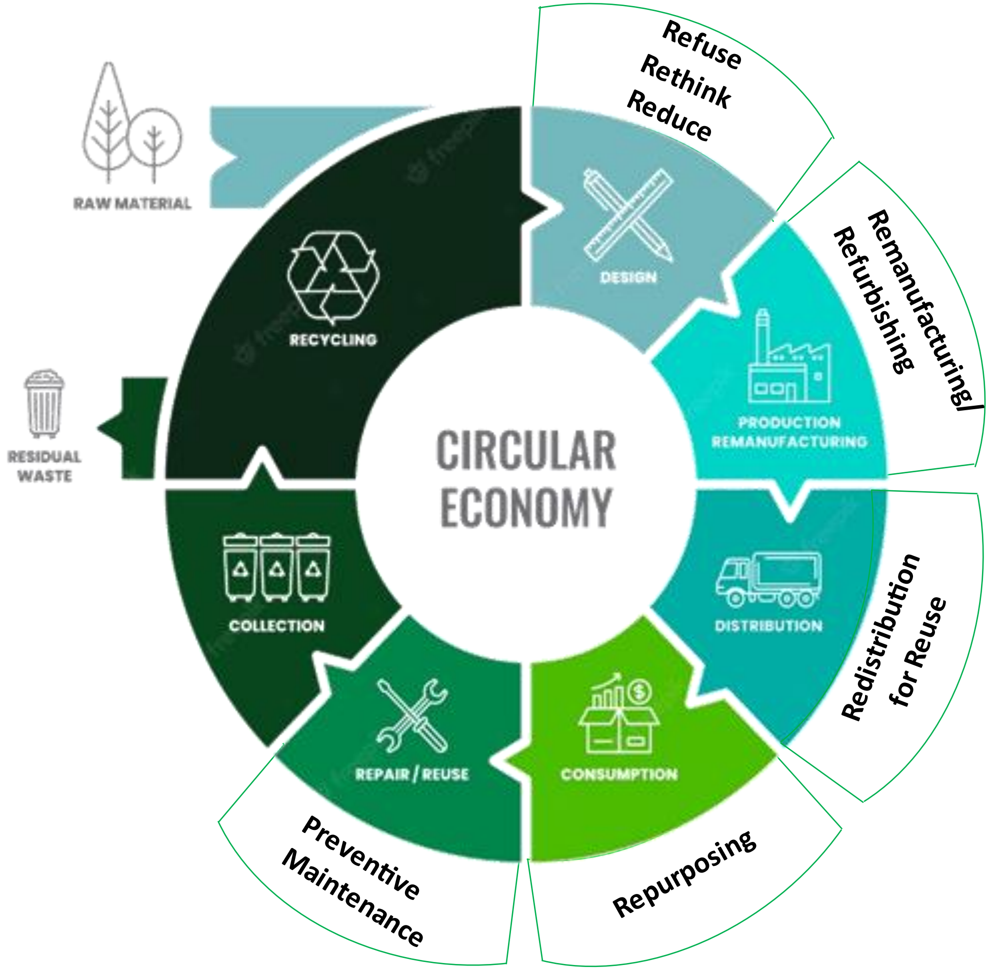
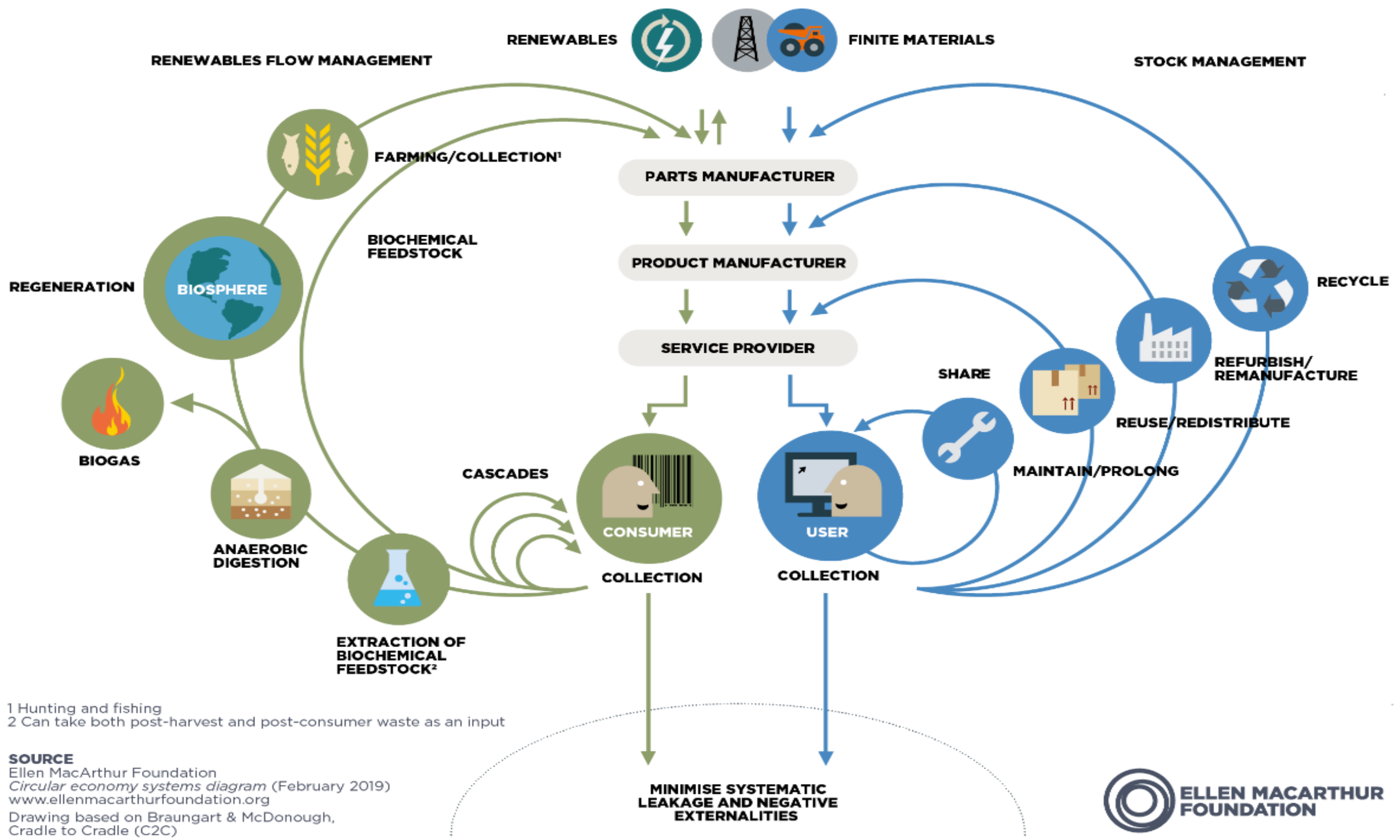


Fig.1 Extension of the Circular Economy paradigm



The classic butterfly diagram of The Ellen MacArthur Foundation highlights two main types of cycles- the Technical and the Biological cycles or loops with different stakeholders involved with each of these cycles imbibing 3 basic principles driven by design

- **Eliminate** waste and pollution
- **Circulate** products and materials
- **Regenerate** nature

Fig.2 Butterfly diagram of Circular Economy

There are many measures being undertaken across industries with the Redesign and novel conception of current-day products to make them more suitable for the circular economy, not excluding the revision of associated business models to enable their recirculation. However, specific application or translation of circular design principles into guidelines and subsequently in the embodiment design of the products still remains an open topic to quite an extent [9]. This paper therefore looks into how such circular design principles, many of which have been established widely for the implementation of different strategies like Reuse, Repair & Maintenance, Refurbishing and Remanufacturing, can be translated into design guidelines to enable the conception and/or redesign of current-day products bringing forth circular product solutions. Generated design guidelines could also be used to guide collaborative development which is primordial to realizing circular solutions with multiple stakeholders spread across the value network.

THE CIRCULAR PRODUCT

For products to be attuned to the Circular Economy, a clear understanding of the circular strategies is very important. Within the Circular Economy 3.0 concept, the ***3Rs*** can be seen reorganized into a ***10R hierarchy*** ranging from ***R0 – Refuse to R9 – Recover*** associating themselves to different *'Value-retention'* options as they aid in slowing, narrowing and/or closing the loops, enabling parts, components, or materials to be reutilized or recirculated over different stages of the product life cycle as indicated in **Fig. 1** [10], [12], [13],[8]. Since value retention could be seen as an opportunity to (re)utilize the product's residual value at its End-of-Life, the 10Rs are also termed as Circular or CE strategies.

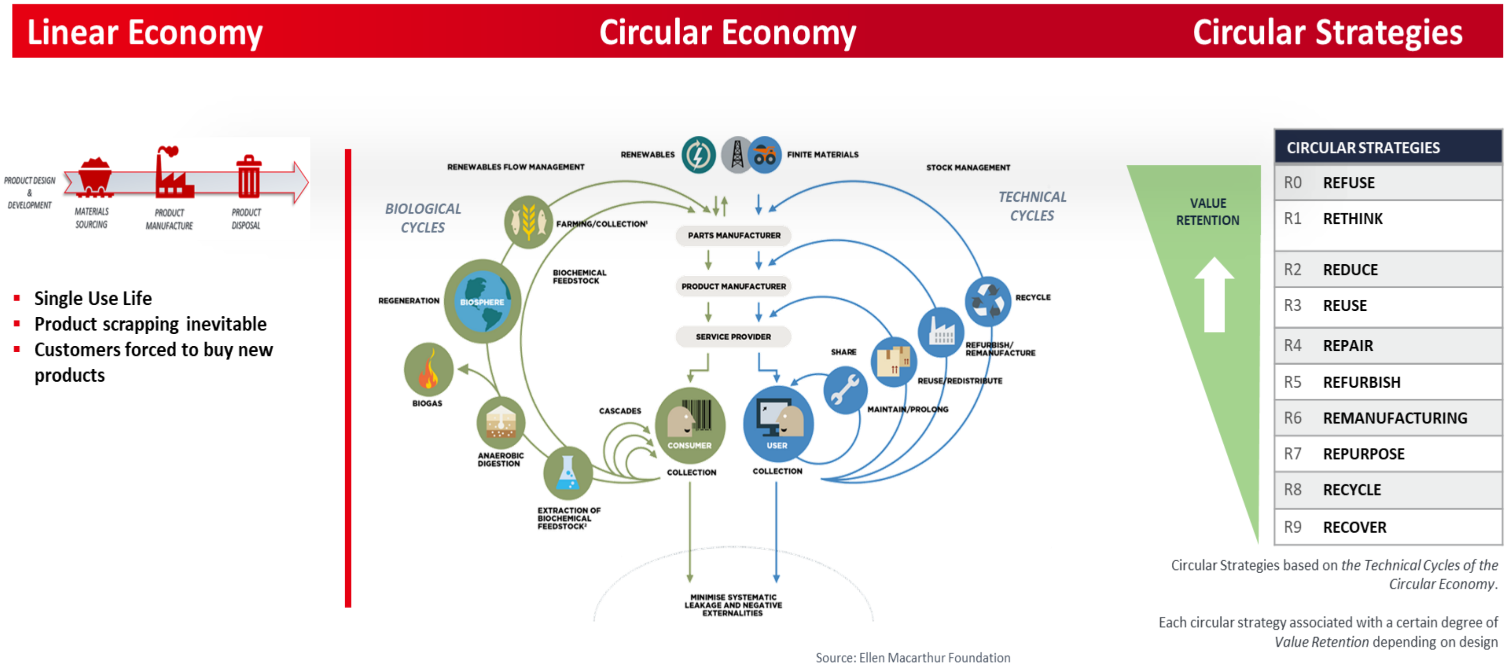


Fig.3 Options for Product Value Retention for transitioning towards Circular Economy

Product complexity refers to the maturity of the product or the part in question in terms of its selected application.

Higher the product complexity involved, higher would be the potential of value-retention of the product with the respective circular strategy implementation.

Products that are designed to realize one or more circular strategies can be termed **'Circular Products'** and with the level of **value-retention** achieved, the product's **'Circularity'** could be defined.

CIRCULAR DESIGN APPROACH

The Circular Design Approach presented in this white paper takes into account various circular design principles that could be utilized for the realization of any of the circular strategies listed earlier. For the implementation of these circular design principles in a product to make it more circular, generation of guidelines would be necessary. Therefore, this white paper discusses a way such guidelines could be generated as well. Defining the CE-strategies in Table 1 below, considering the framework previously identified by Potting et al. [10] and Reike et al.[8], could be taken as the starting point for the approach. It can also be noticed that moving from R0 to R9 could require an increasing degree of investment, either in terms of money, materials, resources etc.

Circular Design Principles

Since there are up to 9 different CE strategies that could be used to make a particular product more circular, definition of specific aspects of design which would make the product relevant to one or more strategies becomes necessary. Some of these aspects have been indicated amongst many of the DfX design approaches such as Design for Assembly & Disassembly, Design for Environment (DfE), Design for Recycling, Upgradability, Reliability etc. [15] in addition to others such as Design for Attachment & Trust, Design for Ease of Maintenance & Repair and Design for Standardization & Compatibility [13]. Since design principles act like the goals while the design guidelines provide the avenues [16], many of such approaches/design strategies including those from the DfX framework are indicated as circular design principles which can be used to guide the process of circular product design and development for the facilitation of one or more circular strategies[15].
With the addition of few more of such design principles as in Table 2 below, these design principles elaborate upon the three basic principles of Eliminate, Circulate and Regenerate (that also relate themselves to the different circular strategies to quite an extent) and hence can be used to undertake 'Design Rethink' or in other words Rethinking Design to generate circular product designs.

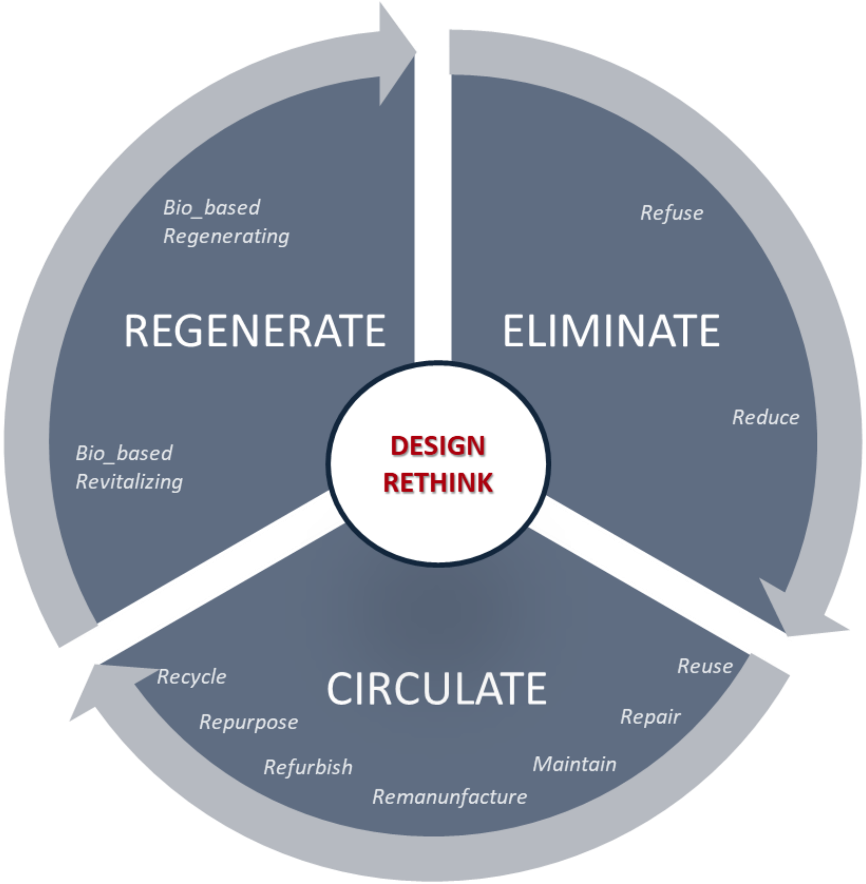
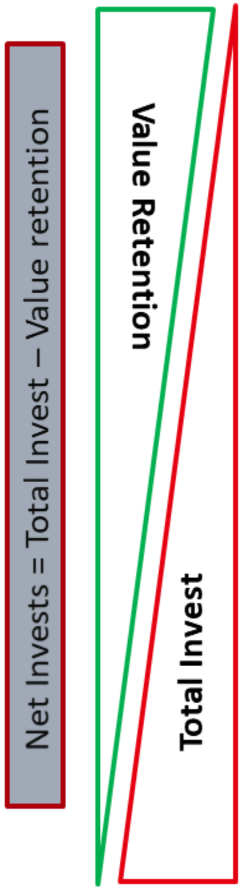


Fig.4 CE Strategies and the 3 basic design principles of Circular Economy



	Circular Strategy	Definition
Smarter Product use and Manufacture	**R0- REFUSE**	Refuse avoidable risks, non-fulfilment of functionalities over multiple lives, toxic ingredients
	R1- RETHINK	Make products fitting for use over multiple life cycles. Making product use more intensive even involving radical redefinition or disruptive design of products
	R2- REDUCE	Reduction of wastes or any other unwanted characteristic of parts/products/materials along with reduction in natural resource consumption and synthetic ingredients
Extend lifespan of products and its parts	**R3- REUSE**	Reuse of parts/modules/complete product for the same/original function by same or another customer without any further processing
	R4- REPAIR	Repair & maintenance of parts that are damaged in the product to bring back product to working condition
	R5- REFURBISH	Restore complete product to ensure or maintain the up-to-date working condition
	R6- REMANUFACTURE	New products providing original function manufactured using parts/modules from products at End_of_Uselife
	R7- REPURPOSE	Further use products or its parts at End_of_Uselife in a new product with a different function
Useful application of materials	**R8- RECYCLE**	(Re)Process materials to obtain the same (high grade) or lower (low grade) quality
	R9- RECOVERY	Incineration of material with energy recovery

Table 1 Definitions for the Circular Economy (CE) Strategies

Circular (CE) Strategy										Circular Design Principles
R0	R1	R2	R3	R4	R5	R6	R7	R8	R9	
X	X	X	X	X	X	X	X	X	X	▪ Refuse alternatives to product parts/modules which compromise product durability, safety & reliability ▪ Refuse alternatives to product parts/modules that are not sustainable and viable only for a single use life ▪ Refuse toxic ingredients
	X	X	X	X	X	X	X	X		▪ Disruptive designs to realise 'Upgradeable' & 'Repurposable' products (Demand_driven Design) etc. for use over multiple lives and for ease of Recycling ▪ Design for Performance - Efficiency, Durability/Robustness, Safety and Reliability ▪ Accurate Prediction & Simulation of Failures and assessements on Parts compatibility
		X		X	X	X		X		▪ Reduction of wastes associated with processing - Manufacturing/END_OF _LIFE processing ▪ Reducing the extent of use of synthetic or non-biodegradable ingredients ▪ Reduce sources of Failure including accidential ▪ Reduce the number of parts, material mixes and Design complexity to bring down manufacturing/processing efforts and eventually carbon footprints
	X	X	X	X	X	X				▪ Reuse of parts/modules at End_of_Life ▪ Design for Modularity with ease of Assembly and disassembly especially of parts that could be reused ▪ Design for Preventive Maintenance ▪ Definition of Optimal Use conditions – Explicit operating conditions for product use to ensure product reuse by another user without any further processing
	X	X		X	X	X	X			▪ Design Modularity for safe assembly, disassembly and reassembly ▪ Design for Modularity to also aid in ease of detection of damaged components and ease of repair ▪ Design for Standardization & Exchangeability, especially of parts that are prone to damage ▪ Design for Self healing/Reconditioning for 'automatic' repair of parts subjected to unfavorable conditions ▪ Design for ease of identification of 'critical' and 'valuable' parts
	X	X			X	X	X			▪ Product ReDesign for Refurbishing incl. Design for Advanced Manufacturing ▪ Design for Inspection & Quality Control for Refurbishing requirements ▪ Design for Standardization & Compatibility ▪ Design for Upgradeability/Customization
	X	X				X	X			▪ Product ReDesign for Remanufacturing incl. Design for Advanced Manufacturing ▪ Design for Inspection & Quality Control for Remanufacturing requirements including quality control/assurance of individual parts/modules ▪ Design for Reprocessability to achieve original quality of parts,modules and entire product ▪ Design Modularity to differentiate between Reusable, Reprocessable, and Exchangeable parts
	X	X	X				X			▪ Design Parts for Multi-use
X	X	X	X	X	X	X	X	X		▪ Utilization of metallic and non-metallic materials which can be easily recycled ▪ Utilization of bio_based recyclable materials for different applications
X	X	X							X	▪ Design for material and energy extraction from scrap mixes ensuring ease of extraction of individual components ▪ Design for secondary fuel generation ▪ Design for low toxic emissions during incineration

Table 2 – Circular Design Principles and their mapping with different circular strategies

Generating Design Guidelines

Design principles can be realized in product designs utilizing specific design guidelines. And this applies to all the circular design principles as well. Such guidelines could be used to enable designers meet the principles defined or targeted for a particular product, as they are set as specific tangible instructions that can be implemented for a specific product/application. Generating and implementing the guidelines generated for such circular design principles would hence aid in deriving circular product solutions that in turn enable in the implementation of associated circular strategies through product design.

For every design principle, there could be one or more design guidelines that can be generated and vice versa. Guideline definition is guided with the clarity provided in the instruction. If a component needs to be reused for instance, the 'how' needs to be answered using the guideline. Hence, Guideline formulation is a very important aspect in design processes.

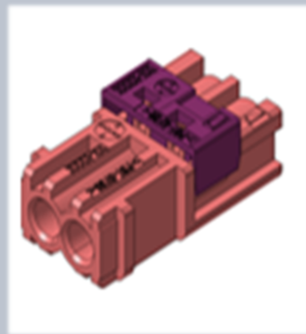
As a first step in the generation of design guidelines, an understanding of the application itself is of paramount importance. Depending on the application, suitable circular design principles need to be chosen since not all design principles can be universally applied to every application. With an understanding of the application, relevant interpretation of the chosen circular design principles can be done to generate associated design guidelines. When considering some applications, it will often be necessary to consider more than one design principle at the same time depending of course on the product/ application. The selection of the design principles would depend on host of factors including criticality of the parts involved, the associated carbon footprints, related Hotspots etc.

Design guidelines are formulated here taking into consideration the host of relevant design principles simultaneously for the specific application. It also makes sense to associate design guidelines to select *general product attributes* such as *Durability, Robustness, Complexity, Function and/or Part criticality, mechanical, electrical & thermal characteristics* etc. to make the guidelines more specific to the designer.
An important distinction between what we call the *General* and the *Circular Product attributes* should be noted here. While the *General product attributes* reflect characteristics that could/need to be modified while making the product more circular, the *Circular product attributes* refer to those that are built into the product as a result of the application of circular design principles. Accordingly, attributes such as *Modularity, Standardization, Simplicity, Recyclability* or *Bio content,* to name a few, fall under the category of *Circular Product attributes*. The design guidelines are therefore generated in a way to serve the following purposes.

i. Adjustment or modification of the *general product attributes* to suit the implementation of related design principles
ii. Aid in building the *circular product attributes* in the product
iii. Providing stepwise instructions with tangible measures considering multiple relevant design principles simultaneously for the associated application

In the following table, generation of some design guidelines is illustrated for *Connection Systems Applications* taking related circular design principles into consideration. Current state of research and state of art also sometimes needs to be taken into consideration while generating such guidelines.

Circular Design Principles
Refuse toxic ingredients
Design for Reuse of Parts at End_of_Life
Design for Modularity
Design for Robustness and Durability Refuse alternatives that compromise Product Durability, Safety and/or Reliability
Design for Repair
Design for Ease of Assembly and Disassembly
Design for Inspection & Quality Control
Ensure Sustainability of Resources (Use of Green materials including Bio_Based and Recyclable materials)
Design for Exchangeability, Standardization and/or Compatibility
Reduce sources of Failure including accidential
Reduction of wastes associated with processing - Manufacturing/End_Of_Life processing
Reduce the extent of use of synthetic/non-biodegradable components
Design for Miniaturization



Generated Design Guidelines

- Define parts as per the function they serve
- Categorizing critical and non-critical parts
- Avoid critical and non-critical parts in the same module to the extent possible
- Categorize parts in low, medium and high robustness levels
- Categorize parts in low, medium and high standardization indices
- Putting parts with similar robustness levels in one module
- Categorize parts into low, medium and high complexities(process and design-wise)
- Formulating highly complex parts in one or more separate modules which can be assembled and disassembled safely and repeatedly
- Identifying/formulating modules so that they can be easily dis/reassembled
- Formulation of modules with at least a certain level of standardization
- Formulating parts with high and low robustness levels in separate modules
- Formulating modules with high part robustness to be compatible with exchange of other modules
- Formulating parts with low robustness into one module which can be disassembled more easily from the overall product than others
- Identification of critical failure modes that could rely on parts with low robustness
- Keeping parts that are critical and complex in a module separate to those containing other parts
- Standardization of critical and complex modules to support different product variants and/or families
- Identification of multi material components
- Standardization of multi material(material-mix) components to the extent possible
- Increasing durability of multi material(material-mix) components/modules
- Formulation of multi material(material-mix) components to the extent possible in a module separate to those containing monomaterial components
- Identification of non-critical, less demanding parts for application of green materials
- Elimination or replacement of parts containing toxic ingredients with materials from renewable sources(Bio_based and/or recyclable)
- Categorization of parts as per their different mechanical, thermal and insulation requirement grades

Table 3 Design Guidelines generated for Connection Systems applications

REFUSE | RETHINK | REDUCE | REUSE | REPAIR | REMANUFACTURE | REFURBISH | REPURPOSE

RECYCLE | RECOVER

Circular Design Principles

- Refuse alternatives to product parts/modules which compromise product durability, safety & reliability
- Refuse alternatives to product parts/modules that are not sustainable and viable only for a single use life
- Refuse toxic ingredients

CIRCULAR STRATEGY	DESIGN PRINCIPLE	DESIGN GUIDELINE
R0- REFUSE	**R0.1** Refuse alternatives to product parts/modules which compromise product durability, safety & reliability	***R0.11*** *Parts that are prone to extreme conditions need to be able to withstand a higher thermal, mechanical(vibration & shocks included) and chemical effects*
	R0.1 Refuse alternatives to product parts/modules which compromise product durability, safety & reliability	***R0.12*** *Parts that are prone to extreme conditions need to be able to withstand Manufacturing aberrations and Dis/Reassembly operations*
	R0.2 Refuse alternatives to product parts/modules viable only for a single use life	***R0.21*** *Check for part or module functionality at the end of the First Use life*

Table 4 Design Guidelines generated for the Refuse CE strategy

Design Guidelines can be generated in accordance with a selected circular strategy as well.

An example has been presented herewith citing the design guidelines generated from the design principles of the *'Refuse'* circular strategy for components of *high-performance applications.*

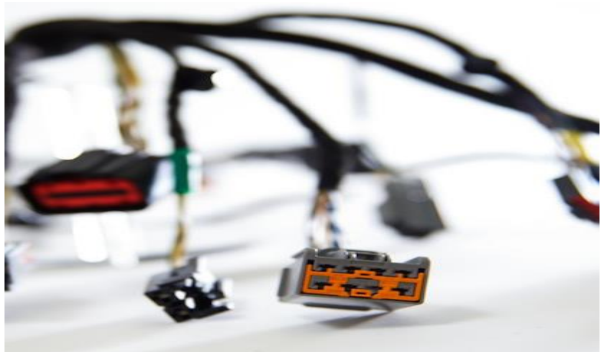
For generating the design guidelines from the non-tangible design principles, tangible factors/aspects in relation to the design principles need to be determined. For example, when generating guidelines for Design principle- 'Refuse alternatives to parts which compromise product durability, safety & reliability', it is beneficial if the guideline could specify or take into consideration how each of the quality factors like durability, safety and reliability for the product would be defined.

Depending on the product/application therefore, each of the guidelines can be further refined. Respective application can be further refined as part of this exercise as well. For e.g., when considering engine and HV components, the specific requirements to ascertain the fulfilment of guidelines like the ability to withstand multiple dis/reassembly operations, or multiple use lives need to be defined. The guidelines themselves can then be refined in terms of the number of Use lives or the number of dis/reassembly operations deemed feasible for such applications. There could be many more guidelines generated in addition to the ones mentioned here including those that even emphasize on the *scope of improvement* in product designs. For instance, identifying parts having high robustness levels, but difficult to disassemble/reassemble.

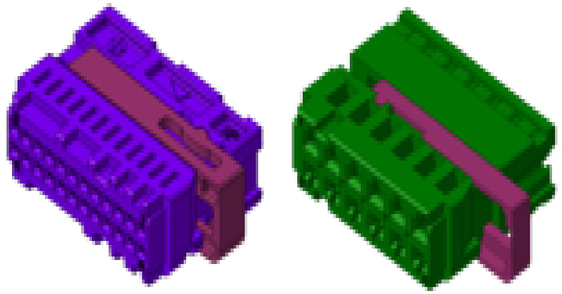
Deriving Circular Product Solutions

Implementing such design guidelines like the ones mentioned above, helps in generating configurations of the product in question aligned with the different design principles such as Design for Modularity, Part Reuse, Safe assembly & disassembly, Robustness, Standardization and Exchangeability taken into consideration at the same time for a given application. Selecting materials and part designs accordingly, different circular designs can be generated ensuring comprehensive solutions that are feasible considering associated circular strategies. Most of such design solutions generated would, in most cases, exhibit a level of disruption more suited to R&D, involving not just advanced product development but also concordant development of advanced production and processing technologies including pre- and postprocessing.

For instance, considering the *Reuse Strategy*, further Reuse of specific *Connector Modules* can be ensured with such modules displaying high robustness that can be easily disassembled to be further used even in different connector variants. A particular level of standardization or compatibility in the design of these modules to different variants has to be hence considered. This could enable robust modules stay in use for a longer time. Material and processing costs invested in associated high-performance materials(including material mixes or composites) for such modules need not be expended again and again when bringing new products to market while also saving on the higher costs that could be associated with their recycling. Material and processing cost benefits can also be attained when using present-day seemingly cost-intensive Green materials including Bio-based and recyclable materials for such Reusable and Robust connector modules.



On the other hand, *ability to exchange modules that are highly complex or contain highly complex parts which are prone to wear & tear* with safe disassembly & reassembly options can ensure reliable functionality from the overall product after End-Of-life practices like Repair & Maintenance, Remanufacturing etc. Such complex parts could include high precision parts, or parts that are highly miniaturized. Standardization with ease of exchangeability of such complex parts/modules, compatible with different product variants could help ensure minimal processing and material costs. This is especially beneficial in cases where such complex parts are also critical to the functionality of either the overall product assembly or of the specific component/subassembly itself.



Since Repurposing or further reuse of parts/modules that are *complex and critical* to the functionality of a particular product/application over multiple life cycles could often be difficult, standardization of such parts/modules can help redeem significant benefits including quality and reliability costs when implementing circular strategies such as Repair, Refurbishing and Remanufacturing.

Taking into consideration a different application of *Grommets* often used in the automotive sub-module harnesses, bringing circularity in context would involve taking into consideration different factors such as modularity of the overall system and associated carbon footprints for part and material processing, which are high for such applications. Therefore, modularization needs to be carried out with the implementation of guidelines keeping in mind design principles like Design for Reuse, safe assembly & disassembly, Robustness & Durability etc. Accordingly, *Reuse of Grommets* stands as a possible circular solution, particularly in the case of '*Push-in Grommets'*. Reusability of Grommets poses a question on the other hand, how old grommets that are kept in inventories and have not been in use so far could still be used in future generation of cars. Hereby, wire harness designers would need to look at how harnesses could be designed so that they remain compatible to earlier versions of wire harness components.

Summary and Conclusion

There are many design solutions that are possible depending on the guidelines that are applied. However, the framework for all these circular solutions can be set by the design principles that are considered starting with a deeper understanding of the application itself.
On the other hand, when targeting a particular circular solution, the circular design guidelines can be used to create *assessment matrices to guide the respective product development also dictating the way circular product attributes like modularity and standardization are defined/built into a product for realizing the different circular solutions.* In such a way, circularity in the products can be built concurrently during product design and development instead of retrospectively using tools like LCA(Life Cycle Assessments).

Sources

[1] An Introduction to Circular Economy; Lerwen Liu, Prof. Dr. Seeram Ramakrishna ISBN - 978-981-15-8509-8. https://doi.org/10.1007/978-981-15-8510-4
[2] Bovea, M.D., Pérez-Belis, V., 2018. Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. https://doi.org/10.1016/j.jenvman.2018.08.014
[3] Ellen MacArthur Foundation; ANBI RSIN nummer: 8257 45 925
[4] COM 614, 2015. Closing the Loop: an EU Action Plan for the Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. https://doi.org/10.1017/CBO9781107415324.004
[5] Flipsen, B., Bakker, C. A., & de Pauw, I. C. (2020). Hotspot Mapping for product disassembly: A circular product assessment method. In M. Schneider-Ramelow (Ed.), Electronics Goes Green 2020+ (EGG): The Story of Daisy, Alexa and Greta
[6] Ijomah, W. L., McMahon, C. A., Hammond, G. P. and Newman, S. T. (2007) 'Development of robust design-for-remanufacturing guidelines to further the aims of sustainable development', International Journal of Production Research, 45:18, 4513 – 4536
[7] Martin Geissdoerfer, Paulo Savaget, Nancy M.P. Bocken, Erik Jan Hultink, The Circular Economy – A new sustainability paradigm?, Journal of Cleaner Production, Volume 143, 2017, Pages 757-768, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2016.12.048. (https://www.sciencedirect.com/science/article/pii/S0959652616321023)
[8] Reike, D., Vermeulen, W.J.V. & Witjes, S., 2018. The circular economy: New or Refurbished as CE 3.0? – Exploring Controversies in the Conceptualization of the Circular Economy through a Focus on History and Resource Value Retention Options. Resources, Conservation and Recycling, 135, pp.246–264. Available at: https://doi.org/10.1016/j. resconrec.2017.08.027
[9] G.M. Kane, C.A. Bakker, A.R. Balkenende, Towards design strategies for circular medical products, Resources, Conservation and Recycling, Volume 135, 2018, Pages 38-47, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.07.030.
[10] Potting, José & Hekkert, M.P. & Worrell, Ernst & Hanemaaijer, Aldert. (2017). Circular Economy: Measuring innovation in the product chain, https://www.researchgate.net/publication/319314335_Circular_Economy_Measuring_innovation_in_the_product_chain
[11] Piero Morseletto, Targets for a circular economy, Resources, Conservation and Recycling, Volume 153, 2020, 104553, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2019.104553.
[12] Braungart, M., P. Bondesen, A. Kälin and B. Gabler,"Specific Public Goods for Economic Development: With a Focus on Environment."in British Standards Institution(eds),Public Goods for Economic Development. Compendium of Background papers, United Nations Industrial Development Organisation, Vienna, (2008)
[13] Nancy M. P. Bocken, Ingrid de Pauw, Conny Bakker & Bram van der Grinten (2016) Product design and business model strategies for a circular economy, Journal of Industrial and Production Engineering, 33:5, 308-320, DOI: 10.1080/21681015.2016.1172124
[14] Willskytt, Siri, and Sergio A. Brambila-Macias. 2020. "Design Guidelines Developed from Environmental Assessments: A Design Tool for Resource-Efficient Products" Sustainability 12, no. 12: 4953. https://doi.org/10.3390/su12124953
[15] Mesa, J.A. Design for circularity and durability: an integrated approach from DFX guidelines. Res Eng Design 34, 443–460 (2023). https://doi.org/10.1007/s00163-023-00419-1
[16] Telenko, Cassandra & Seepersad, Carolyn & Webber, Michael. (2008). A Compilation of Design for Environment Principles and Guidelines. Proceedings of the ASME Design Engineering Technical Conference. 5. 10.1115/DETC2008-49651

[17] Bernd Bilitewski, The Circular Economy and its Risks, Waste Management, Volume 32, Issue 1, 2012, Pages 1-2, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2011.10.004.