D3.4- Circular design methodologies

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List of abbreviations

Abbreviation	*Explanation*
EoL	End-of-Life
CPR	Circular Product Readiness
Method	Methodology
OEM	Original Equipment Manufacturer
PJM	Product Journey Map
R-strategies	Repair, refurbishment, remanufacturing, recycling etc.

Executive Summary

This report presents the results of task 3.4. It details the development, application and validation of circular design methods that can deal with multiple scenarios, with a concurrent focus on reuse, remanufacturing and recycling, and a long time-horizon.

In report D3.3 Circular design methodologies, interim results were presented of how to support companies in the transition towards developing circular products and four design methods that could assist in this process. This report presents the further development and validation of two methods; the Circular Product Readiness and Product Journey Map, that were in preliminary stages of development during WP3.3. It also presents the final version of all four design methods, that each in their unique way aim to support this transition: 1) Circular Product Readiness; 2) Product Journey Map; 3) Disassembly Map; 4) Co-creation Impact Model.

The first method, the Circular Product Readiness method, is used to monitor and steer the design process from a design management perspective, using a comprehensive set of indicators to assess a company's readiness level to design circular products. A second level of this method consists of additional indicators from literature, to dive deeper in selected topics.

The second method, the Product Journey Map, is a strategic design method that visualises the journey of a product throughout its lifetime and contains a product's interaction with the various stakeholders to gain insights in opportunities to capture value.

The third method, the Disassembly Map, is a method that gives a schematic representation of a product's architecture with the goal to provide insight in the disassembly routes for its parts and optimize them for different R-strategies (i.e. repair, refurbishment, remanufacturing, etc.).

And finally, the Co-creation Impact Model is a method that helps put co-creation into effective use in the process of shifting towards increased servitization, by providing an overview of the impact of co-creation at different product-service system development phases.

1. Introduction

This document is the result of WP 3 task 3.4: developing and applying multiple-scenario case-specific circular design methodologies. This task is focused on developing design methods that are able to deal with multiple scenarios, with a concurrent focus on reuse, remanufacturing and recycling, and a long-time horizon. This task correlates with tasks 3.1, 3.2, 3.3 and 3.5, and uses input from demonstrator work packages 6 and 7.

1.1. Document scope and structure

This report builds on the analysis conducted in task 3.3 Circular design methodologies. In report D3.3 (confidential), we described the rationale behind the selection of four strategic priority areas for the development of design methods, based on the OEM roadmaps, gaps found in scientific literature, as well as industry needs. Four design methods were proposed that each contribute to one of the strategic priority areas 1.) Circular Product Readiness, 2.) Product Journey Map, 3) Disassembly Map, and 4) Co-creation Impact Model. Report D3.3 already reported on the development and implementation of the latter two methods in both demonstrators. The first two methods were only presented as preliminary design directions, based on the analysis of two of the strategic priority areas, but were still under development. This report updates on the further development and validation of those first two methods; the Circular Product Readiness and Product Journey Map and presents the final version of all four design methods. Chapters 2 and 3 describes the further development and validation of the Circular product Readiness and Product Journey Map methods based on what was presented in D3.3. Chapters 4 and 5 present the final versions of the Disassembly Map, and Co-creation Impact Model. The final section, chapter 6, reflects on the work done and proposes opportunities for further work in the development of design methods. An overview of the goal and scope of the methods and what will be addressed in this report can be found in (Table 1).

Table 1 Overview of the four circular design methods

Circular design method	Goal	Scope	Addressed in this report
Circular Product Readiness	- Monitoring circular implementation - Identifying opportunities for circular design	Generic product-level assessment	- development - validation - final design method
Product Journey Map	- Identifying opportunities to align product design features with business and stakeholder requirements	Early stage road mapping of product-service systems	- development - validation - final design method
Disassembly Map	- Optimizing product architecture - Identifying opportunities to improve ease of disassembly	Technical/embodiment level product re-design	- final design method (full description can be found in De Fazio et al., 2021)
Co-creation Impact Model	- Determining the desired impact of co-creation sessions	Business model servitization and stakeholder engagement	- final design method (full description can be found in van Dam et al., 2021 and report D3.2)

2. Development of the Circular Product Readiness method

This chapter describes the further development of the Circular Product Readiness (CPR) method. The following elements will be described within this chapter: purpose of the method, the method description, validation of the method, and the opportunities for future research.

2.1. Introduction

Industry's ambitions for producer responsibility, incentivized by the European Commission and NGOs, drives the practical implementation of circular product design (Kalmykovaa et al. 2018). Kircherr et al. (2018) found that circular economy is a difficult-to-implement concept, because of its fundamental differences with linear production. Examples of the fundamental differences for product design are to sell functionality or performance as the core value over selling a product itself, to steer towards customer satisfaction over steering towards consumerism, and to think in terms of End-of-Use of products instead of End-of-Life after the first use (EEA 2017). Where linear products are designed for a single use-cycle, circular products should be designed for multiple use-cycles, which adds to the design complexity (Boorsma et al. 2022). All events and desired behaviours of a product throughout its entire lifecycle, from strategy to recovery, can be facilitated through design (Bakker et al. 2014a).

Taking a strategic design perspective can contribute to embedding circular design in existing processes (Boorsma et al. 2020). With the use of indicators, companies can track circular design implementation to get insight in their performance (Kalmykovaa et al. 2018), by assessing all aspects associated with circular design including strategic design (Boorsma et al. 2020). Based on a review of 30 micro-level (i.e. single firm or product level) indicators, Kristensen & Mosgaard (2020) conclude that the existing indicators are not evenly spread over the R-strategies. Also, the scope for micro-level indicators is not well defined (Cayzer et al 2017; Kristensen & Mosgaard 2020), leaving a gap for standardized evaluation methods (Elia et al 2017). After a review of product-focused indicators, Linder et al. (2017) conclude that the Material Circularity Indicator by the Ellen MacArthur Foundation contains the most ambitious set of indicators (EMF & Granta Design 2015). This tool measures the effectivity of a company's transition based on material flows, and can support designers in decision-making. While different sets of existing indicators contain information that is valuable to designers, none of these sets was made from a design perspective. There is a need for indicators that use design language, address all the phases of a design process, and are presented in a format which is easy to apply in industry, and that could help design teams monitor their readiness level to design circular products.

2.2. Background

Based on literature review and desktop research – purpose is to give an overview of existing indictor methods, establish the need for the CPR, and derive criteria that will guide the development of a high-quality method.

2.2.1. Existing circularity indicator methods

Existing circularity indicator methods either focus on a company level, which the product's circularity is part of, or a material level, where circularity is measured based on material flows. In addition, product-specific indicators that have been collected, categorized, and reviewed in several academic studies (Linder et al. 2017; Corona et al. 2019; Saidani et al. 2019; Kristensen & Mosgaard 2020). The main purpose of these indicators is to measure either the more generic dynamics of design management, or one specific aspect of circular product design, usually expressed in quantitative units (such as the longevity expressed in time, the recycling rate in percentage or a remanufacturability score).

- Circulytics[1], by the Ellen MacArthur Foundation is a method to measure the circularity performance of companies, using a broad set of metrics about the organisation as well as the products. These are divided into the following 11 themes: Strategy and planning, people and skills, innovation, operations, external engagement, products and materials (Figure 1), services, plant, property and equipment assets, water, energy, and finance (EMF, 2020). The product design indicators focus on resource origin and flows, design principles, level of hazard of materials, and number of uses. They evaluate the effect of all of the company's products on the circularity of resources, but do not evaluate the effect of the decisions leading up to the circularity of these designs in detail. Evaluating the extent to which specific design decisions are attuned to circular product development is unaddressed.

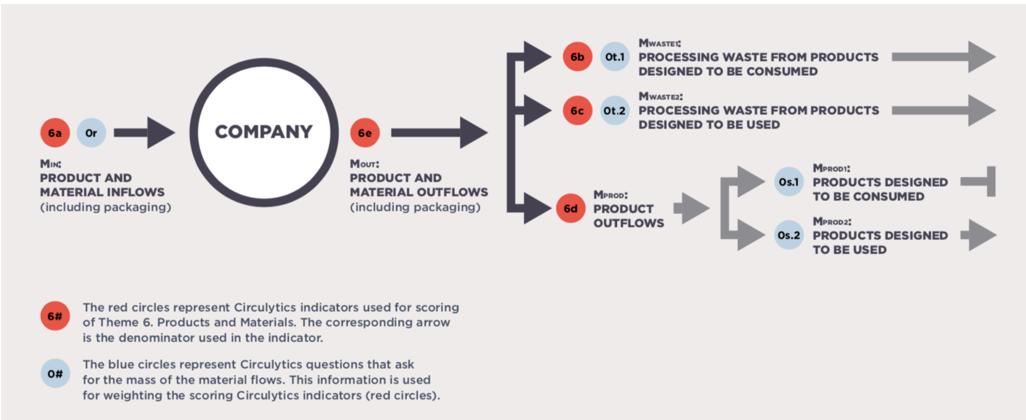

Figure 1 Material flow diagram of theme 6 (products and materials) (EMF 2020)

- Material Circularity Indicator[2] tool by the Ellen MacArthur Foundation and Granta Design allows companies to identify the circular value of their products and materials by measuring the circularity of material flows (Figure 2). It enables users to analyse and evaluate a range of environmental, regulatory, and supply chain risks (EMF & GD 2019). The product design indicators considered for this tool concern the resource

[1] https://ellenmacarthurfoundation.org/resources/circulytics/overview
[2] https://ellenmacarthurfoundation.org/material-circularity-indicator

origin and flow, duration and intensity of use, level of hazard and scarcity of materials, and recommendations for the classical circular design principles (e.g. R-strategies). The effects in resource flows are not linked to (circular) product design activities or solutions.

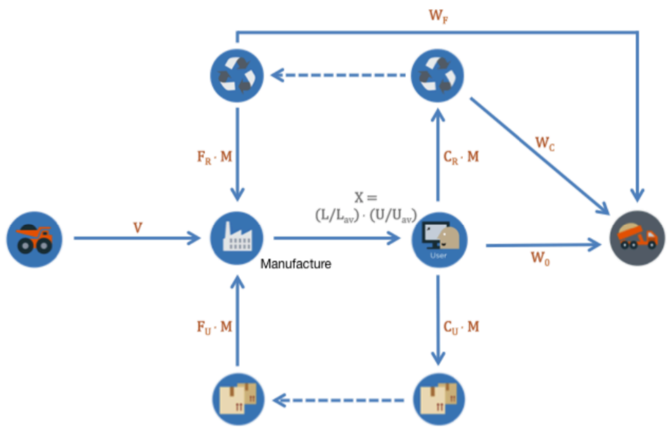

Figure 2 Diagram of material flows (EMF & GD 2019)

- The MATChE Readiness Assessment Tool[3] is a method developed by researchers at the Technical University of Denmark by which a company can assess their readiness for circular economy and learn about the opportunities. The method uses 30 questions divided over 8 dimensions: organisation, strategy & business model innovation, product & service innovation, manufacturing & value chain, technology & data, use, support & maintenance, and takeback & end-of-life strategies (Figure 3) (Pigosso & McAloone 2021). The product design indicators separately evaluate the application of lifetime extention and EoL strategies on a generic level. In addition, they focus on the specific services that enable recirculation of products and that influence use intensity. What design decisions should be considered for applying these design strategies are not addressed.

Figure 3 Product and service innovation dimension as part of the full assessment overview (DTU 2020)

- CEIP – In their paper, Cayzer et al. (2017) evaluate their Circular Economy Indicator Prototype (CEIP) to evaluate circular product performance. The goal of this study is

[3] https://ready2loop.org/

to assess companies' readiness level to design circular products, by taking a lifecycle perspective (Figure 4). CEIP was developed based upon a pilot project of the Material Circularity Indicator and the circular economy principles of the Ellen MacArthur Foundation at the company Kingfisher (EMF 2012; EMF & GD 2015). The tool consists of 15 questions divided over 5 themes. Topics addressed in relation to product design are resource origin, eco-design principles, and supporting services (e.g. warranty, repair, and recirculation). This tool has the strongest orientation towards product design of all evaluated tool. The indicator questions are relevant and in-depth, yet the selection of topics is not exhaustive and lacks cohesion.

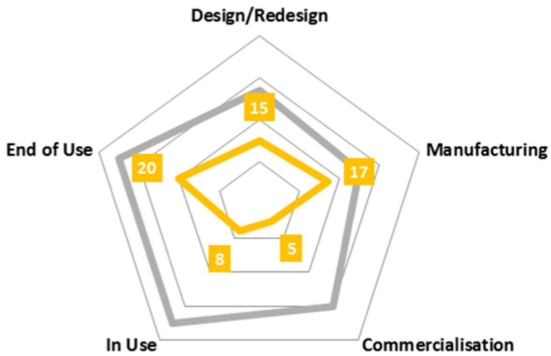

Figure 4 Tool interface showing results of the 5 main themes (Cayzer et al. 2017)

- Circular economy: measuring innovation in the product chain – Potting et al. (2017). For this model, three types of transitions are considered, that of new technology, socio-institutional change, and the required enabling technology. The conceptual framework is based on the 2005 policy evaluation scheme of the Netherlands Court of Audit (NCA 2005). This study focuses on measuring policy achievements and effects on the flows depicted in Figure 5. This tool includes a selection of priority questions for product design, like advancement in lifetime extension, disassemblability, supporting services, and waste minimalisation, yet the scope does not allow a broader spread of design-related questions.

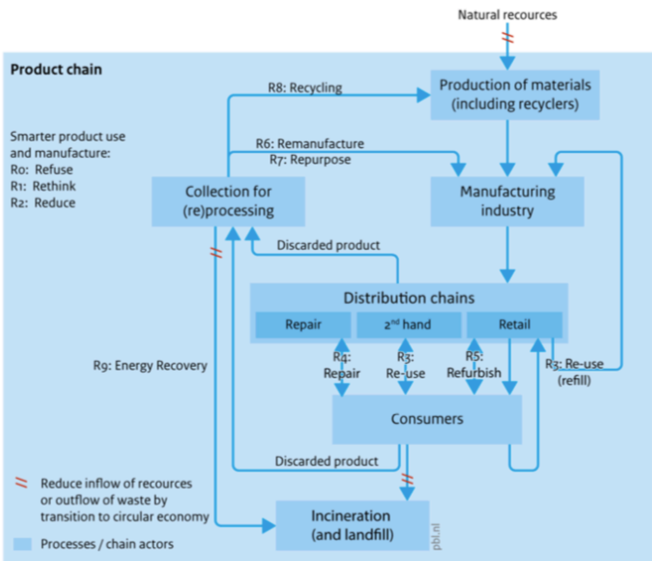

Figure 5 Circularity strategies and actors of a production chain (Potting et al. 2017)

- The Circularity Calculator, de Pauw et al. (2021).
  This indicator tool helps designers evaluate and compare the circularity potential of product concepts at early-stage design, to determine viability of the circular concepts. The tool combines different indexes to reflect the flows of resources in all loops (Figure 6). It focuses on providing an overview and showing what the effects are on the system by focussing on specific loops. The indicators link a (potential) product design characteristics to resulting resource flows. The tool does not address how circular design principles can be applied to arrive at the required characteristics.

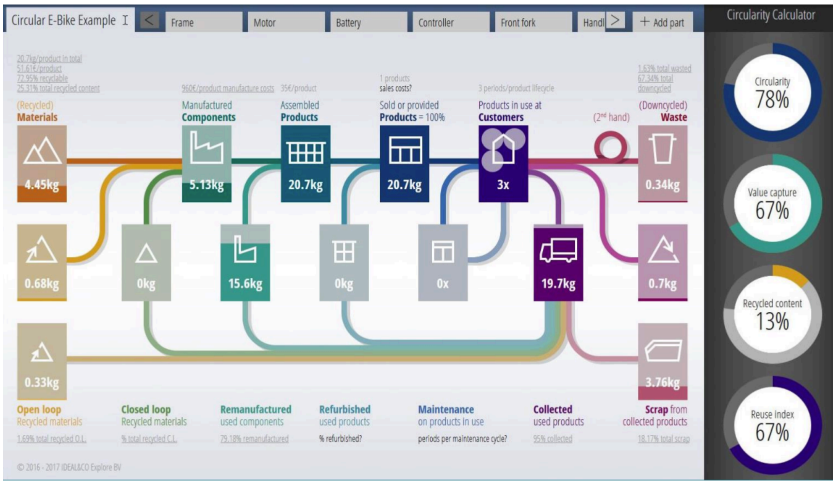

Figure 6 Dashboard with the resource flows of a circular e-bike example (de Pauw et al. 2021)

None of the existing methods and (sets of) indicators are using a comprehensive set of design variables and indicators that measure the readiness to develop circular products and related service offering. Effectively managing a circular design transition requires taking a multi-diverse design perspective on the product service system.
Concluding, a dedicated assessment method that focuses on circular product and service design is needed. A method that can be used by manufacturers to monitor the implementation of a circular design in their current offering and serve as a guidance in the transition to an improved circular offering.

2.2.2. Quality requirements for indicators

Indicators can be used to serve various purposes, examples are to measure performance, to classify products, or to inform legislators, as part of a predetermined wider strategy (Franceschini et al. 2007; Linder et al. 2017). Periodical measurements allow professionals to monitor progress over time (Franceschini et al. 2007). For the measured information to reflect the performance of a product justly, the indicators should be selected to meet the intended scope (while continuing to acknowledging the complexity of the system under evaluation) (Franceschini et al. 2007). Linder et al. (2017) consider the following construct valid to measure circularity "the fraction of new products that come from used products", to set circularity apart from company or sustainability performance. Instead of evaluating the circularity of a product, for this study, the scope would be attuned to evaluating the readiness level of design teams to design circular products, based on the description of the gap found in section 2.2.1. The following requirements for testing the Circular Product Readiness method were derived from literature:

Table 2 ReCiPSS quality requirements for the indicators

ReCiPSS requirements	Explanation	References
Reliability	Consistency of outcomes over multiple measurements.	Bannigan & Watson 2009; Linder et al. 2017
Construct validity	The indicator measures what was defined as the construct. The indicators are representative of, and meaningful to, the construct.	Bannigan & Watson 2009; Drucker & Maciariello 2008; UNI 11097 2003
Content validity	The indicators cover the full content of the construct. The indicators offer a complete representation of the construct.	Bannigan & Watson 2009
Comprehensibility	The indicators are understandable, meaningful, simple, and are easy to interpret.	Drucker & Maciariello 2008; Franceschini et al. 2007; UNI 11097 2003
Operationability	The extent to which the indicators can be adopted in ongoing processes in an effective way.	Drucker & Maciariello 2008

The selected requirements will be tested through co-creation sessions with circular design experts and validation sessions with companies.

2.2.3. Criteria for method development

The first set of criteria for the method development was presented in the ReCiPSS EU project deliverable D3.3. Additional criteria, based on the indicator quality requirements, and the design vision of ReCiPSS were added during the course of the study.

Method criteria from ReCiPSS EU project deliverable D3.3:

- The method should cover a complete range of design factors, from strategy to recovery, to ensure completeness of the assessment (based on the design vision of ReCiPSS, in consultation with the OEMs).
- The method should allow for additional in-depth measurements on specific design factors of interest, to ensure that the method also indicates how improvements can be made, in addition to indicating what improvements can be made (based on the design vision of ReCiPSS, in consultation with ReCiPSS project partners working on the development of key performance indicators).
- The method should measure fully implemented strategies as well as design strategies for which implementation is planned or initiated, to enable reflecting on the design improvements that are in progress (based on consultations with the OEMs).
- The method should be generic, applicable to any industry (high transversality) (Linder et al. 2017) (based on the requirements from task 3.4).

- The method should allow for ease of communication of the results, to ensure information can be spread effectively throughout the organisation and value chain partners (based on the design vision of ReCiPSS).

Additional method criteria from this report (D3.4):

- The visual through which the results are presented should be divided into four different levels, ranging from an aggregated metric to a metric that shows the sub-facets to reflect nuances (high dimensionality) (Drucker & Maciariello 2008; Cayzer et al. 2017; Linder et al. 2017):
    - A single metric
    - A theme-specific metric
    - An indicator specific metric
    - A question-specific metric
- The method requires a deep understanding of the product under assessment. The method uses design terminology and assesses circular design through a designer's lens (based on the design vision of ReCiPSS).

In summary, the method requirements are the following:

- The method takes a full lifecycle focus (D3.3)
- The method indicates areas for improvement (D3.3)
- The method differentiates in levels of implementation (D3.3)
- The method has a high level of transversality (D3.3)
- The method allows for ease of communication of the results (D3.3)
- The method has a high level of dimensionality (D3.4)
- The method is attuned to use by designers (D3.4)
- The method includes indicators that meet the indicator requirements of section 2.2.2 Table 2 (D3.4)

2.3. Approach to develop the design method

This study aims to develop an assessment method for companies that covers all elements critical to implementing circular design. The content of the method was created based on insights from conducting a literature review, from doing co-creation sessions with circular economy experts, and from company testing.

(1) Literature review
A literature review was done to develop the basis for the Circular Product Readiness method. This helped in developing the themes, indicators, and questions, as well as the method template. The overall goal of the literature review was to find and select indicators that 1.) offer information about requirements to successfully apply (strategic) design resources and principles, and/ or 2.) give an indication of how this can be influenced through (strategic) design decision-making.

The data bases of Web of Science, Google Scholar, and Scopus were searched to find papers by using in the search terms: circular, design, product, service, and indicator, with a year range of 2017 to 2021. A total of 110 articles were retrieved of which 50 papers were read in full. Snowballing was applied to find additional information on the relevant circular design strategies.

The assessment method will be used in a design context, therefore the inclusion of papers that address the following topics:

- Validated micro-level indicators that measure circularity
- Design considerations influence circularity for particular design strategies
- How to successfully apply circular design at any of the stages, ranging from strategic design, to design for recovery, and/or design for multiple use-cycles
- How the circularity of products can be influenced through (strategic) design decision-making
- Ways to improve circular product design in the scope of Circular Economy Action Plan of 2020, section 2.1 (EC, 2020)

Topics that are regulated by law, like private and secure data exchange, warranty, and the use of hazardous materials are excluded from the assessment (Council directive 1999/44/EC; Council directive 2011/65/EU; Council directive 2016/679).

(2) Identification and categorization of indicators

The circularity and sustainability indicators from academic and grey literature were analysed to develop themes for assessing the readiness level of companies to design circular products. The goal was to meet the following criteria through several rounds of iterations:

- The themes should cover design activities relevant to all phases of the lifecycle of a product
- The themes should have minimal overlap
- The themes should be sequential to make them intuitive and easy to understand

(3) Indicator questions and answer options

On the basis of these themes and indicators, the questions to the indicators were formulated. This was again done based on the existing indicators found in literature, and the design aspects that researchers associate with those indicators. After several rounds of iterations, a preliminary set of questions was developed.

The answer options of the questions were standardized as much as possible for all the questions, to facilitate a uniform scoring system. This also optimized the recognition of the answer options by the user to reduce the time needed to interpret the answer options. The answer options were adapted to the content of the question where needed.

(4) Co-creation sessions with experts

The purpose of the co-creation sessions was to assess the completeness, applicability, and priority/ significance of the first draft indicator questions that was based on literature. Eight co-creations sessions were organised with researchers specialized in different elements of circular design, all working at the Design for Sustainability research group of the faculty of Industrial Design Engineering at the Delft University of Technology. 14 out of 20 indicators were evaluated through the co-creation sessions. The indicators that were not covered in the co-creation sessions were either sufficiently covered by scientific literature and did not require input from an expert, or were added at a later stage of the design process.

Table 3 Co-creation expert sessions - participants

Indicator number and topic	Participant(s)
Session 1 1. Design budget (Strategy & Planning) 2. Know-how (Strategy & Planning) 3. Customer research (Strategy & Planning) 4. Value proposition (Strategy & Planning)	**Dr. Sonja van Dam**
Session 2 1. Design budget (Strategy & Planning) 2. Know-how (Strategy & Planning) 3. Customer research (Strategy & Planning) 4. Value proposition (Strategy & Planning)	**Dr. Ingrid de Pauw**
Session 3 8. Maintenance & repair (Hardware & Software design) 13. Professional support (Product support Service) 17. Disassembly (Recoverability)	**Sagar Dangal**, PhD Researcher - Design for Reparability and Longevity **Dr. Beatriz Pozo Arcos**
Session 4 10. On- & Off-boarding (Customer Experience & Care)	**Dr. Flora Poppelaars** **Prof. Dr. Conny Bakker**
Session 5 10. On- & off boarding (Customer Experience & Care) 11. Use efficiency (Customer Experience & Care)	**Renske van den Berge**, PhD Researcher – Consumer perception of circular products
Session 6 5. Materials (Hardware & Software Design) 20. Recycling (Recoverability)	**Jelle Joustra**, PhD Researcher – Composites in a circular economy **Prof. Dr. Ruud Balkenende**
Session 7 14. Spare part supply (Product Support Service) 18. Refurbishment (Recoverability) 19. Remanufacturing (Recoverability)	**Dr. David Peck**
Session 8 General: social aspects of circular product design	**Karlheinz Samenjo**, PhD Researcher – Circular medical devices in low resource settings

The co-creation sessions took place in September 2021 and lasted 45 to 75 minutes. The procedure was as follow:

The participants received the following information in forehand:

- An overview of all indicators
- The indicator questions for that particular indicator
- The goal of the session: to evaluate the completeness and priority of the question, as well as to collect relevant references

The schedule for the co-creation sessions was as follow:

- Introduction to the session set-up and goal (5 min)
- Discussion (15 min)
- Brainstorm session (15 min)
- Evaluation (10 min)

The session was structured using a Miro-board in which the indicator questions could be rated based on priority (Figure 27 in Appendix I). The input provided by the experts was collected through note-taking. The notes were analysed after the sessions and served as input to sharpen and clarify the formulation of the questions, and add or delete questions.

(5) Development of the visual

The development of the visual used to present the outcome of the Circular Product Readiness method was done based on design iterations. Existing techniques to visualize indicators were used as a reference. For this reason, the radar diagram was selected as the central element of the visual, and a visual report was created to provide more detail to the data presented in the radar diagram. The visuals adjusted following to the changes made in the contents of the themes, indicators, and questions.

(6) Validation

The ReCiPSS demonstrator companies, Gorenje and Bosch, were asked to fill in the questions independently and provide feedback during a one-hour evaluation interview, using the method criteria. Based upon the results, the questions went through another round of iteration.

As a final step, the method criteria were again evaluated by the researchers to see to what extent the criteria were met by the final design.

2.4. Development of the Circular Product Readiness method

The demonstrators of the ReCiPSS project both have roadmaps with a comprehensive description of the kind of circular products they envision for the future. However, despite the ambitions put forward by the companies, the roadmaps do not offer specific guidance on how to organize their product design capabilities, how to establish which capabilities may need further development, how and where to allocate design resources, and how to monitor the implementation of circular design strategies. In order to have an indication of the implementation progress of circular design, it is beneficial to know which design variables should be measured and how they can be measured in a meaningful way.

2.4.1. Development of themes and indicators

The circular indicator methods from paragraph 2.2.1, and two additional indicator sets described in literature, were analysed in more detail (Table 4; tables 11-15, Appendix I). For each of these methods, we described the themes and indictors used, in order to understand which indictors should be part of the CPR. See Table 4 for an example indicator framework from literature:

Table 4 Themes and indicators of the Circular Economy indicator prototype (CEIP) (Cayzer et al. 2017)

Themes	Indicators
Design/ redesign	Use of recovered materials Dematerialisation Presence of bill of materials
Manufacturing	Presence of bill of energy Manufacturing waste management
Commercialisation	Product packaging Warranty Rental schemes
In use	Usage status and ID Repair options Reuse options Waste reduction
End of Use	Availability of take-back schemes Product recovery Reintroduction of product's materials

A table with a collection of insights from the analysis of indicator frameworks was created (Table 5). These insights were derived based on the needs as described in section 2.2.3. In general, all of the evaluated indicator tools have a scope broader than that of circular product design, yet there are valuable take-aways that should be considered for the development of the new method framework. These insights concern the scope of the indicators and how to structure them. In particular, they provided information about how the method can become as complete as possible, seen all the different topics that were addressed in the indicator frameworks.

Table 5 Analysis of indicator frameworks from (grey) literature

Indicator frameworks	Pros	Cons
Cayzer et al. 2017	- Lifecycle structure that includes 'in use' and 'end of use' - Tool with strongest design orientation (compared to other indicator tools)	- No clear delineation between themes - Incomplete list of indicators - Coherence of topics is missing
Saidani et al. 2019	- Focus on different levels of abstraction - Indicators were categorized according to dimensionality, which refers to the level of aggregation of the results (high	- Specific success factors for individual circular design principles is missing

	dimensionality is more suitable to designers, since it provides more detail) - Indicators were categorized according to the level of transversality, which refers to their generalizability amongst industries - Type of performance useful for design - Distinction between loops	
Kristensen & Mosgaard 2020	- Distinction between loops - Value retention strategies - Energy efficiency is considered - Distinction between material cycles (techno, bio)	- Specific success factors for individual circular design principles is missing
Pigosso & McAloone 2021	- Strategic view included - Value proposition development is considered - Specific circular design strategies included - Specific (professional) actions to monitor/ maintain products during use - Take-back strategies considered	- Does not address specific design decisions for application of the design strategies
EMF 2020	- Strategic view included - Project briefs included - User-centeredness included - Role of customer included	- Not attuned to evaluating at the level of specific design decisions
Potting et al. 2017	- Priority aspect of circular design included	- Narrow scope on design aspects

With insight collected form the analysis of existing indicator methods, the first version of themes and indicators in Appendix I was further developed in several design iterations, with, as a result, the final set of themes and indicators in Appendix II.

Table 6 The final set of themes and indicators and their purpose

Themes	Indicators	Indicator purpose
Strategy and planning	Design budget	indicates commitment through having a clear objective, a task division with a lead figure, and early stage integration of circular design.
	Access to circular design know-how	indicates the extent to which circular design can potentially be implemented. This can for example be done through consulting the repair/ maintenance/ refurbishment/ remanufacturing technicians, through consulting circular design experts or through hiring circular design experts.
	Customer research attuned to needs in multiple use-cycles	indicates whether customer research also includes researching customer needs beyond the first use and therefore the ability to prepare products to meet market needs for all use-cycles.
	Circular value proposition design	indicates how well the circular product offer is attuned to the needs of customers and how well the benefits are communicated to optimise customer perception
Hardware and software design	Materials	indicates the potential of a product to circulate in loops while maintaining high-quality, without harming the environment, and at the same time supporting fair production.
	Longevity	indicates the potential for a product to last as long as reasonable from a profit, market and environmental perspective.

	Standardization across the product portfolio	indicates the level of product homogeneity that allows for sufficient volume of products to run viable recovery operations, i.e. standardization of interfaces, backward compatibility, etc..
	Maintenance & repair	indicates the potential for a product to be repaired and maintained with the lowest possible effort, time and costs, relative to the function and value of the product.
	Software support	indicates the extent to which the product's design facilitates software updates during the time that the product's function is in demand.
Customer experience and care	On- and off-boarding	indicates the extent to which the benefits of the product/ service are clear to the user, and the extent to which the procedure and responsibilities to access and disposal of the product/ service are clear and convenient.
	Product use efficiency	indicates the extent to which the product's function is maximised while the use of consumables, and the potential environmental harm, is minimized.
Product support services	Warranty	indicates the expected lifetime during which a product functions properly without unforeseen recovery activities.
	Professional support	indicates the commitment and ability of a company to facilitate high product quality beyond the point-of-sale, including post-warranty, in terms of service.
	Spare part supply	indicates the commitment and ability of a company to facilitate spare part availability beyond the point-of-sale.
Recirculation service	Return program	indicates the likelihood of companies to retrieve their products back from the market after use.
	Product retrieval	Indicates the conditions for returning products.
Recoverability	Disassembly	indicates the extent in which a product is designed to be taken apart in terms of safety, time, and costs.
	Refurbishment	indicates the extent to which a product is designed to be refurbished in terms of safety, time, and costs.
	Remanufacturing	indicates the extent to which a product is designed to be remanufactured in terms of safety, time, and costs.
	Recycling	indicates the extent to which a product's materials are designed to be recovered while minimizing the use of non-recyclable or non-repurposable materials.

2.4.2. Development of the indicator questions

Literature review and design iterations formed the basis to the development of the indicator questions and the method visual. Based on the insights from the existing indicator frameworks, a first set of questions was developed (Table 27, Appendix I). This was fine-tuned over time through iterations and feedback loops within the research team of the TU Delft. In addition, co-creation sessions were organized to assess the quality of the indicators.

2.4.2.1 Justification of the indicator questions

The final set of questions can be found in Table 7. The second column shows the justification of the indicator questions based on literature and the co-creation sessions. The questions together with the answer options can be found in Appendix II.

Table 7 Development of indicator questions and their justification based on literature

Indicator questions	**Justification based on literature review and co-creation**
1. CIRCULAR STRATEGY	
1.1 Design budget	

1.1.1 Has your company made a budget available for circular design?	Allocating budget to circular design underpins the strategic value of circular design and their level of commitment to prioritizing the associated design requirements (Boorsma et al. 2022)
1.2 Know-how	
1.2.1 Does your company have access to circular design expertise?	The development of, or having access to circular design competencies is seen as a success factor to implement circular design, looking at the financial, operational and structural challenges (Sumter et al. 2021). The question was added as a result of Co-creation sessions 2, 7 and 8.
1.2.2 Does your company have channels to exchange product design information with stakeholders, like repair and remanufacturing technicians?	The integration of circular design is strongly linked with the frequency and quality of data exchange between technicians who perform recovery operations and design engineers (Hatcher 2013).
1.3 Customer research	
1.3.1 To what extent are the needs of customers not only considered in the first use-cycle, but also in the subsequent use-cycles of the product?	Market demand is seen as the strongest incentive for companies to adjust design requirements, collecting data about customer needs with regards to circular design helps in building arguments to implement circular design (Boorsma et al. 2022). The question was rephrased as a result of Co-creation session 1.
1.4 Value proposition	
1.4.1 Does the circular value proposition and its related service and product offer new benefits to customers?	Circular product offers are established in value networks and are effective when all partners gain value from the offer (Bocken et al. 2014). The fact that circular products are taken back and recovered can offer additional unique value can be offered to customers, like access to use information and access to exclusive features (van Dam et al. 2021). The question was added as a result of Co-creation session 8.
1.4.2 To what extent does value proposition design support high product quality not only in the first use-cycle but also in subsequent use-cycles for the products?	The brand- and product identity help customers build trust in, and accept, products that serve multiple use-cycles (Boorsma et al. 2022). Building this quality perception also helps in getting buy-in from employees (ibid.). The question was rephrased as a result of Co-creation session 1.
2. HARDWARE AND SOFTWARE DESIGN	
2.1 Materials	
2.1.1 What fraction of the material value, by cost price, consists of recycled and/ or reused materials calculated over all use-cycles?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product (Cayzer et al. 2017). The question was rephrased as a result of Co-creation session 6.
2.1.2 What amount of the material value, by cost price, consists of critical materials? (See Appendix I for more information)	Critical materials, commonly used by design engineers, tend to have rare material characteristics, yet they are labelled critical, for instance, due to constraints in supply chains, volatile prices, or implications to the environment (Peck et al. 2015). Circular design is seen as a promising solution to diminish risks and offer a more sustainable alternative to using these valuable resources (ibid.).
2.1.3 What amount of the material value, by cost price, consists of conflict materials?	Mineral trade can be involved with inhumane activities, like forced labour, labour under harsh working conditions, or criminal activities (EC 2017). The OECD recommends traceability systems to map upstream supply chain stakeholders in collaboration with industry bodies (OECD 2016).
2.1.4 Does the product contain easily separable biodegradable or compostable components?	Following the “power of pure circles” principle of the Ellen MacArthur Foundation product circularity increases through separating material streams to their purest possible form, at the core separating the bio- and the techno-cycles (EMF 2013).
2.1.5 Does the product contain composite materials that are designed to last?	Closing the material loop for composites through recycling remains suboptimal, because of the material use and structure (Joustra et al. 2021). Therefore, choosing long lasting application through careful designs consideration should be favoured (Ibid.).
2.1.6 Does the product packaging consist of recyclable, biodegradable, or compostable materials?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product (Cayzer et al. 2017).
2.2 Longevity	
2.2.1 How does the total lifetime of the product compare to the market average?	Comparing a product’s lifetime against the market average is considered a valuable indicator to measure utility (EMF & GD 2015).

2.2.2 After what period of time will the user experience noticeable degradation of the product?	Functional, emotional, and social values play a role in the attachment users experience towards their products (van den Berge et al. 2021).
2.2.3 Does the product indicate to customers what key components are critical to the duration of either the technical lifetime or the economic lifetime (relevance to the market)?	An aspect from circular design is to determining what components are expected to degrade first and, if these components are critical, look for design solutions to prevent this (IRP 2018).
2.2.4 Does the product allow for enhancing a product's functionality and/or cosmetic condition throughout its lifetime?	Design strategies, like modularity, can allow product's functionality or appearance to be enhanced during its lifetime (Schischke et al. 2019).
2.2.5 Is the product designed to have a timeless aesthetic?	The selection of design style links with timelessness and can influence market acceptance of circular products significantly, which can increase longevity (Wallner et al. 2020). The question was rephrased as a result of Co-creation session 7.
2.3 Standardization	
2.3.1 Are Design for Standardization and (backward) compatibility applied throughout the whole product portfolio to support recovery options? (See Appendix I for more information)	Standardization and compatibility of sub-assemblies and components across product platforms allow for products to be used over multiple use-cycles (Schischke et al. 2019).
2.4 Maintenance & repair	
2.4.1 Is the product designed for ease of maintenance?	If the product requires maintenance to preserve its performance, then it should allow for ease-of-maintenance (Co-creations session 3). In case maintenance cannot be 'designed-out', minimizing the time and effort to maintain a product is recommended to enhance simplicity, reliability, and supportability (Mulder et al. 2012). The implementation of Design for Maintenance has a positive effect on other recovery activities (Ingemarsdotter et al. 2021;).
2.4.2 Does the product come with information, like a manual, on how to take care of it?	Informing a user about the possibilities for product care, makes the user aware of his or her influence on a product's lifetime (Ackermann 2020).
2.4.3 Does the product come with information, like a manual, on how to diagnose faults in key parts?	Providing information about fault diagnosis can help in restoring a product's function in a time-efficient, safe, and cheap way (Arcos 2021).
2.4.4 Does the product come with information, like a manual, on how to repair faults for key components?	Providing information about repairing faults can help in restoring a product's function in a time-efficient, safe, and cheap way (Dangal et al. 2022).
2.4.5 Does the product have visual or auditory design cues supportive of maintenance and repair by consumers?	A product's design can help navigate the user in following the simplest and time-efficient route for disassembly in order to maintain or repair a product (Arcos 2021).
2.4.6 Is the safety risk for customers minimized during repair of the product?	A product's design can be built facilitate safe maintenance, disassembly, and repair, not only by providing manuals, like mandated by EU legislation, but also through the physical design features (Arcos 2021).
2.5 Software support	
2.5.1 Does the product make use of any software?	A product that uses software to operate (a part of) its functionality.
2.5.2 Does software support form a bottleneck for products to live longer than the expected lifetime or for the extension of the product lifetime through re-use or remanufacturing?	Products that run software and serve for multiple use-cycles, should have hardware to support continuous software updates and upgrades, as well as availability of new versions of this software (Schischke et al. 2019).
3. CUSTOMER EXPERIENCE AND CARE	
3.1 On- & off boarding	
3.1.1 Are the obligations and responsibilities for access, use, and end-of-life of a product communicated to customers?	A central design intervention in gaining acceptance of users in product-service-systems has to do with communicating a clear and consistent message (Poppelaar et al 2020a). The question was rephrased as a result of Co-creation session 4.
3.1.2 Is the onboarding process tested with customers on clarity and convenience?	Major contributors to rejection of a product-service-system relate to a lack of understanding and lacking service quality, test and design

	iterations help prevent design flaws (Poppelaar et al 2020a). The question was rephrased as a result of Co-creation session 4.
3.1.3 Is the customer supported in letting go of the product at the end of life, either emotionally or practically?	Design interventions focused on emotional support help increase the readiness level and willingness of end-users to return their product, through reducing uncertainty and confusion (Poppelaar et al. 2020b). The question was rephrased as a result of Co-creation session 4.s
3.2 Use efficiency	
3.2.1 Does your product make use of consumables? This includes energy and water use.	For certain products to fulfil a function, they require consumables which can be either dissipative (e.g. washing detergent) or disposable (e.g. razorblades) (Willskytt 2020). The question was rephrased as a result of Co-creation session 5.
3.2.2 Does your product maximize the use-efficiency of consumables, compared to the market average?	Use efficiency that can be influenced by design relates to facilitating correct use, adjusted to the use context, as well as using appropriate products in the right quantities (Willskytt 2020). The question was rephrased as a result of Co-creation session 5.
3.2.3 Does the product activate customers to opt for sustainable use options?	Sustainable use can be promoted by complicating the more unsustainable options or simplifying the most sustainable option(s) (Wever et al. 2008). The question was rephrased as a result of Co-creation session 5.
3.2.4 Does the product require the use of consumables that contain critical or conflict materials?	Critical or conflict materials can be avoided or minimized through careful material selection (Willskytt 2020). The question was rephrased as a result of Co-creation session 5.
3.2.5 Does the product require the use of consumables that contain contents that can be hazardous to the environment in which they are discarded?	Hazardous materials can be avoided or minimized through careful material selection (Willskytt 2020). The question was rephrased as a result of Co-creation session 5.
4. PRODUCT SUPPORT SERVICES	
4.1 Warranty	
4.1.1 Does the product's warranty period last longer than what is legally required?	Warranty is provided for longer than the 2- or 5 years than mandatory from a legal perspective to guarantee a product's durability (Maitre-Ekern & Dalhammar 2016).
4.1.2 Are products that are returned by the customer as part of warranty repaired, refurbished or remanufactured?	Closing the loop for all of a product's material streams adds to the circularity of a product, and is a proven concept for companies to pursue remanufacturing operations (Boorsma et al. 2022; Inderfurth & Mukherjee 2008).
4.2 Professional support	
4.2.1 Does your company, or partnered companies, offer in-warranty maintenance & repair services for the product?	In cases where a product stops functioning within the warranty period, the product should be replaced. Turing to repair to restate the function of the product is the preferred action from a circular economy point of view (Maitre-Ekern & Dalhammar 2016).
4.2.2 Does your company, or partnered companies, offer any paid maintenance & repair support service for the product?	The availability of professional repair services as a route to lifetime extension to meet the need for repair in cases where self-repair is impossible or not desired (Niskanen & MacLaren 2021).
4.2.3 Is the customer informed about the professional maintenance and repair service?	Awareness of the professional support services offered are necessary to close make such services truly operational (Niskanen & MacLaren 2021).
4.2.4 Does your company, or partnered companies, offer an upgrade service for your product?	Upgrade services allow customers to update and personalize product performance during a use-cycle (Poppelaars 2014).
4.2.5 Is the customer informed about the possibility to upgrade the product?	The possibility for a customer to upgrade their product should be communicated through the accompanied service (Poppelaars 2014).
4.3 Spare part supply	
4.3.1 Are the spare parts to support self-repair by customers affordable?	The availability of spare parts is essential to benefit from a product's reparability (Repair Café IF 2020). Affordability of such spare parts is a key factor in motivating customers to invest in repair (Sabbaghi et al. 2016).
4.3.2 Does your company produce extra spare parts for recovery, to enable refurbishment or remanufacturing?	The availability of spare parts is essential in performing recovery activities, including the required number of spare parts in the calculations for production is one of the ways to secure availability (Boorsma et al. 2022). The question was rephrased as a result of Co-creation session 7.

4.3.3 Can customers return their used parts, that they have replaced, to your company?	Taking back used parts that are released from product through, for example, repair, can be valuable for several reasons: they can help increase circularity though (1) recovery for spare part supply (2) dedicated material recovery (De Giovanni et al. 2016; Inderfurth & Mukherjee 2008). The question was rephrased as a result of Co-creation session 7.
4.3.4 Are parts that are returned by the customer repaired, refurbished or remanufactured?	Closing the loop for all of a product's material streams adds to the circularity of a product, and is a proven concept for companies to pursue remanufacturing operations (Boorsma et al. 2022; Inderfurth & Mukherjee 2008). The question was rephrased as a result of Co-creation session 7.
5. RECIRCULATION SERVICE	
5.1 Return program	
5.1.1 Does your company have a program to actively retrieve products from the market?	Products can be sold in combination with services, or as services, with the benefit of securing the return flow at end-of-use (Tukker 2004). Having a return program prevents products to turn into waste or move into recycling before the product has reached its technical End-of-Life (Guide et al. 2006).
5.1.2 What percentage of the sold products are returned to the company or to partnered companies?	The number of products returning from the market has a significant influence on the effectiveness of a closed loop system (Shaharudin et al. 2017).
5.1.3 Are customers informed about the product return options?	Proactively marketing the options for customers to return products helps increase the awareness of the options and the likelihood of customers to engage with the options (Ren 2018).
5.1.4 At what point are customers informed about the possible return options?	Circular design can be used to (emotionally) support customers in returning their products through design interventions at different moments in time to increase product returns (Ren 2018).
5.2 Product retrieval	
5.2.1 Does the company provide re-usable packaging for return options?	Packaging materials typically have a short lifetime and generate a lot of waste, which can be reduced radically by replacing single-use by reusable packaging (Sarkar et al. 2017).
6. RECOVERABILITY	
6.1 Disassembly	
6.1.1 Does your company list the key parts for disassembly?	Key components refer to those components in a product that are technically, economically, or environmentally valuable to the recovery activities to reach to enable maintenance, repair, replacement or parts harvesting (De Fazio et al. 2021; IRP 2018). The question was rephrased as a result of Co-creation session 3.
6.1.2 Is product disassembly and reassembly optimised for time, cost efficiency, simplicity and tool availability?	Design for disassembly helps make the disassembly process of a product feasible, while minimizing damage caused to parts, optimizing part re-use, optimizing the disassembly route to access a key part, and reducing the disassembly complexity in terms of tools, knowledge and skill needed (De Fazio et al. 2021). The question was rephrased as a result of Co-creation session 3.
6.2 Refurbishment	
6.2.1 Does your company list what parts make the refurbishment operations feasible and viable?	The parts or sub-assemblies of a product can contribute to recoverability in different ways, like through increasing viability or feasibility. Understanding their role can help in optimizing their added value through design (Boorsma et al. 2022). The question was rephrased as a result of Co-creation session 7.
6.2.2 Which fraction of the material value, by cost price, can be refurbished?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product (Cayzer et al. 2017).
6.2.3 Does your company provide refurbishment instructions and protocols to the relevant departments or third parties?	Having standardized instructions for recovery operations is the first recommendation towards lean production (Kurilova-Palisaitiene et al. 2018). The question was rephrased as a result of Co-creation session 7.
6.2.4 Does your company have a clear diagnosis procedure for products returning from the market?	Diagnostics is seen as the critical first, and potentially time-consuming step, of the recovery process (Du et al. 2012; Zhang et al. 2021). Standardization of this process helps avoid deviations and avoid unnecessary time loss (Kurilova-Palisaitiene et al. 2018). The question was rephrased as a result of Co-creation session 7.

6.3 Remanufacturing	
6.3.1 Does your company list what parts make the remanufacturing operations feasible and viable?	The parts or sub-assemblies of a product can contribute to recoverability in different ways, like through increasing viability or feasibility. Understanding their role can help in optimizing their added value through design (Boorsma et al. 2022). The question was rephrased as a result of Co-creation session 7.
6.3.2 Which fraction of the material value, by cost price, can be remanufactured?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product (Cayzer et al. 2017).
6.3.3 Does your company provide remanufacturing instructions and protocols to the relevant departments or third parties?	Having standardized instructions for recovery operations is the first recommendation towards lean production (Kurilova-Palisaitiene et al. 2018). The question was rephrased as a result of Co-creation session 7.
6.3.4 Does your company have a clear diagnosis procedure for products returning from the market?	Diagnostics is seen as the critical first, and potentially time-consuming step, of the recovery process (Du et al. 2012; Zhang et al. 2021). Standardization of this process helps avoid deviations and avoid unnecessary time loss (Kurilova-Palisaitiene et al. 2018). The question was rephrased as a result of Co-creation session 7.
6.4 Recycling	
6.4.1 Which fraction of the material value, by cost price, can be recycled?	Calculating the ratio of the recoverable share of a product denotes the progress towards the circularity potential of a product (Cayzer et al. 2017). Expressing this ratio in value provides an inclusive image with respect to, for example, minor metals, that are often used in small quantities (Co-creation session 6; van Nielen et al. 2022).
6.4.2 Does the product fall apart into separate homogeneous or compatible material fragments in the shredding process?	Separating the materials of a product into uncontaminated material streams is a key factor to high-quality recycling (Joustra et al. 2021; van Nielen et al. 2022).
6.4.3 Are general recycling processes available for the materials in your product?	However recyclable a material is, whether a material gets recycled in reality depends on the availability of formal recycling processes, technology, and infrastructure (Li et al. 2022). The more common a material is, in type and mass, the more likely it is that general recycling processes are available. The question was added as a result of Co-creation session 6.
6.4.4 Is there an End-of-Use repurposing plan for the materials that are non-recyclable?	While their use is not uncommon, closing the loop for non-recyclable materials remains a challenge. Until recycling technology progresses, designers should to turn to repurposing scenarios to extend the lifetime of such materials to make continued use of the value of these materials' existing form and characteristics (Joustra et al. 2017; van Schaik & Reuter 2016).

2.4.3. Answer options and scoring system

The answer options were selected in a way that offers a sufficient level of differentiation between different levels of implementation, considering that design implementation can also be 'planned' or 'initiated', if not yet fully implemented. Most questions have 'not applicable' as an answer option, to let companies tailor this method to their own business type and context.

Simultaneously, a scoring system was developed. The scoring system would impact the way results are presented onto the method visual, and was therefore developed in parallel. The questions were answered using a multiple-choice format. This helped in standardizing the scores. A maximum of 1 point can be scored for each question, which equals a score of 100% for that question. Adding up all scores for one indicator, divided by the amount of scored questions, gives the average percentage scored for that indicator. Adding up all indicator scores within one theme, divided by the number of indicators, will give the average percentage scored for that theme. Similarly, adding up the scores for all themes

divided by the number of themes, gives the average percentage scored on the full assessment. All questions, indicators, and themes have the same weighing.
The scoring system that was applied in this assessment can be found in Table 8. All the themes, indicators, and questions have equal weighing. Adding up the score for a specific unit (theme, indicator, or question) and dividing this total score by all included units, will give the average score. By multiplying this number by 100, the percentage for that unit can be found.

Table 8 Circular Product Readiness - formulas for the scoring system

Final score of the assessment **=** **(A+B+C+D+E+F)/ 6**	A. Strategy & Planning = (H+I+J+K)/ 4	H. Design budget = score/ 1 I. Know-how = score/ 2 J. Customer research = score/ 1 K. Value proposition = score/ 2
	B. Hardware & Software Design = (L+M+N+O+P)/ 5	L. Materials = score/ 6 M. Longevity = score/ 5 N. Standardization = score/ 1 O. Maintenance& repair = score/ 6 P. Software support = score/ 1
	C. Customer Experience & Care = (Q+R)/ 2	Q. On- and off boarding = score/ 3 R. Use efficiency = score/ 3
	D. Product Support Services = (S+T+U)/ 3	S. Warranty = score/ 2 T. Professional support = score/ 5 U. Spare part supply = score/ 4
	E. Recirculation Service = (V+W)/ 2	V. Return program = score/ 4 W. Return rates = score/ 1
	F. Recoverability = (X+Y+Z+AA)/ 4	X. Disassembly = score/ 2 Y. Refurbishment = score/ 4 Z. Remanufacturing = score/ 4 AA. Recycling = score/ 4
** The scores for all themes added up divided by the number of included themes, multiplied by 100 to get the percentage.* *** Themes that were marked as N/A for all indicators should be excluded from the calculation*	** The scores for all indicators added up, divided by the number of included indicators, multiplied by 100 to get the percentage.* *** Indicators that were marked as N/A for all questions should be excluded from the calculation*	** The scores for all questions added up, divided by the number of included questions, multiplied by 100 to get the percentage.* *** Questions that were marked as N/A should be excluded from the calculation*

2.4.4. Development of the visual

Several criteria formed the basis for the development of the visual that shows the results of the assessment. The visual should allow for ease-of-communication of the results, on the four different levels (overall, themes, indicators, and questions), and it should show opportunities for improvement.

2.4.4.1 Design iterations based on indicator visuals from literature

Indicator visuals from literature were used as a reference for the development of the final visual. These indicator visuals tend to be radial and show the different axes of evaluation. Scores are indicated by lines and numbers. Colours were used to label different indicators.
Indicator visuals from literature:

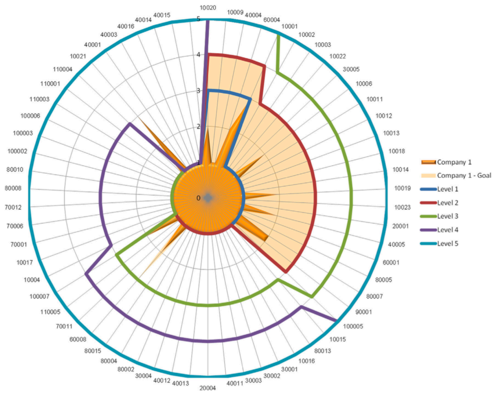

Figure 7 Ecodesign maturity radar (Pigosso et al. 2013)

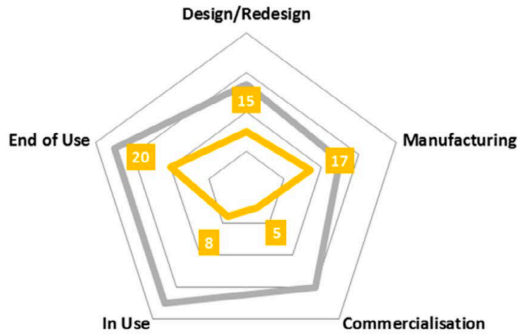

Figure 8 CEIP interface (Cayzer et al. 2017)

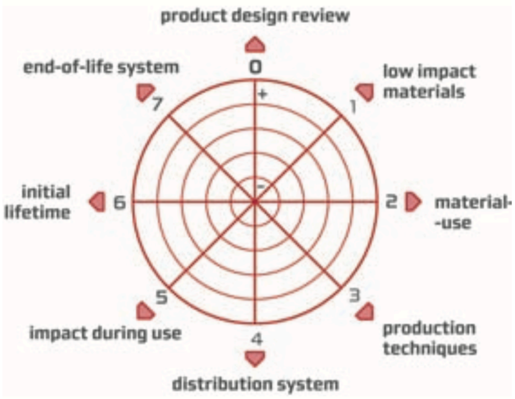

Figure 9 D4S Strategy Wheel (Crul et al. 2009)

Based on the insights from the indicator visuals and internal feedback loops, the first versions of the visual were created (Figure 10, Figure 11). The visuals were updated along with progress in the theme and indicator development. Factors like ease-of-communicated of the results, and having a coherent form language played an important role in the development of the final visual (Figure 12).

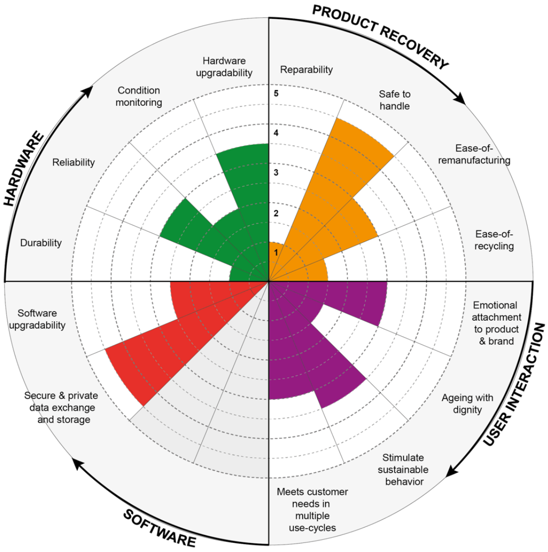

Figure 10 Design method visual - Version 1, November 2020

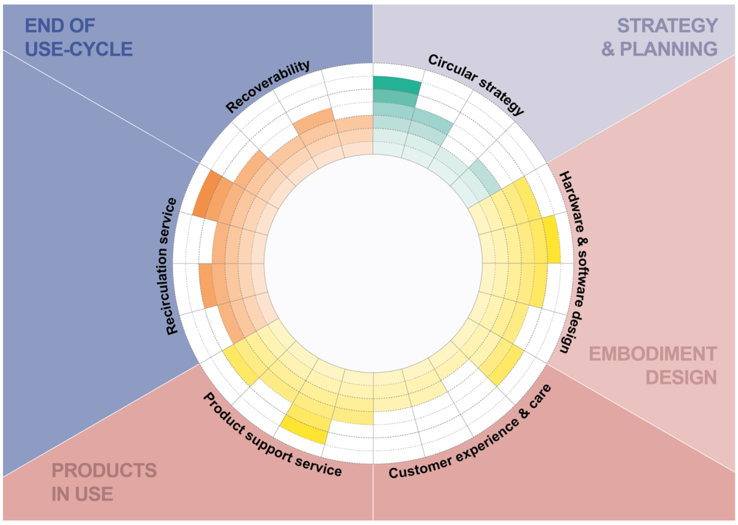

Figure 11 Design method visual - Version 2, September 2021

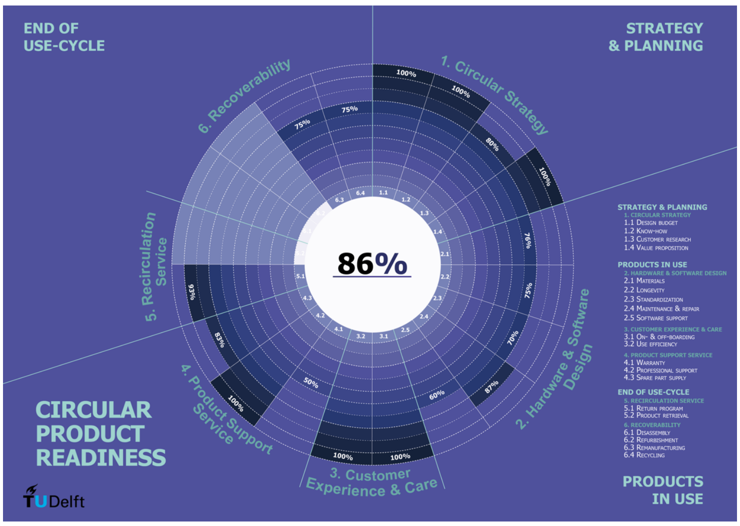

Figure 12 Design method visual - Final version, December 2021

2.5. Validation

This circular design method was implemented at both the white goods demonstrator and the automotive demonstrator of the ReCiPSS project. This was done by providing the companies with a link that contains the assessment questionnaire and with providing instructions that explain its use. Gorenje completed the assessment for their ASKO appliance. Bosch completed the assessment for their Common Rail Injector. The results were shared with the TU Delft through the online form, after which the results were analysed and translated into the method visual (Figure 14, Figure 15).

The implementation of the method was evaluated with Gorenje through a one-hour semi-structured interview. Bosch was presented an online questionnaire of 10 questions to evaluate the following four themes: general (time spent, role of respondent), completeness (themes, questions, missing topics), purpose (needs, and relevance), and usability (clarity, guidance, required data). A summary of the insights from the evaluation can be found in Table 9.

Table 9 Insights from method validation

Method criteria	**Gorenje**	**Bosch**
Has full lifecycle focus		- The method provides a full view on the topic
Indicates areas for improvement for circular design	- Gorenje sees the potential of the method to help the company progress over the years - The assessment helped evaluate the company's goals and is expected to be of support for their design road mapping activities	
Differentiate in levels of implementation	- the results of the assessment helped Gorenje to get insight in their readiness level for circular design - For a number of questions, the company required more differentiation between the answer options, to more accurately reflect their progress	- Circular concept is foreseen overall in Diesel product development already -
Have a high level of transversality		
Allows for ease of communication of the results	- From looking at the visual they could spot opportunities to learn about how to evolve even further - The method was helpful in communicating the results visually to colleagues	
Has a high level of dimensionality		
Attuned to use by designers	- The company indicated that it took 30 to 45 minutes to complete the assessment - For some questions the choice of words could be slightly adjusted	- It took 60 minutes to complete the assessment
Meets indicator requirements	- appropriateness: the themes and indicators were highly relevant to the company	- completeness: Assessing the general core availability and customs/tax/cross border regulations would also be an interesting scope to us

	- completeness: one additional question was proposed regarding the selection of packaging material - representation: it would be helpful to have a reference for the scoring - utility: the ideal user would be an employer working with marketing and branding together with a project lead	- utility: the questions were not fully clear - utility: the guidance to provide to answer the indicator questions was sufficient

Based upon the validation, a question concerning the packaging material selection was added and the wording of several questions was adjusted. In addition, the answer options were evaluated to allow for optimal differentiation of implementation levels. Another insights gained from the validations, is that companies should be able to use the Circular Product Readiness method as independently as possible. For this reason, a printable visual template was created on which companies can fill in the assessment scores (Figure 13 & Appendix III).

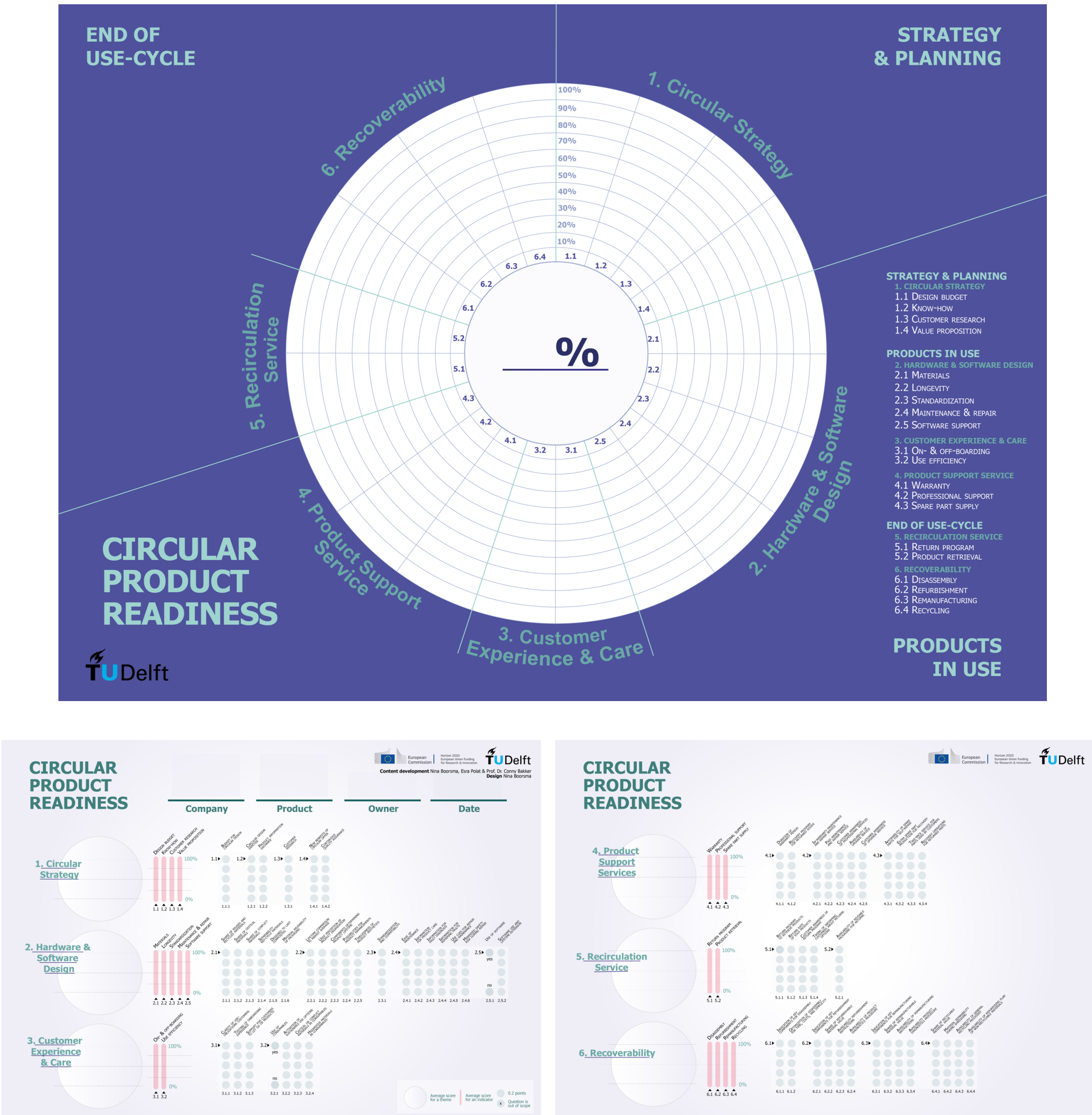

Figure 13 Circular Product Readiness printable template for companies

Based upon literature reviews, analysis of existing indicator methods, industry needs, the ReCiPSS task descriptions, and the design visions of the ReCiPSS, method criteria were compiled. These criteria were used to develop the assessment method through several design iterations, co-creation sessions, and through company testing. Table 10 shows in what ways the method criteria from section 2.2.3 were met through the application of the different approaches.

Table 10 Evaluation of the method criteria

Method criteria	**Evaluation**
Has full lifecycle focus	This requirement was met. The assessment method takes into consideration themes from the strategic design phase on, until the recoverability phase. Co-creation sessions and validation with companies helped assessing the completeness of themes and indicators to cover the full lifecycle.
Indicates areas for improvement for circular design	This requirement was met. The method visual makes it easy to interpret what the areas for improvement are, by showing the score for each individual indicators and question separately.
Differentiate in levels of implementation	This requirement was met. The different levels of implementation are reflected by the differentiation of the answer options. The level of implementation is reflected in the method visual by the number of points earned for each question.
Have a high level of transversality	This requirement was met. The transversality is supported by the answer option 'N/A (Not Applicable)', which allows design teams to exclude questions from the assessment that are out of scope. This is reflected in the method visual by crossing out/ greying out questions or indicators that are out of scope.
Allows for ease of communication of the results	This requirement was met. The method visual was designed in a way that allows for ease of communication of the results on the level of an individual answer, as well as more aggregated scores, like that of an indicator or an overall score.
Has a high level of dimensionality	This requirement was met. The circular strategies were assessed in great detail to reflect the nuances to successfully designing circular products. Four levels of dimensionality were distinguished for the scoring system: the overall score, themes, indicators, and individual questions.
Attuned to use by designers	This requirement was met. The accessibility to designers was evaluated in the company tests. All questions were answered, considered in scope, and had a clear relation to circular design. The wording was optimized in a final iteration to further improve the accessibility.
Meets indicator requirements	**The following criteria were met through co-creation**: The co-creation sessions allowed for the finetuning of the indicators and questions. Based on these sessions, questions were added, deleted, and adjusted, to meet reach reliability, construct validity, content validity, generality, comprehensibility, and transparency. **The following criteria were met through the visual**: The method visual enables users make updates to the results of the assessment, ensures that the results are comprehensible, transparent, and follow aggregation principles by distinguishing different levels for the scoring. **The following criteria were met through validation**: Through validation with the companies, the construct and content validity of themes and indicators was tested, whether the assessment is comprehensible, and, finally, its operationability was assessed, by looking at the time spent on completing the assessment and the clarity of questions and answers.

The next step for the method development is to complete the assessment for different product categories at the OEMs. This is to start building a reference for the scoring as well as to spread knowledge throughout the companies so that other company divisions can benefit as well. It will also provide insight into the usability of the method, in terms of familiarity with the wording and the type of information, and to test whether the method is truly stand-alone.

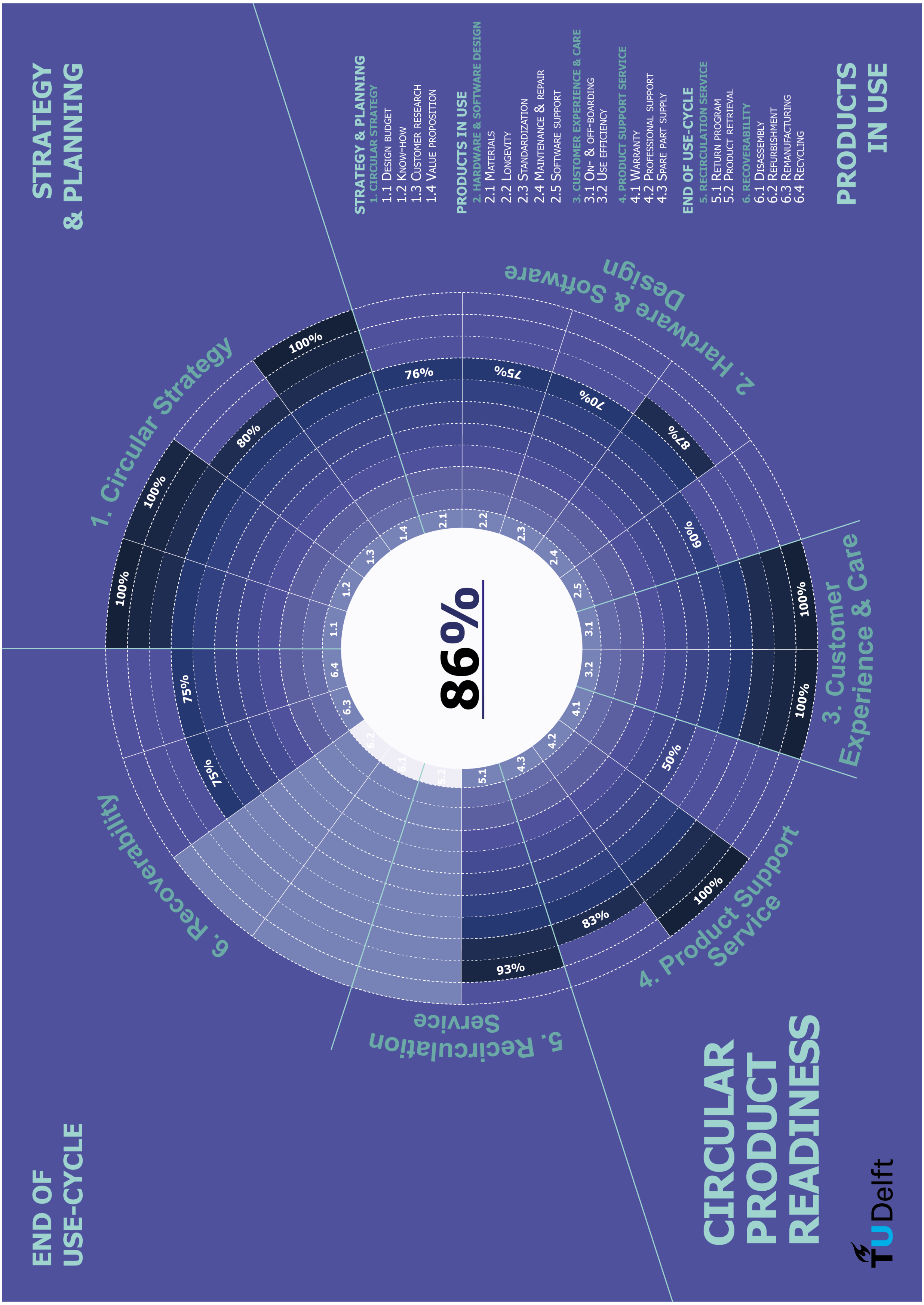

Figure 14 Final visual for the Circular Product Readiness method – results of Gorenje

CIRCULAR PRODUCT READINESS

Company	Product	Owner	Date
gorenjegroup	ASKO washing machine	Aleš Mihelič & Simon Kotnik	16-11-2021

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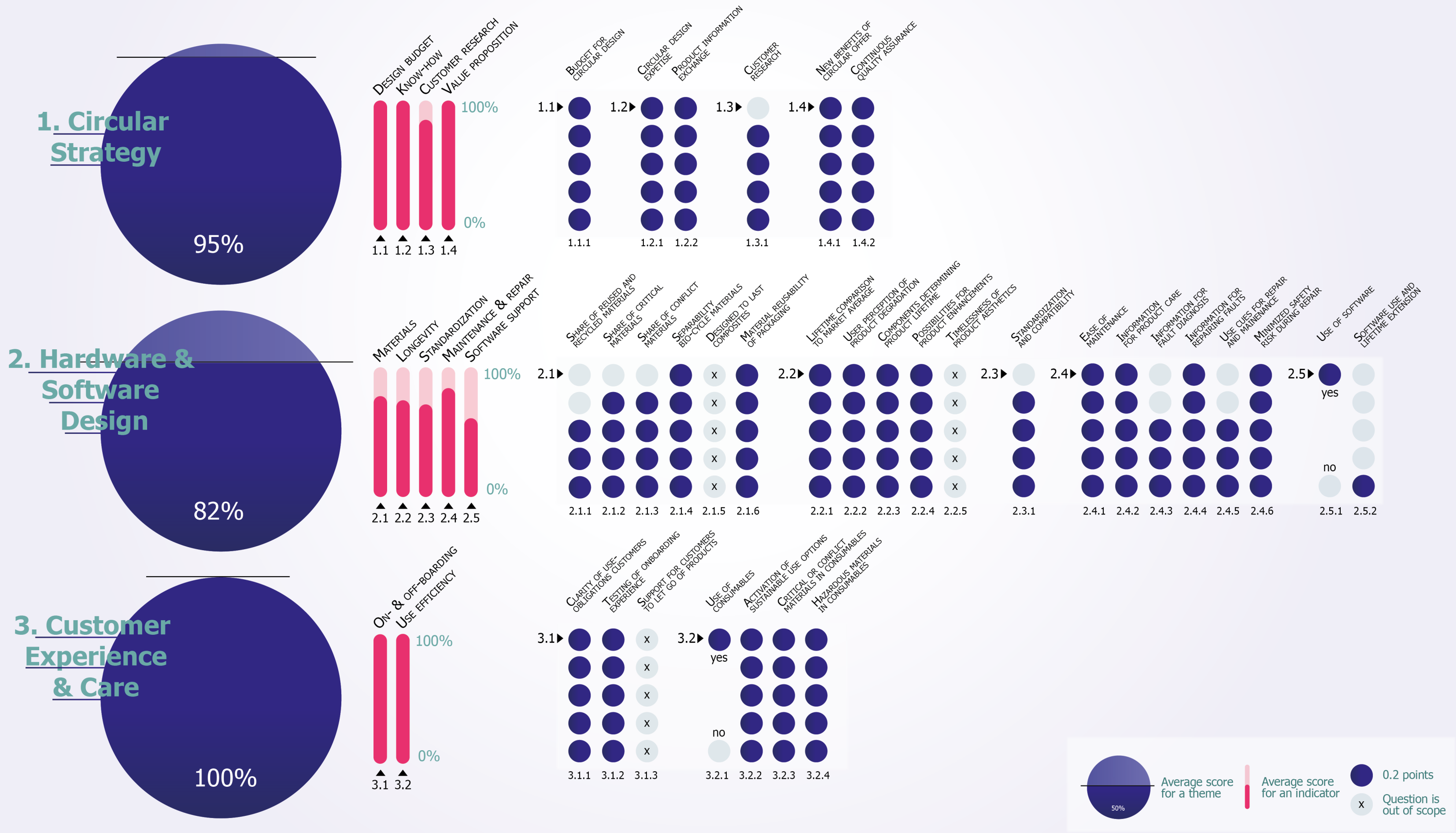
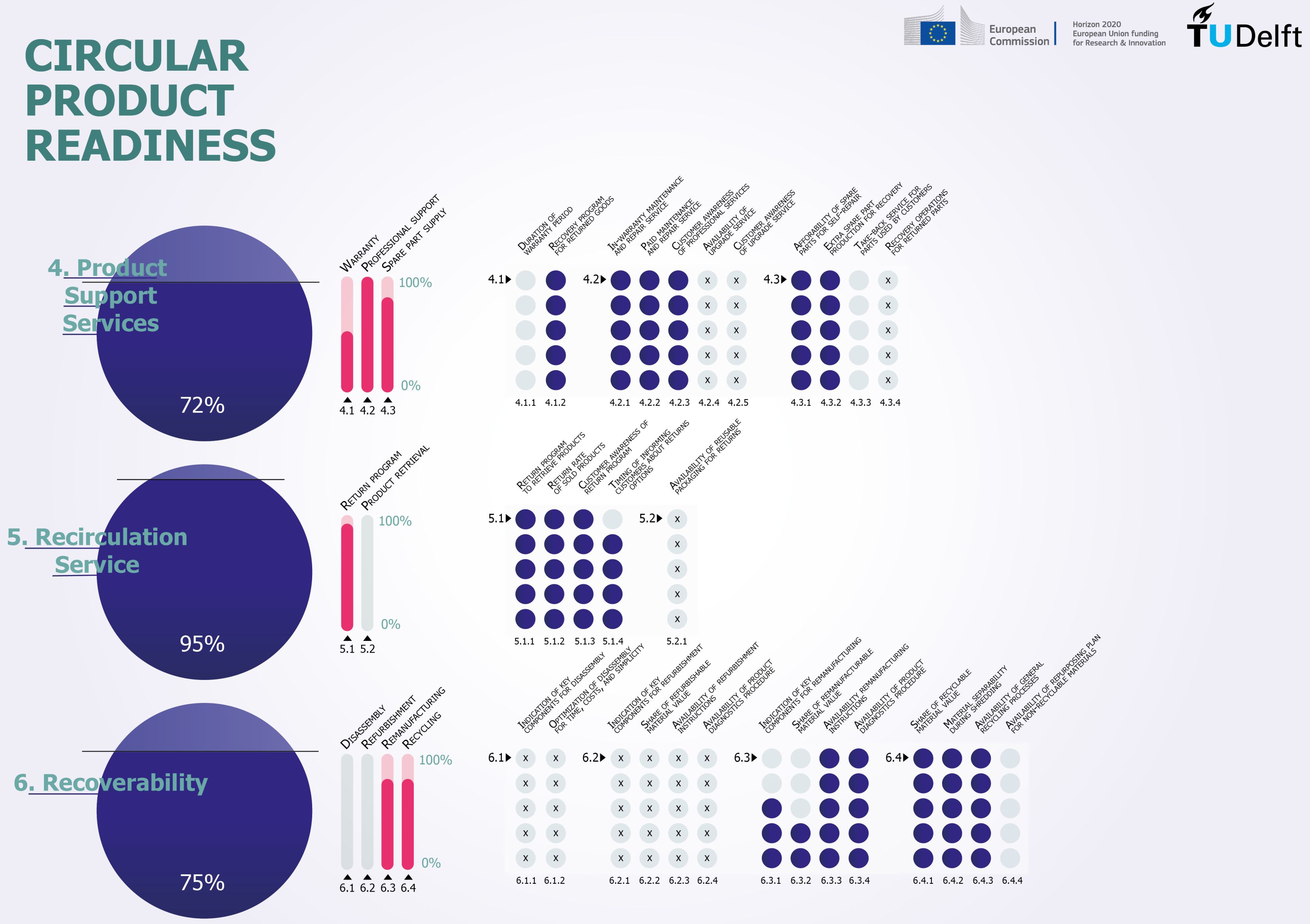
TU Delft

Content development Nina Boorsma, Esra Polat & Prof. Dr. Conny Bakker
Design Nina Boorsma



CIRCULAR PRODUCT READINESS



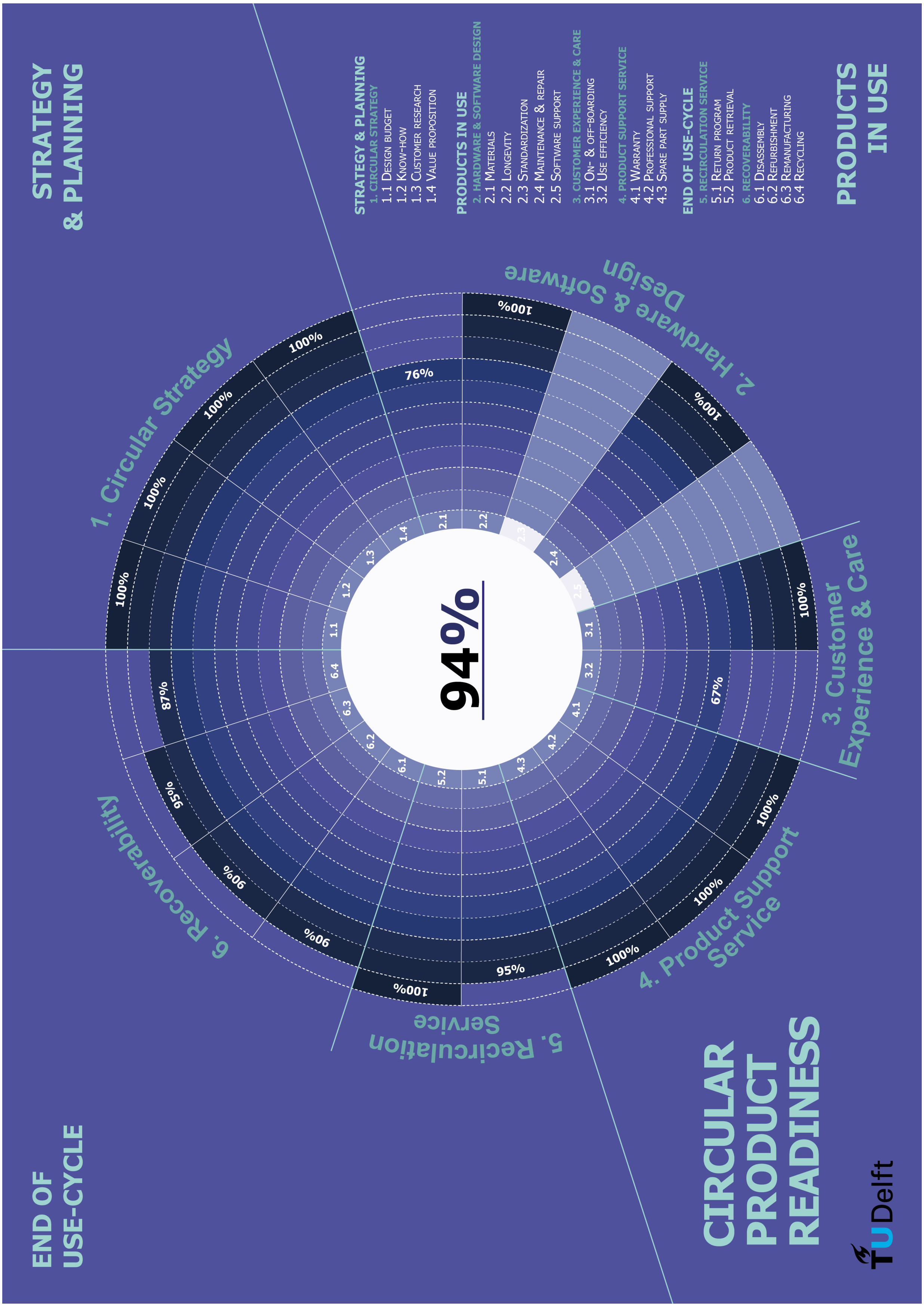


Figure 15 Final visual for the Circular Product Readiness method – results of Bosch

CIRCULAR PRODUCT READINESS

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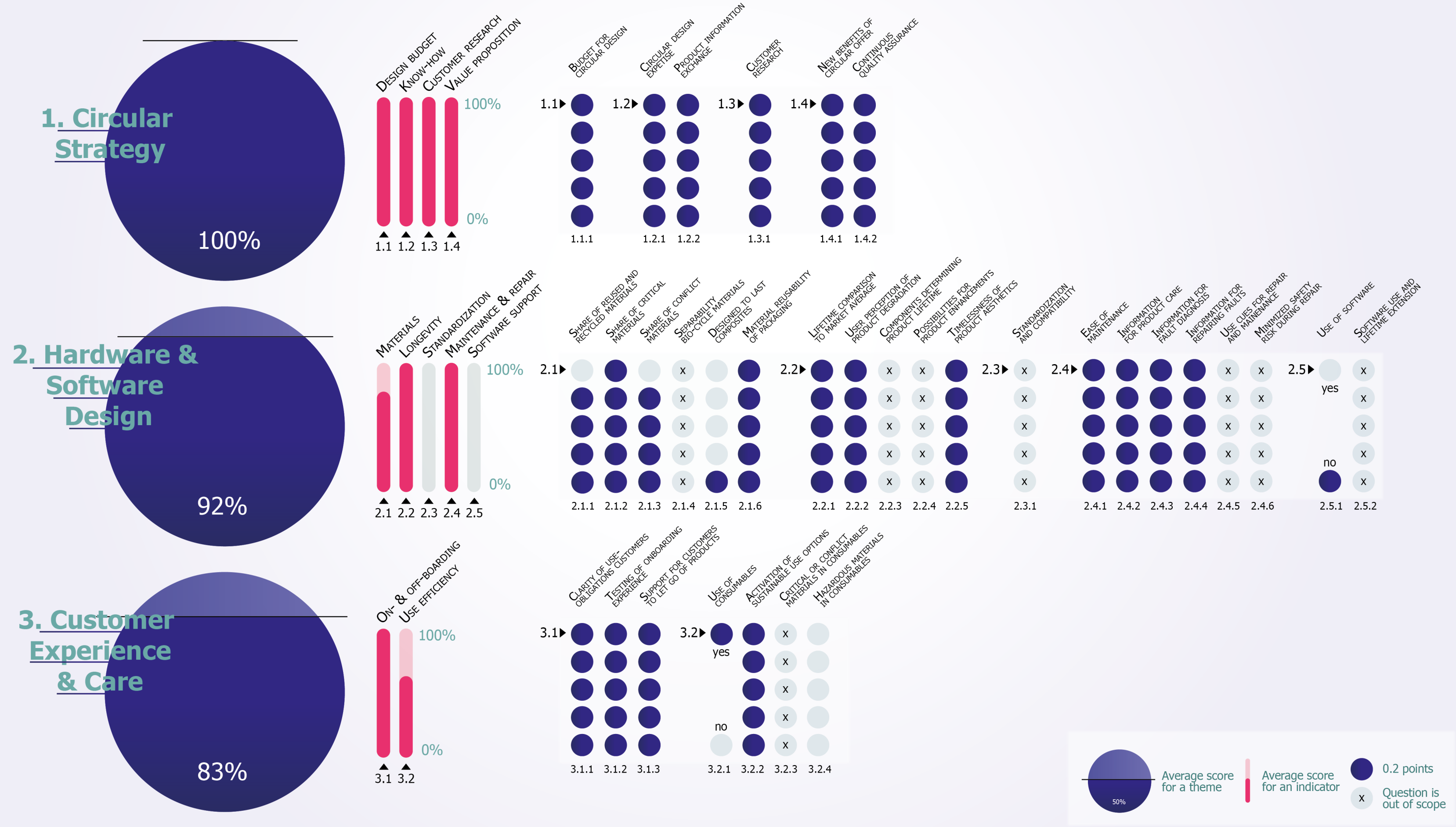
Design Nina Boorsma

Company	Product	Owner	Date
BOSCH	Common rail injector	Product marketing	20-12-2021



CIRCULAR PRODUCT READINESS

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2.6. Discussion and conclusions

Growing implementation efforts to shift towards circular design, brings out a need for monitoring methods at the design management level. There is a need for companies to learn about the effectivity of their actions, as well as to learn about opportunities for improved implementation.

This study aimed at developing a method that indicates the readiness level of companies for designing circular products. What was missing from existing indicator methods is that they either (1) lack depth with regards to circular design (2) are incomplete, and/ or (3) lack a designer's perspective.

The Circular Product Readiness method takes a design perspective and provides a means to give guidance to and monitor the status of circular design implementation. It helps companies assess their readiness level to design the different aspects of circular product service systems. The method shows the overall score, and the score for all themes, indicators, and questions separately, as well as the possibilities for improvement.

The body of literature on circular design indicators is growing rapidly (Cayzer et al. 2017; Kristensen & Mosgaard 2020; Linder et al. 2017; Saidani et al. 2019). The expectation is that new indicators will be developed for a broad range of design factors. Since no company is the same and all have their own specific goals and challenges, having a richer basis of indicators to choose from will benefit the accuracy and level of details of the measurements. Further development of this method will therefore be to continuously evaluate the scope of design factors and add to the current selection of indicators. Another point for development is the platform for the method. Currently the method runs on excel. For future versions, more advanced platforms can be considered to maximize usability, to improve on data visualization, and to increase accessibility of the method.

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3. Product Journey Map

This chapter presents the development of the Product Journey Map (PJM). The following elements will be described within this chapter: purpose of the method, the method development and description, the validation of the method, and the opportunities for future research.

3.1. Introduction

Despite the growing importance of circular design strategies, companies do not design products for multiple use-cycles (Boorsma et al. 2022; EC 2020). To facilitate this process, designers need design methods that help identify all possible design requirements to analyze a product's entire lifespan.

Companies follow different routes to adopt circular ways of producing. Some companies are product-oriented (Figure 16), as is the case for Bosch. Here, the provider (Bosch) transfers ownership of the automotive part and incentivises the return of used automotive parts from the aftermarket. In the case of Gorenje, the company keeps ownership of the washing machine and provides it as-a-service in a use-oriented model.

The products of both OEMs have very different 'journeys' throughout their service lifetime than would be the case in a linear sales system. It is therefore important to map these journeys in time and show where the products interact with the different stakeholders in their ecosystems. Mapping a product's journey over time creates overview, allows the OEM to identify potential areas of improvement and opportunity, and helps align internal departments by giving them a shared visual and vocabulary.

One method that attempts to provide designers with a complete and systematic way to analyze a product's lifespan, is the Product Journey Map. The first version of the PJM was published in the Delft Design Guide, but further development in terms of the procedure and method visual to be easily adopted by industry (van Boeijen et al. 2020). The objectives for the further development of the method, therefore, are: (1) to develop a formal structure for the method, and (2) to create an actionable and informative visualization that designers can use for internal communication, further development, and optimization of the product-service system.

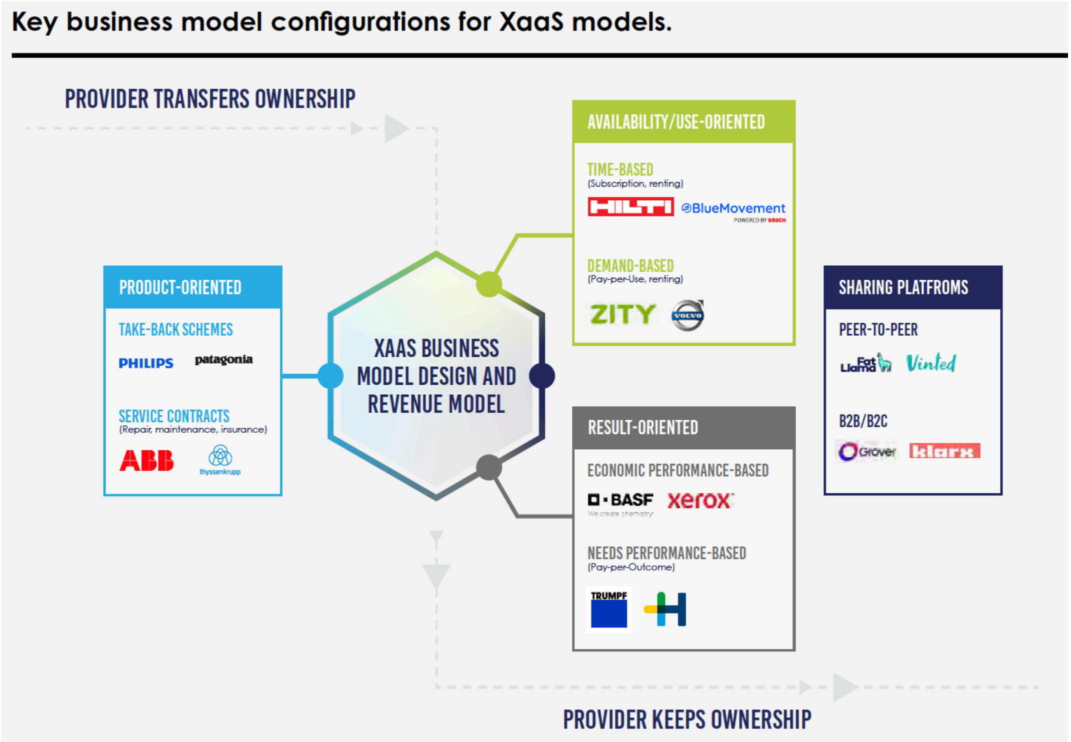

Figure 16 Key business model configurations for XaaS: Everything-as-a-Service (Braun et al. 2021, based on Tukker, 2004).

3.2. Background

The purpose of this new circular design method is to (pre)determine the journey of a product, and its interaction with the various stakeholders, throughout its lifetime. The journey map should contain the sequence of events through which a product interacts with customers, the manufacturer, and network partners. Creating a product journey map will enhance value capture from a company's products by improving the efficiency and effectiveness of the various touchpoints. It will be a strategic method that helps designers to prepare scenarios for a product's journey in its consecutive life-cycles to see where potential service touchpoints and opportunities for capturing value may occur. This section reviews existing journey mapping methods and concludes with criteria for the development of this new circular design method.

3.2.1. Existing journey mapping methods

A literature review was conducted to establish the extent to which current (circular) design methods exist which enable the mapping of a product's journey. Journey mapping can prove to be a helpful method in getting insight in the additional, or changed, requirements circular products need to meet. Conversely, it helps designers analyse the inherent circular potential of a part and select the appropriate journey to

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maximise that potential. Visualizing journeys can be used as a method to inform strategy, by pointing to opportunities for innovation. It can also help align department goals, build empathy amongst relevant stakeholders, break down siloed thinking, and provide insight in complex systems. When applying this method, it is expected that new design opportunities can be identified and translated into requirements for product development.

The tables in this section summarise the descriptions and insights from analysing four design methodologies (Table 11). Based on the analysis of these design methodologies, learnings could be derived for the development of the Product Journey Map. The first method that was analysed is the Customer Journey Map (Table 11).

Table 11 Insights from Customer Journey Mapping

Customer Journey Mapping (CJM)	Description	Insights
Rationale	"A process or sequence that a customer goes through to access or use an offering of a company." (Følstad & Kvale 2018; Tueanrat et al. 2021) Customer journey mapping focuses on human experiences, visualizing the story of a specific actor as a sequence of steps (Figure 17).	Insight: just like the CJM, the PJM can be used to map the 'story' of a specific product as a sequence of steps
Framing	Can be useful in several stages of the design process. In the beginning, they can help to understand people's experiences with a product or a service. Later on, they can help make decisions on a certain design direction or when ideating new solutions.	Insight: the method is adaptable to the stage of the design process (it can have different levels of abstraction; from generic to highly detailed)
Goals	To understand the user experience, to help in decision making and to help in the ideation process.	Insight: a method can have multiple goals

What can be learned from the CJM, is that a storyline can be created by sequencing the events an object or person experiences or interacts with. In case of the CJM, a customer is put central to create the journey. For a PJM, the focus shifts to putting a product central to the journey. This story can be attuned to specific stages of the design process, by detailing at the right abstraction level. This implies that the tool can be used for multiple goals.

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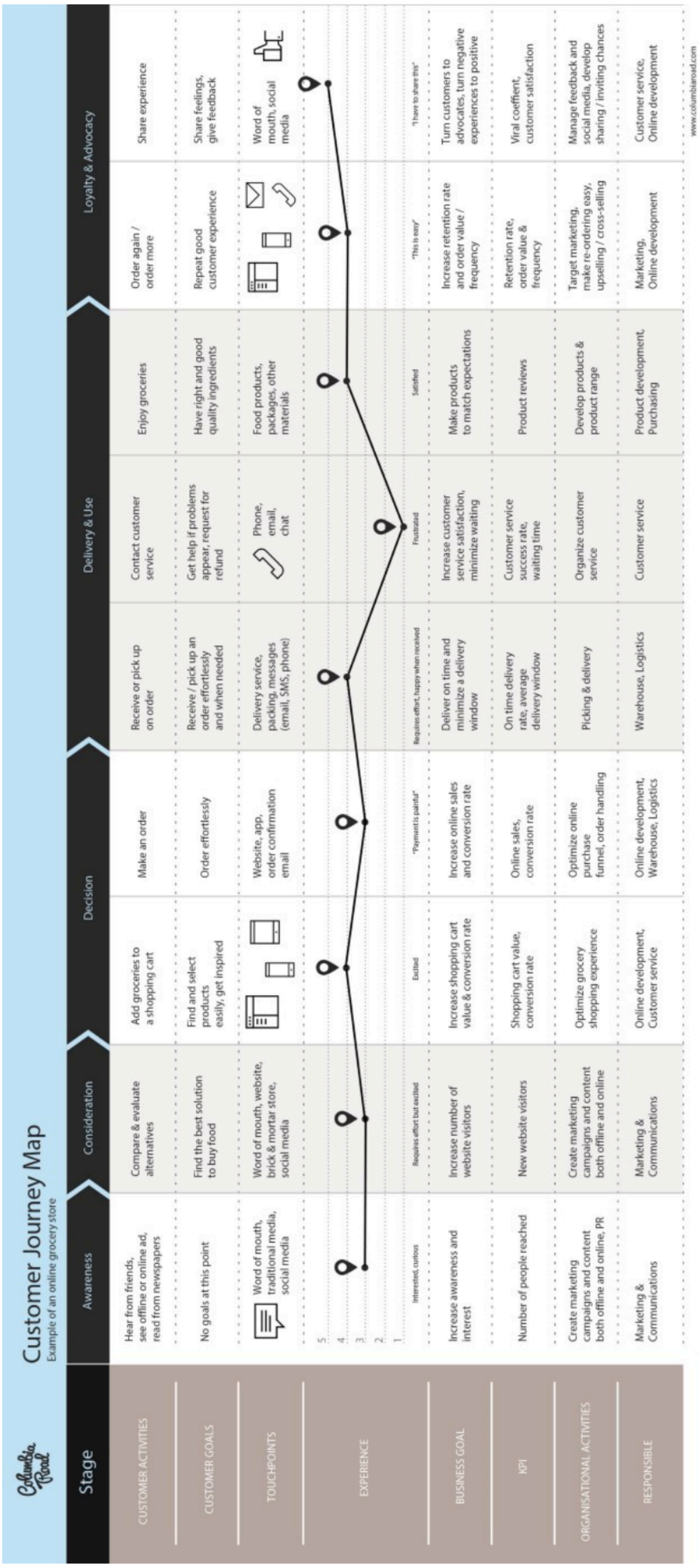

Figure 17 Example of a Customer Journey Map (Columbia Road, 2017)

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The next method is the Sankey Diagram (Table 12). In the context of creating a product journey map, its functionality can be used to manage all of a products components and material streams, the incoming and outgoing streams can be mapped, while showing the interdependencies between different streams and actors. According to the specific design goal, the type of data set and scale should be selected. By carefully setting the boundaries condition to meet the selected goal, the flows of resources can help optimize a specific functional unit.

Table 12 Insights from the Sankey Diagram

Sankey Diagram	Description	Insights
Rationale	A map that displays (scaled) material flows on the basis of product or system data (Lupton & Allwood 2017, Schmidt 2008a) (Figure 18). To interpret and analyse data and learn about quantity relations (Schmidt 2008b).	Insight: mapping all incoming and outgoing material flows helps to learn about the interdependencies of the flows.
Framing	To visualise complex flows with a predetermined focus for optimalization (Schmidt 2008b). Making this map requires data related to a period in time or a functional unit and is therefore done 'ex post', to evaluate a situation that has already taken place, or 'ex ante', based on assumptions and historical data (Saidani et al. 2019; Schmidt 2008b).	Insight: this method can be built from different scales and types of data.
Goals	To obtain the full overview of material flows and to optimize selected material streams to meet quality conditions and avoid unaccounted resource leakage (Lupton & Allwood 2017).	Insight: visualizing and analysing material flows can help optimize a functional unit, like a product unit.

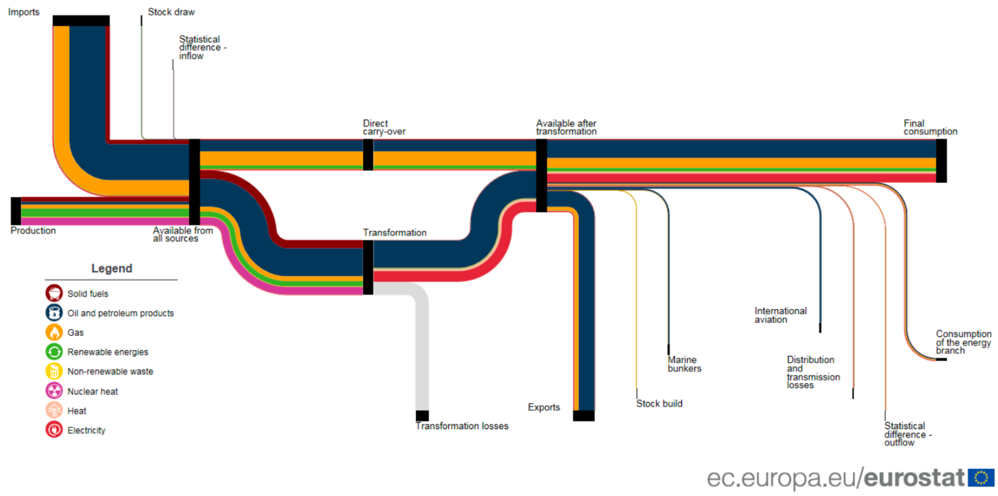

Figure 18 Example of a Sankey Diagram (Eurostat, 2020)

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The third method to be analysed is the Value Mapping tool (Table 13). What can be learned from the Value Mapping tool is the notion that value creation takes places within a value network, and relies on the ability of its actors to collaborate and assist each other is value creation. Gaining insight in all of the actors' needs at an early stage helps to optimize the system's design, and increase a systems sustainability potential.

Table 13 Insights from the Value Mapping Tool

Value mapping tool (Bocken et al. 2013)	Description	Insights
Rationale	An iterative process for analyzing sustainable value creation opportunities from a multi-stakeholder perspective. The tool allows for investigation of value exchanges across a detailed list of stakeholders (Figure 19).	Insight: Sustainable value creation takes place within a value network, thus reaching outside the company walls.
Framing	To gain a better understanding of the value proposition and embed sustainability into the core purpose of the firm and its network of stakeholders.	Insight: Evaluating the involvement of (potential) stakeholder at an early stage helps in drafting and comparing different scenarios.
Goals	To redesign and realign stakeholders' interests by identifying value tensions and opportunities, especially in relation to society and the environment.	Insight: each stakeholder can contribute to sustainability in their own way, value can be maximized by aligning these contributions.

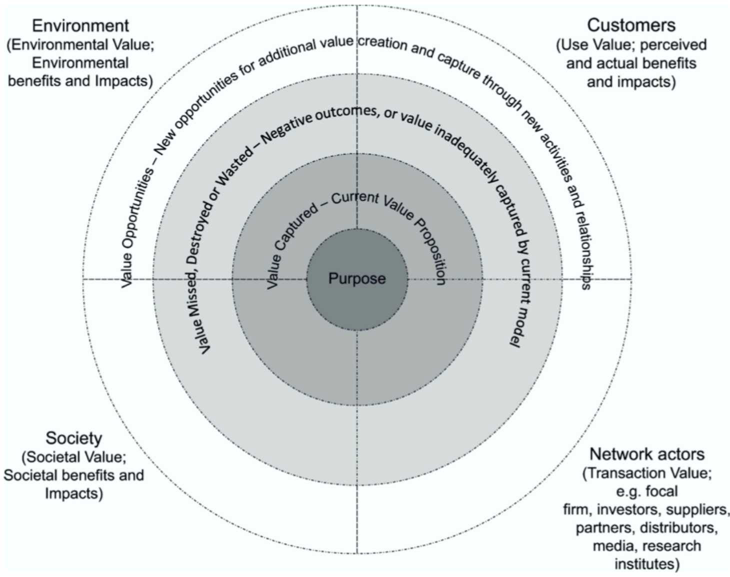

Figure 19 The value mapping tool (Bocken et al. 2013)

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The final method that was analysed is the Multi-method Simulation (Table 14). In this method the individual components of product have their own ideal circular path, that may be dissimilar to that of a full product. Optimizing the sub-sets of a product contributes to the resource efficiency of the whole product and helps align the product- and business model design.

Table 14 Insights from the Multi-method Simulation

Multi-method simulation (Lieder et al. 2017)	Description	Insights
Rationale	An explorative approach to prepare a product for multiple life-cycles, by assigning end-of-life strategies to individual components.	Insight: the life-cycle of a product's components may be dissimilar from that of other components or the full product.
Framing	A strategic tool that helps outline a components' best preferred circular scenario to find new opportunities for improved resource efficiency (Figure 20).	Insights: the life-cycles of individual components can be optimized for improved resource efficiency.
Goals	To provide reliable decision support at the intersection between circular product design and circular business models, expressed in costs and CO2 emissions.	Insight: information on components' optimized life-cycles can be used for aligning circular product design and circular business model design.

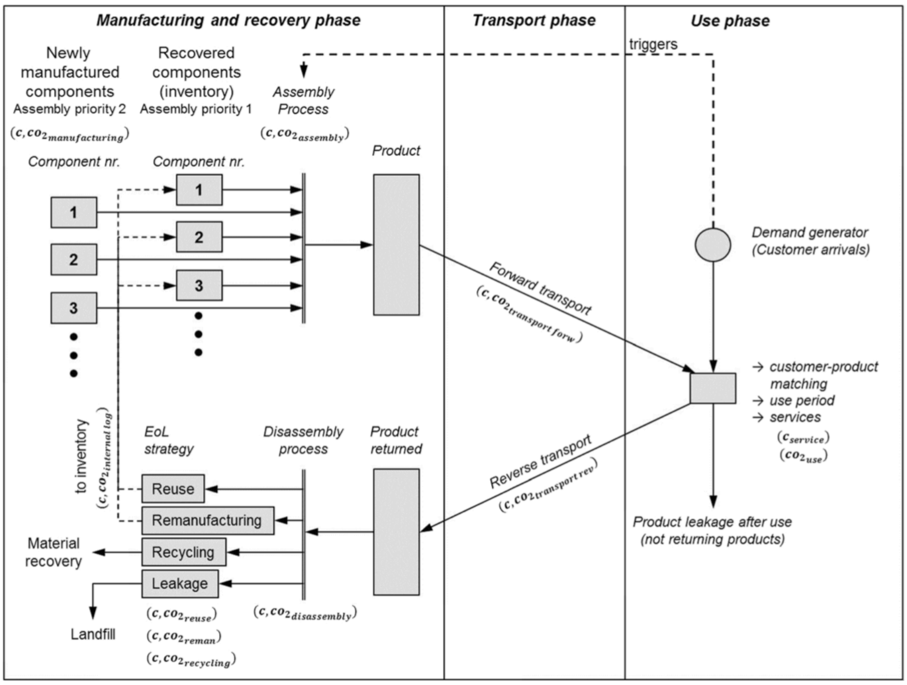

Figure 20 Circular supply chain process model as part of the multi-method simulation (Lieder et al. 2017)

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In summary, the following learnings could be derived for the development of the Product Journey Map:

- Sequencing a product's life-cycle steps can help build and visualise a storyline
- The method can serve multiple goals and/ or design stages through the selection of the data set, scale, and system boundaries.
- Different streams of resources, i.e. components or materials, can be mapped to arrive at lifecycle scenarios.
- Indicating the interdependencies between streams and actors can offer valuable insights
- Taking into consideration the needs and requirements of all actors involved can help strengthen the circular system.
- The method can uncover opportunities for increased circularity and resource efficiency.

3.2.2. Criteria for method development

The criteria for developing the Product Journey Map are a combination of previously established criteria from the ReCiPSS D3.3 report (confidential report), learnings from literature on developing new design methods, and learnings from literature on existing journey mapping methods (section 3.2.1).

The following criteria were established in ReCiPSS report D3.3:

- The method should capture all lifecycle events that influence design into one overview, to create a product journey that meets all lifecycle- and stakeholder needs (based on the results of EU project ResCoM).
- The method should be able to show a product's interactions with different stakeholders (based on consultations with the OEMs and the results of EU project ResCoM).
- The method should generate a company-specific map that is based on company data and substantiated assumptions (based on the requirements from task 3.3).
- The method should allow for ease of communicating its results (based on the requirements from task 3.4 and the design vision of ReCiPSS).

Literature on the development of new design methods discuss two main criteria. These two important criteria are the accessibility and usability of a method (Daalhuizen 2014). Accessibility relates to the ease with which a designer can access (the contents of) the method. This applies to a wide range of elements within a method, such as a method's description, the structure, and the data requirements. Usability refers to the ease at which the method can be applied after it has been selected. This refers to the used format: use of illustrations, proper language, and

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examples of applications, or to the information needed to apply it properly - conditions of use and theoretical underpinnings). Therefore, the following two criteria were added to the list:

- The method should be optimized for usability
- The method is optimized for accessibility

To conclude, the final set of criteria will be the starting point for the development of the Product Journey Map:

- The method facilitates mapping of lifecycle events of a product that affect design (Based on section 3.2.1 - D3.4, and the results of EU project ResCoM).
- The method includes the requirements of all relevant stakeholders (based on consultations with the OEMs, the results of EU project ResCoM, and section 3.2.1, D3.4).
- The method generates a company-specific map that is based on company data and substantiated assumptions (Based on the ReCiPSS project proposal task 3.3 and the design vision of ReCiPSS)
- The method provides insight into the flow of the product and parts over time (section 3.2.1 - D3.4)
- The method is optimized for usability (this section)
- The method is optimized for accessibility (this section)

3.3. Approach to develop the design method

The development of the PJM takes place in three steps: design iterations, detailing of the final concept, and validation. The three steps are described in more detail below.

(1) Design iterations using case studies
The method procedure and visual are developed simultaneously through design iterations. Different visualisation techniques are used to structure and organise the information. A case study product was used to test the series of design iterations. The concepts were evaluated based on the method criteria from section 2.2.3.

(2) Detailing of the final concept
Daalhuizen & Cash (2021) state that a successful method contains of five elements: method rational, method framing, method goal, method procedure, and method mindset. Firstly, the method rationale provides justification for the method goal. Secondly, the method framing corresponds to the context(s) in

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which the method is to be used. Thirdly, the method goal corresponds to how a method can contribute to achieving a design goal. Fourthly, the method procedure corresponds to how a method's prescribed procedure can contribute to reaching the design goal. Finally, the method mindset corresponds to the beliefs and knowledge that users need to possess when using design methodologies.

Early iterations of the method rational, framing and goal were specified in the first section of this chapter, based on literature. The procedure and mindset of the method was developed by studying the literature about End-of-Life decision-making of products, as well as literature on modularization following circular principles.

The final version of the Product Journey Map was presented using these five elements of design methods.

(3) Validation

The method was validated by preparing the Product Journey Map for a case company and by evaluating this in a one-hour interview. The validation was done on the basis of the method criteria from section 2.2.3. Based upon the results, the Product Journey Map went through another round of iteration, to optimize the procedure and method visual.

As a final step, the method criteria were again evaluated by the researchers to see to what extent the criteria were met by the final design.

3.4. Development of the Product Journey Map method

This section presents the development of the Product Journey Map. The analysis of existing design methodologies, in combination with the learnings from the development of 5 PJM concepts (Appendix IV), led to the final concept. This section gives a description of the goal and procedure for this final version.

3.4.1. Development of the building blocks

Several building blocks lay the foundation for the development of the method (Kooijman 2022). These building blocks inform how a product and its sub-assemblies (can) journey through their use-cycles. These elements are the strategic disciplines, product obsolescence profiles, End-of-Life (EoL) scenarios, part categorization, and stakeholders. A description of each of the building blocks can be found in this section.

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Strategic disciplines

The strategic discipline of a product indicates what the strategic value of that product is to a company. This value can be divided into three disciplines: operational excellence, customer intimacy, and product leadership (Treacy and Wiersma 1997). To succeed in the marketplace and differentiate itself from its competitors, a company must focus on one discipline and keep the other two disciplines at a threshold level. Products or parts that are made to support operational excellence are intended to minimize costs, reduce production steps, and optimize business processes, with lean operations as a result. Delivering products at competitive prices and minimal inconvenience is central to this discipline. Products and parts that are made to support product leadership are intended to offer new solutions. This discipline results in state-of-the-art products and services. Products and parts that identify with the customer intimacy discipline, concentrate on customizing products and services in such a way that the product will find customer acceptance. The focus here, is to build customer loyalty and customization. Asif et al. (2021) found value is assigning these disciplines to sub-assemblies of a product, as this can help optimise the circular scenario for these sub-assemblies.

Obsolescence profile

The strategic disciplines can be linked to specific obsolescence types. Products become obsolete when users no longer consider them valuable or significant (den Hollander 2018). At the point a sub-assembly becomes obsolete, the first step is to determine whether this concerns absolute obsolescence, which refers to ability to fulfil a function at the quality as originally intended, or relative obsolescence, which refers to relevance of this function (and appearance) in relation to the available alternatives (Granberg 1997). The next step, is to find out if obsolescence concerns emotional, technological, or functional obsolescence, which are the most common forms of obsolescence (Asif et al. 2021)

When a product is *functionally obsolete*, the particular product fails to carry out its function. An example would be when a piston inside the engine malfunctions. The introduction of new aesthetic designs often trigger *emotional obsolescence* due to the users' desire for newness or lack of attachment with the product for various reasons. Another example of emotional obsolescence is an old iPhone model becoming less attractive to the user upon introducing the new iPhone model. *Technological obsolescence* results from a shift or advancement that makes an old product incompatible with new technologies. An example of technological obsolescence would be when CPU chips changed from 16 bits to 32 and then 64 bits. During this change, operating systems had to accommodate the older architecture.

These three forms of obsolescence are responsible for the disposal of most of the products used in everyday life. A product rarely faces all forms of obsolescence simultaneously (Asif et al. 2021). When a product faces emotional obsolescence, the product might still be functional. An example of this phenomenon is the electronic consumer market, where new designs with, sometimes minor, technological

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improvements enter the market. These new designs make older product models less attractive to the customer, even though they are perfectly functional. A reason for this phenomenon is that different product sub-assemblies face different types of obsolescence at different points in time.
Connecting to the strategic disciplines: product leadership tends to be linked to technological obsolescence, customer intimacy tends to be linked to emotional obsolescence, and operational excellence tends to be connected to functional obsolescence.

End-of-Life scenarios
The combination of the strategic disciplines and obsolescence profiles commonly link to specific End-of-Life scenarios (Asif et al. 2021). Sub-assemblies that face technological obsolescence are generally candidates for upgrading operations at the end of predefined use-cycles (Figure 21). In some cases, upgrading can mean replacing the old sub-assemblies with new ones compatible with the latest technologies.

The following questions can help determine the need for upgrading:

1. Has there been new technology introduced into the market that might make the sub-assembly and the product technologically obsolete?
2. Will the user acceptance rate decrease significantly if the sub-assembly is not upgraded?
3. Does the company have the resources and skills to facilitate the upgrade?
4. Are disassembly and reassembly optimized for time, cost efficiency, simplicity, and tool availability?

Similarly, sub-assemblies prone to emotional obsolescence may need replacement to give a new look or quality perception. Sub-assemblies prone to functional obsolescence are candidates for reuse. These sub-assemblies tend to face functional obsolescence long after technological and emotional obsolescence.

1. Does replacement enhance the functionality or aesthetic condition of the product?
2. Does replacement affect product acceptance significantly?
3. Does the company produce spare parts to facilitate this replacement?
4. Is the sub-assembly standardized and fit for forward compatibility?
5. Are the disassembly and reassembly optimized for time, cost efficiency, simplicity, and tool availability?

Additional considerations in assigning End-of-Life scenarios can be done by identifying the moving components prone to wear and tear that may need regular replacement Ong (2016). Sub-assemblies with high intrinsic value, e.g., shafts and gears, can considered for remanufacturing, since the process has a higher potential to be viable than low-value parts (Boorsma et al. 2022). The status of physical condition of sub-assemblies has also a significant role to play in determining the End-of-Life scenario

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(Ong 2016). When sub-assemblies cannot be recovered through repair, refurbishment, or remanufacturing, they can move into recycling (Granta Edupack, 2022).
A checklist can be consulted to help determine the

In summary, the possible End-of-Life scenarios can be determined using the strategic disciplines and obsolescence profiles of sub-assemblies. This approach allows designers to strategically plan the journey of product over multiple use-cycles.

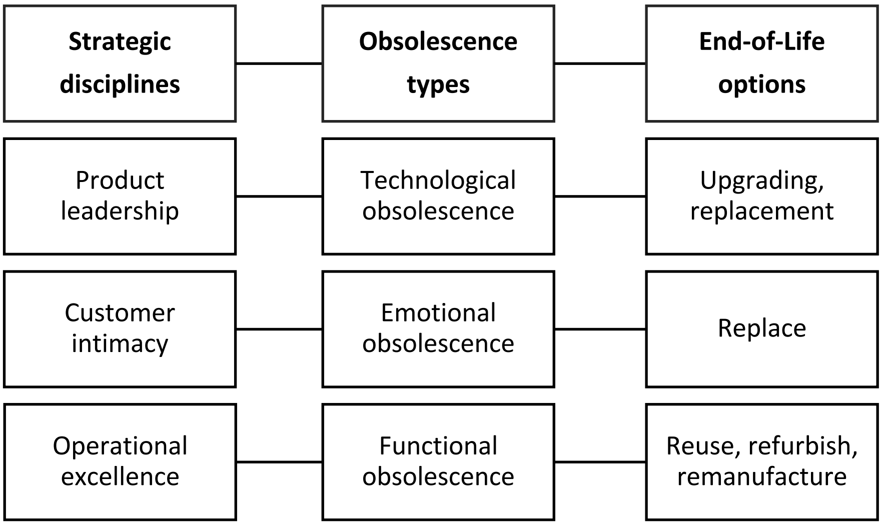

Figure 21 The relations between the strategic disciplines, product obsolescence types, and end-of-Life options

Assigning markings to critical sub-assemblies
Certain sub-assemblies can be marked to indicate unique characteristics that influence how they journey throughout a lifecycle and how they influence the journey of the entire product. Four of these markings can be assigned to the sub-assemblies: high-value, key function, key failure, and high-impact. These are further described below.

High-value marking
The high-value marking indicates a sub-assembly with high intrinsic value that makes the reverse logistics and remanufacturing process viable from a cost perspective (Boorsma et al. 2022). They can be identified using a calculation from the "Hotspot mapping" tool by Flipsen (2012). To find high-value sub-assemblies, the following calcucation can be used:

Value of the sub-assembly = Price dominant material (€/kg) * weight of sub-assembly (kg)

Sub-assemblies that can be marked at a threshold of the 80th percentile.

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Key function and key failure markings
Other priority sub-assemblies can be defined by their functional importance and replacement frequency (Bracquené et al. 2018). Two sub-assembly types can be derived from this: sub-assemblies with high functional importance, which receive a key function marking, and parts prone to high failure rates, which receive a key failure marking. These markings can help designers decide on appropriate EoL scenarios and replacement frequencies.

Stakeholder activities
To make a circular system work, all activities within the stakeholder network should be well-aligned and carefully thought through. Designers need to identify both the appropriate steps in the lifecycle as well as the activities of all involved stakeholders. For this reason, the PJM also includes the required actions for the stakeholders to keep the operations running at high quality. In the journey map, this will be included by adding text boxes linked to the appropriate stage, containing a verb-noun combination e.g., deliver product. As a result, a list of activities necessary to support the new product lifecycle will be generated. This way, the PJM provides us with a complete overview of who is involved, which can help identify additional requirements or gaps, and preferences for the new product.

The above-mentioned building blocks create the foundation for the Product Journey Map. They are interrelated and interdependent and together form the structure for the Product Journey Map. The next section will describe the step-wise procedure to put the Product Journey Map and the building blocks in use.

3.4.2. The final method

The final version of the method is based on design iterations and early-stage testing of several concepts which can be found in Appendix IV. This section will present the resulting method rational, framing, goal, procedure, and mind-set of this final version (Kooijman 2022).

Method rational
The PJM offers designers a systematic approach to identify the most appropriate circular scenario for a product, by visualizing and analysing a product's entire lifespan, and by determining a product's environmental impact. The PJM visualizes a product's story through breaking down a product's lifecycle events into steps. It specifies these events by using symbols that represent actors, recovery activities, environmental impact, and economic potential.

Method framing
The PJM is most effective when used during early-stage design. During these early stages it assists in conceptualizing ideal circular scenarios for products, and, at later

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stages of design, it helps substantiate decision-making for detailing the design direction.

Method goal

The purpose of the Product Journey Map is to provide insight into the flow of a product and its components throughout multiple use-cycles, by mapping different scenarios and the roles of stakeholders. The Product Journey Map guides designers in deciding on the optimal flows of products and their components to support a viable circular system to increase resource efficiency and decrease environmental impact.

Method procedure

The procedure of creating the PJM requires several information points (Table 15, Table 16). The required data and activities of the procedure are described in the following 10 steps:

Step 1: Lifetime estimations of the full product.
Specify the (potential) length of the product lifetime in years or moths. Now, specify the (potential) number of use-cycles, as well as their length in years or moths.

Step 2: Defining the product’s sub-assemblies.
This step identifies the sub-assemblies of the product. Sub-assemblies are part clusters that are easy to disassemble as a whole, have limited connectors to the other components, and often support the same product function. Such part clusters tend to have a comparable lifetime expectancy. The product architecture typically prescribes what the sub-assemblies of a product are. Note down the following information for the sub-assemblies:

- Name the sub-assemblies
- Determine the sub-assembly weights
- Specify the main material(s) used

Step 3: Specifying key function and failure parts.
In this step the key function and key failure parts. Key function parts are parts that are critical to the function. Key failure parts are parts that require frequent replacement. Specify in which sub-assemblies these parts are located.

Table 15 Table for data collection PJM - part 1

Sub-assembly	**Step 2: Name**	**Step 2: Weight**	**Step 2: (Main) material**	**Step 3: Key function part**	**Step 3: Key failure part**	**…**
1						…
2						…
3						…
4						…
…	…	…	…	…	…	…

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Step 4: Determine high-value sub-assemblies.
This step identifies the sub-assemblies with the highest intrinsic-value. This can be determined by, either using the prices of the sub-assemblies, or by multiplying the price of the predominant material (€/kg) by its weight (kg), as a rough estimate. Mark sub-assemblies at a threshold of the 80th percentile.

Step 5: Assign strategic disciplines.
Define the strategic disciplines of each sub-assembly, and list the corresponding product obsolescence type (Figure 21). This information, together with the lifetime estimation, will be used to determine how long each sub-assembly is expected to last in step 6.

Step 6: Determine lifetime expectancy of the sub-assemblies
Determine the number of use-cycles each sub-assembly is expected to last based on the previous steps. For example, key failure parts and sub-assemblies prone to emotional obsolescence will likely last one or a limited number of use-cycles. However, sub-assemblies prone to functional obsolescence will likely last for more use-cycles.

Step 7: Assign end-of-Life options.
Assign EoL options to the sub-assemblies, based on the combination of the strategic discipline, the types of obsolescence, and the part categorization. The following rules of thumb can be followed: (1) Sub-assemblies that are prone to face technological obsolescence, they are candidates for upgrading operations at the end of predefined lifecycles; (2) Sub-assemblies that are prone to emotional obsolescence need to be replaced with aesthetically different ones to give a completely new look; (3) Sub-assemblies prone to face functional obsolescence are candidates for reuse. (4) Functional obsolescence tends to happen at a later stage than technological and emotional obsolescence.
In case product sub-assemblies are replaced, then specify their EoL scenario; will they undergo recycling, remanufacturing, or combustion?

Table 16 Table for data collection PJM - part 2

Sub-assembly	Step 4: Intrinsic value	Step 5: Embodied energy	Step 6: Strategic disciplines	Step 6: Obsolescence type	Step 7: End of use-cycle 1	Step 7: End of use-cycle 2	Step 7: End of use-cycle 3
1							
2							
3							
4							
…	…	…	…	…	…	…	…

Step 8: Scope the journey map.

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A selection of sub-assemblies can be selected to scope the final map. This selection can be made by showcasing sub-assemblies that together account for 80% of the total value.

Step 9: Map the product journey.
Create a horizontal timeline and add the previously identified steps of the lifecycle. Add rows below the timeline, one for each sub-assembly. Map the previously defined sub-assembly specification onto the map, as illustrated in figure 18. Add the icons for the EoL scenarios at the appropriate steps (Figure 22). In case a sub-assembly gets replaced, the timeline will drop downwards to indicate the placement of a new sub-assembly (Figure 23).

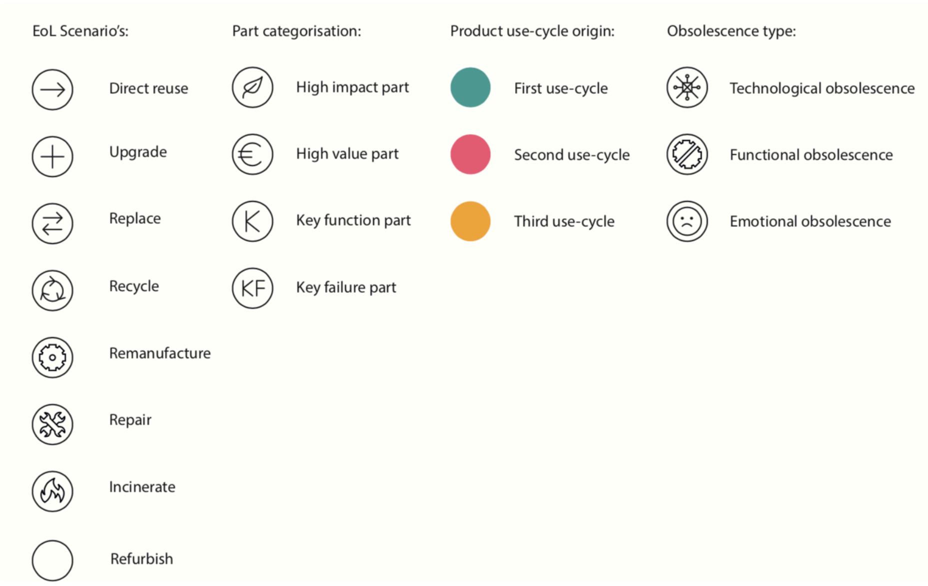

Figure 22 Icons that indicate the part categories (Kooijman 2022)

Step 10: Detail stakeholder activity.
List all stakeholders involved in the product's lifecycle on the y axis, below the rows for the sub-assemblies. For each stage, specify the actions required by the stakeholder in the respective step. Write the stakeholder actions in the form of a verb-noun combinations (e.g., deliver product).

Method mindset
Creating the PJM requires the users to take a long-term view, focusing on what happens over several use-cycles. To use the PJM to its full potential, it is important to have in-depth knowledge on following topics and concepts: the product to be mapped, the strategic disciplines, the product obsolescence types, optional EoL scenarios, information databases (e.g., Granta Edupack), and circular economy concepts like use-cycles and life cycles.

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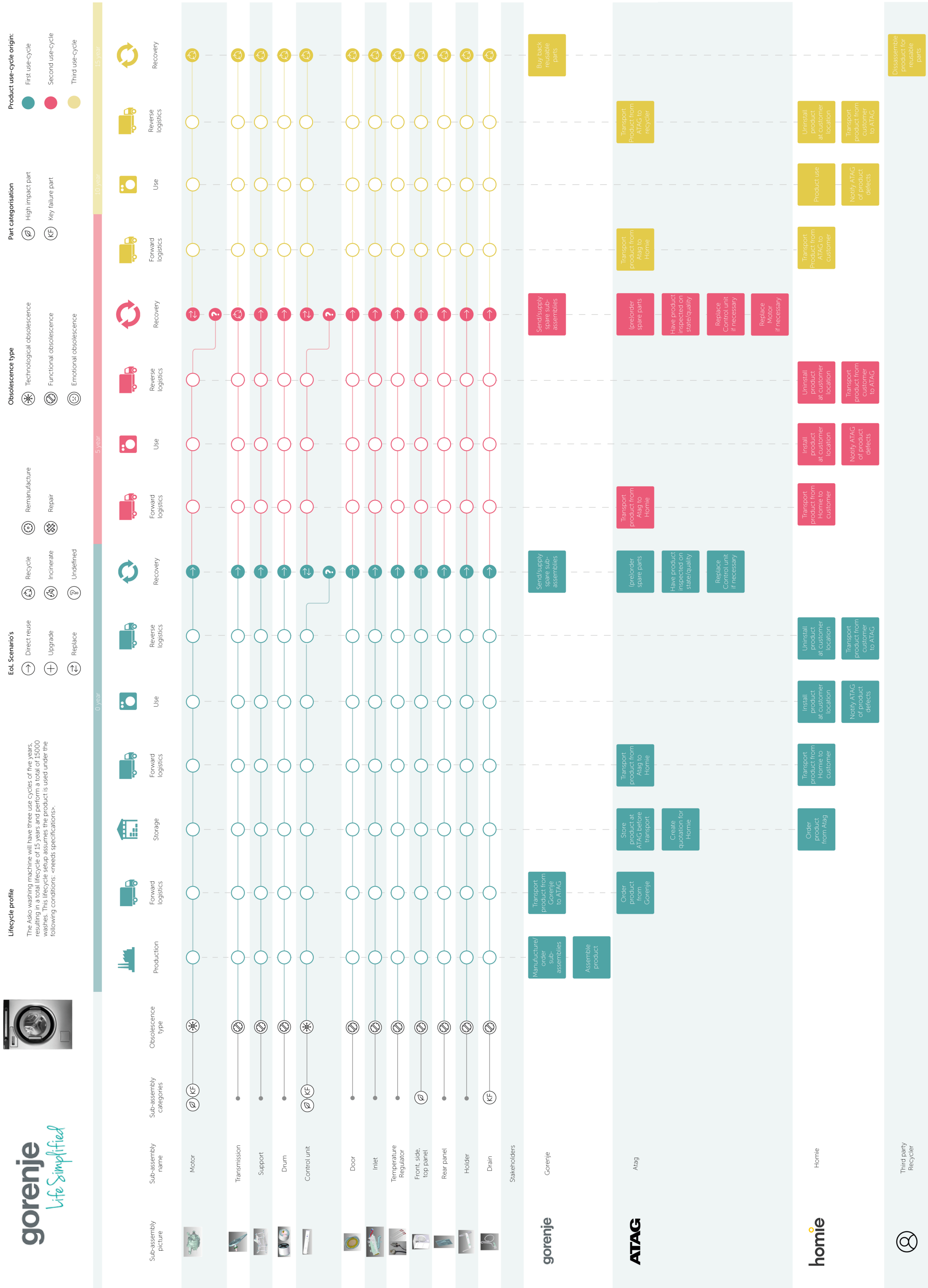

Figure 23 Product Journey Map for Gorenje (Kooijman 2022)

3.5. Validation

The circular design method was implemented at the white goods demonstrators. The business goal for the demonstrator is to bring 400 long-lasting washing machines to the market through a pay-per-use business model. The design goal is to have the washing machines last for three five-year use-cycles, supported by maintenance and repair. At End-of-Life, a third party will dismantle the machines and harvest parts that can serve as spare parts.
A Product Journey Map was prepared for Gorenje based on the design goal and on the available product data from literature (Figure 23). This was evaluating with the company in a 1-hour online meeting with Gorenje.
The goal of this meeting was to evaluate to what extent the circular design method meets method criteria that were established in section 3.2.2. The outcome of this evaluation can be found in Table 17.

Table 17 Insights from method validation

Method criteria	Evaluation
Mapping of lifecycle events of a product that affect design is facilitated	For companies with a lot of experience in circular design, the aim for the Product Journey Map may be more specific than for companies with less experience. Gorenje had a very focused goal for specific parts, since the journey of the remaining parts was already thought trough. Yet, to create the journey for individual parts or sub-assemblies, the map of the full product is useful in providing the context.
The requirements of all relevant stakeholders are included	The PJM looks at stakeholders and their respective functions within the system. They cannot be grouped, but should be considered as unique entities. This provides designers with more detail and a better overview of the entire product journey.
A company-specific map that is based on company data and substantiated assumptions can be generated	The PJM can be set up using the knowledge on strategic disciplines, obsolescence types, EoL scenarios, and the bill of materials.
Insight into the flow of the product and parts over time is provided	The PJM provides insight into the relative impact of sub-assemblies. Additional in-depth calculations are needed to determine their absolute impact.
Usability is optimized	The map was self-explanatory. No additional instruction was needed for Gorenje to be able to interpret the map.
Accessibility is optimized	The level of detail that can be reached with the PJM is dependent on the level of detail of the input data. The more accurate and detailed the input data is, the more advanced map can be created.

Two major adjustments have been implemented based on the learnings. Firstly, calculations were included to track and visualize the impact of product sub-assemblies over time to emphasize the environmental impact of the life cycle. These calculations have been validated (Ansys, 2022) and can easily be implemented to calculate the environmental impact of a cluster. According to the objective of the company, a different unit can be selected as the basis for the calculation, such as the intrinsic value, water consumption, or chemical waste water. Secondly, solely listing the stakeholders required for the lifecycle did not provide enough information. Hence, the

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final version of the PJM includes a systematic way to identify which stakeholders should be included and what roles they would fulfil.

Based upon literature reviews, analysis of design methods from literature, the ReCiPSS task descriptions, and the design vision of the ReCiPSS project, the method criteria were compiled. These criteria were used to develop the Product Journey Map method through several design iterations and company testing. Table 17 shows in what ways the method criteria from section 3.2.2 were met through the application of the different approaches.

Table 18 Evaluation of the method criteria

Method criteria	Evaluation
Mapping of lifecycle events of a product that affect design is facilitated	This requirement was met. Mapping the lifecycle events is facilitated through defining the lifecycle stages and assigning scenarios to the sub-assemblies of the product. Based on the strategic disciplines and the obsolescence profiles, the ideal EoL stages can be selected. After creating this overview, learnings can be derived with regards to design adjustments that can be beneficial to resource efficiency.
The requirements of all relevant stakeholders are included	This requirement was met. For each of the stages of the lifecycles, the relevant stakeholders can be indicated, as well as their roles in the circular system. By adding the stakeholders, a company can not only attain overview of all parties involved, but also see what the gaps are that require additional or new parties to join.
A company-specific map that is based on company data and substantiated assumptions can be generated	This requirement was met. The Product Journey Map is based on real data of products, or substantiated assumptions. The sub-assemblies need to be clearly defined for them to give a realistic reflection of their lifecycle behaviour and possible EoL scenarios. Inserting data with high levels of accuracy and detail, leads to the possibility to make well-funded decisions. A PJM predominantly based on assumptions can still be valuable in the early stages to set an initial direction, but requires to be quantified in more depth over time.
Insight into the flow of the product and parts over time is provided	This requirement was met. Through clustering parts and have them form sub-assemblies, the PJM can differentiate between journeys of different sub-assemblies in the same overview. Literature review pointed out that not all sub-assemblies are likely to have the same lifetime expectancy, which is based on variables like materials, design, and use, and can therefore have varying ideal EoL scenarios. The PJM can help conceptualise different journeys for sub-assemblies.
Usability is optimized	This requirement was met. The visual was found to be self-explanatory. The chosen structure, icons, and layering of the information helps with the interpretation of the information.
Accessibility is optimized	This requirement was met. The PJM requires a certain level of knowledge of a product, like the materials, weight, and product architecture. It also requires designers to make calculations to, for example, find the environmental impact of the sub-assemblies. This information, or the calculations, to not exceed the level of difficulty of an average design assignment.

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3.6. Discussion and conclusions

The earlier a company sets goals for circular design, the more influence it can have in planning ideal scenarios for their products and parts. By developing profiles for the sub-assemblies of a product, based on their strategic disciplines and obsolescence types, (more accurate) scenarios can be drafted for the journeys of these sub-assemblies, which optimises resource-efficiency.

Current journey mapping method are aimed at mapping material flows, customer experiences, or value streams. They do not (1) put a product centre stage, (2) link required actions of stakeholders to the product and its design, and/ or (3) show opportunities to attune a product's behaviour to be more circular, based on real data.

The Product Journey Map gives companies the possibility to create an overview of the lifecycle flow of a product and its parts. It specifies the actions sub-assemblies require throughout different use-cycles stages, as well as which stakeholders are needed to make the circular system work optimally.

The Product Journey Map is a novel design method with the potential of being valuable to design teams at companies. Additional testing will allow for the optimisation of the procedure, data requirement, and method visual. Testing different products will also help to attune the method to the needs of a wide range of products.

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4. Disassembly Map

Method development

The Disassembly Map was developed based on multiple design iterations, using insights from literature, and by using data from seven products disassembly sessions of vacuum cleaners (de Fazio et al. 2021). The choice for vacuum cleaners were made based on their relatively simple architectures, yet diverse enough to draw learnings from comparison.

The analysis was done on basis of the product related parameters defined by Cordella et al. (2019), that are used for repair assessments. The four parameters are:

- Disassembly depth/ sequence
- Disassembly time
- Type of tools
- Fastener reusability

Key components were selected on basis of part characteristics that are often associated with repair:

- Parts that need to be replaced frequently
- Parts that have a high embodied environmental impact
- Parts that have a high economic value

All products were disassembled three times and documented through multiple-view video recording. The part details were documented in an overview, e.g. weight and materials type. After collecting the disassembly data, maps were created based on the disassembly routes to reach key parts, highlighting important actions, and considering alternative or parallel routes. Design iterations and consultations with the product manufacturer resulted in the final format of the Disassembly Map method.

Method description

The Disassembly Map is a schematic representation of a product's architecture with the goal to provide insight in the disassembly routes for its key parts. The time and effort with which components can be reached and disassembled is indicated with icons and colors. The goal is to support companies in improving on the disassembly routes to reach key parts in their products and, with that, make the products more suitable for recovery activities like repair and remanufacturing.

Use of the method

Step 1 – Select the product for evaluation and establish which parts should be denoted as key parts (i.e. the ones that fail most often, that are very expensive to replace and/or that have a high environmental impact).

Estimation of the time required: 15-30 minutes.

Step 2 – Disassemble the product while documenting all the actions in the accompanied format.

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Estimation of the time required: 60-120 minutes.
Step 3 – Pay special attention to uncommon actions or actions that are difficult to perform, as these actions might be marked with penalties as an indicator of opportunities for design improvements.
Estimation of the time required: 15-30 minutes.
Step 4 – Digitalise the results and determine disassembly routes to reach the priority parts.
Estimation of the time required: 30-45 minutes.
Step 5 – Decide which design improvements are needed to improve the disassembly route, in terms of time, cost, or complexity.
Estimation of the time required: 30-45 minutes.

Implementation of the method

The Disassembly map was applied for the white goods demonstrator and has generated useful insights in the product architecture of the washing machines, based on the company feedback on the report in ReCiPSS D3.3. Two washing machines of the company were disassembled and the resulting disassembly maps were compared (Figure 24 & Figure 25). From creating the disassembly maps, and from the comparisons, design recommendations could be done for improving the ease of disassembly of the machines. Such recommendations can lead to opportunities for improved maintenance, reparability and remanufacturability.

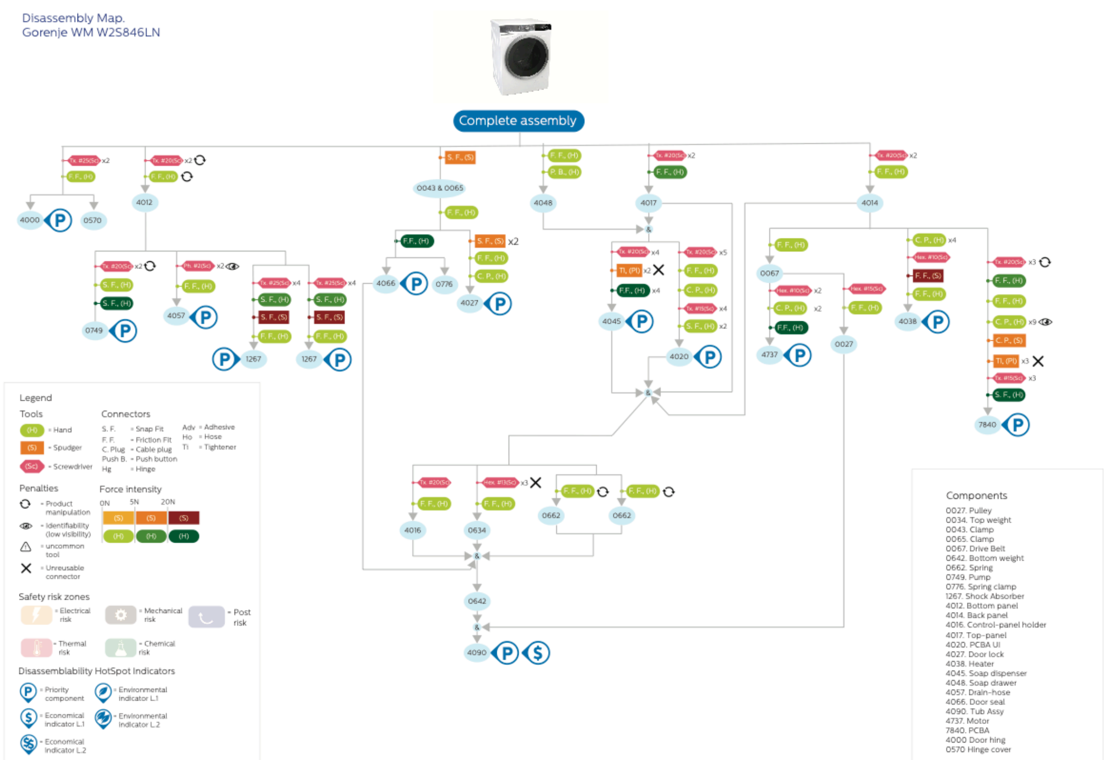

Figure 24: Disassembly map of the Gorenje WM W2S846LN

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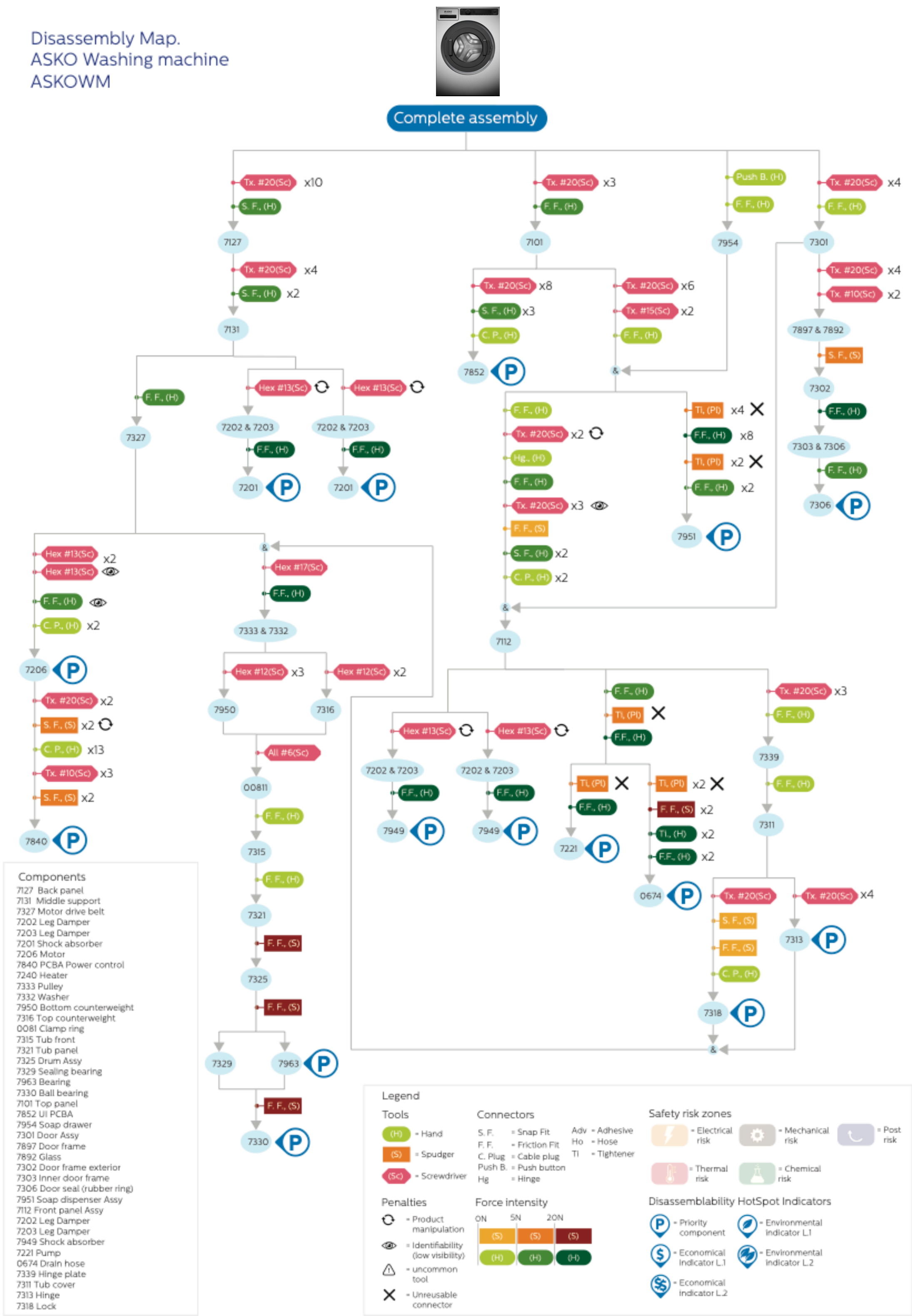

Figure 25: Disassembly map of the ASKO WM

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The Disassembly Map will be used to assist Bosch with the development of new manufacturing options (like additive manufacturing) for components such as high-performance injector, which must take into account remanufacturing options. It can help conceptualize the most optimal product architecture that meets the disassembly requirements for this part.

Future research

Increased standardization can be considered to further develop the disassembly map. This can be done, for example, by standardizing the dimensions of the map, to make them representative of the level of difficulty of disassembly. In the initial development of the disassembly map, research has been focused around a single group of consumer products, namely vacuum cleaners. Future research can look into possible improvements of the method in case it is applied to other product groups or markets, like business to business. It may also be interesting to research opportunities for improvement when applied to other circular approaches, like refurbishment or remanufacturing.

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5. Co-creation Impact Model

Method development

The Co-creation Impact Model was developed based on the findings of a case study within the whitegoods demonstrator (van Dam et al. 2021). A co-creation study was conducted in two countries, the Netherlands and Slovenia. This gave the ability to verify if the same needs, concerns, and opportunities were valid in different cultural contexts.

Five company benefits of using co-creation were identified in this study:

- Benefit 1: Helped create added value in offering the washing machine as a service
- Benefit 2: Allowed the development of attractive pricing and contract options
- Benefit 3: Helped find unique value propositions
- Benefit 4: Identified potential user concerns
- Benefit 5: Helped pinpoint cultural differences

One year after the co-creation phase, three members of the company project team (the head of pre-development of R&D, the project manager, and the lead R&D engineer) were interviewed to reflect on the co-creation process. They were asked about their expectations beforehand, whether these expectations were met, what kind of impact the co-creation process had, and which factors facilitated/obstructed the use of the co-creation insights. The interview resulted in valuable insights about the impact on the company, the impact on the design of the PSS, and the factors that made co-creation successful in creating impact in these areas:

- Company impact 1: Company-wide support for the pay-per- wash concept.
- Company impact 2: Development of employee's competencies.
- Company impact 3: Broader use of co-creation within company.
- PSS Impact 1: Shift from dedicated washing machine to software innovations.
- PSS Impact 2: New servitization innovations.
- Success factor 1: Product champion who took the lead and drove the process of turning insights into ideas.
- Success factor 2: Positive energy emanating from creative process.
- Success factor 3: Infographic posters as valuable carrier/medium to convey insights. I

These insights are used for the visualization of the impacts of co-creation for service transformation in the Co-Creation Impact Model.

Method description

Unique to this method is the way the opportunities to create impact through co-creation are identified in the context of service transformation of companies. Companies in any phase of adopting servitization can benefit from the method in preparing their co-creation sessions. The method forms an extension to earlier work in academic literature about the more generic benefits of co-creation.

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Use of the method

Step 1 – Determine the design challenge(s) that is/are being faced in the development of the product-service system.
Estimation of the time required: 60-120 minutes.

Step 2 – Determine the information gaps related to stakeholders and end users that need to be filled to make well informed decisions during development, as well as the target audience that can deliver the required information.
Estimation of the time required: 60-120 minutes.

Step 3 – Use the Impact Model Co-creation as a reference to evaluate which gaps can be filled through co-creation and make a list of these desired impacts.
Estimation of the time required: 30-60 minutes.

Step 4 – Proceed with the preparations and execution of the co-creation in guidance of the previously set goals for the desired impact.
Estimation of the time required: 3-5 days.

Step 5 – Analyze the results and present insights to the company in a manner that maximizes impact on PSS development, competencies, and the company.
Estimation of the time required: 2-4 weeks.

Implementation of the method

The procedure was extensively tested with the demonstrators of this project. The model is the validated result of the experience gained in this project.

Co-creation has generated valuable input for both demonstrators concerning new market and customer insights. The demonstrators have used these insights to build up and finetune their circular offers. The Impact Model Co-creation identifies where and how co-creation can be beneficial to new product-service system development and servitization (Figure 26).

Future research

Co-creation is an advantageous approach that merits more use within the field of circular economy, though care should be taken when implementing the results to avoid effects that are counterproductive to circularity. In this regard, new ideas should be weighed as to their effect on the overall circularity of the product so that PSSs can be developed that are both successful and fully circular. Future research could expand on this work by also exploring the product launch and customer's use of the new PSS as well as strengthening co-creation methodology by investigating how to make the impacts of co-creation measurable. Furthermore, while there are clear benefits to implementing co-creation within circular product development, co-creation cannot answer all our pressing questions. For instance: What would it take to normalize (shared) access models in society, and what are the underlying values that impede this process? How can users be enticed to use a (long-lasting) product in an access model for as long as possible and also avoid the “don’t be gentle, it’s a rental” conundrum?

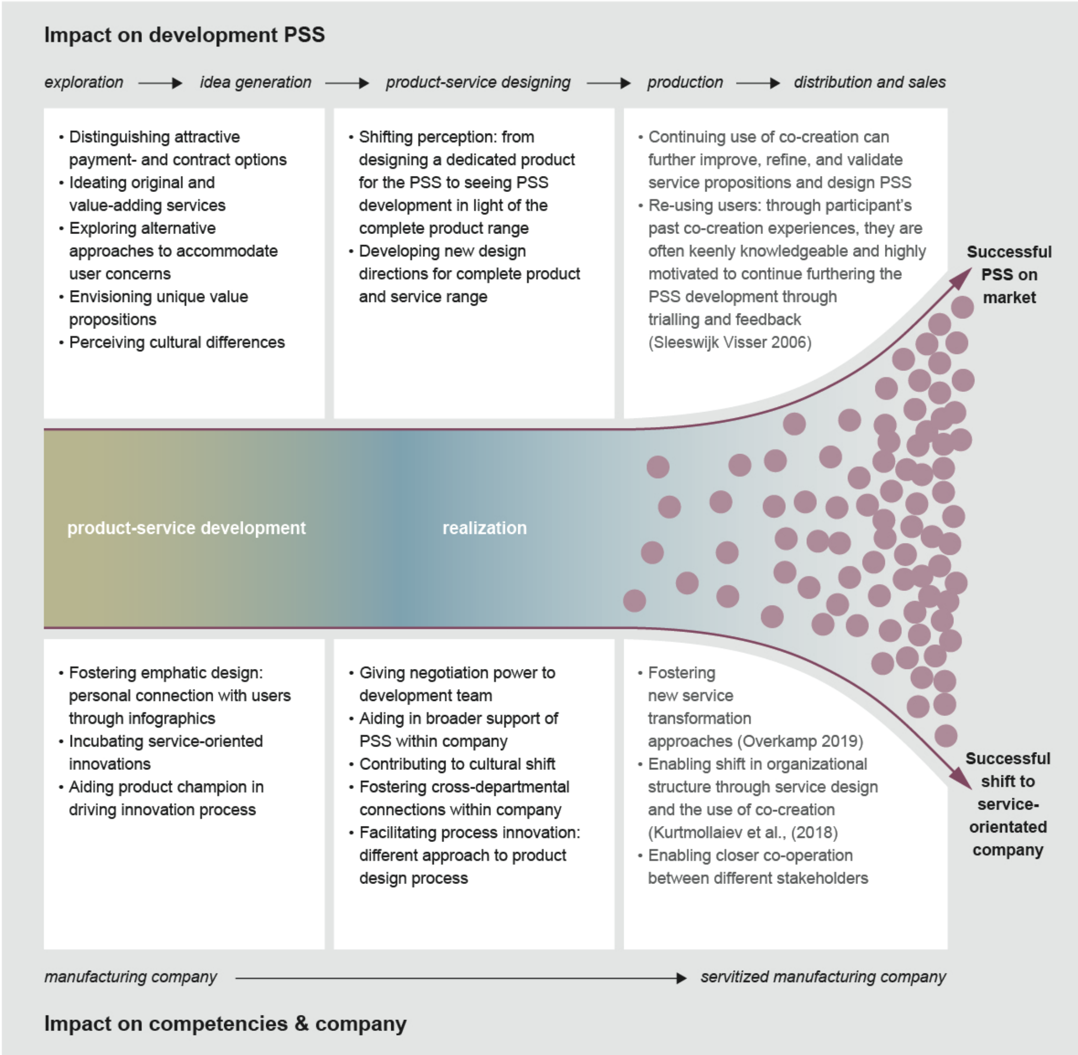

Figure 26 The Co-creation Impact Model

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6. Discussion and conclusions

This report has presented the four circular design methods developed during the course of the ReCiPSS project. As a package, the four methods comprehensively support the development of circular products. The methods assist in making early-stage design decisions that enable recovery activities during the use phase or at the end-of-life of the product. These early-stage strategic design decisions are important for the development of products that serve for a long period of time and should be applicable for different future scenarios. They support in seeking alignment with market needs and help in the embodiment design of the technology to support product recovery. Lastly, the methods support in coordinating the design process and embedding the newly acquired skills into the existing processes. By developing and validating them in close cooperation with both demonstrators within the project their applicability in practice was ensured.

The Circular Product Readiness method's added value over other indicator tools is that it is   in-depth and incorporates a design perspective. The advantage of this for companies is that it enables a detailed view and specifies success factors for circular design that are applicable to them.

The Product Journey Map is particularly useful in the early stages of the design process as it gives companies the possibility to create an overview of the lifecycle flow of a product and its parts. It specifies the actions sub-assemblies require throughout different use-cycles stages, as well as which stakeholders are needed to make the circular system work optimally.

Co-creation has generated valuable input for both demonstrators concerning new market and customer insights. The demonstrators have used these insights to build up and finetune their circular offers. The Impact Model Co-creation identifies where and how co-creation can be beneficial to new product-service system development and servitization.

The Disassembly map was applied for the white goods demonstrator and has generated useful insights in the product architecture of the washing machines. It helped in finding opportunities for design improvements that can lead to improved maintenance, reparability and remanufacturability.

Together, these methods enable designers to structure the design process of circular products, giving specific method for specific stages of the development process. Future work could focus on finetuning them by applying them to a larger product range to ensure their applicability across diverse product categories.

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Appendix I

I.A Co-creation sessions with circular design experts

The sessions were structured using a Miro-board with the indicator questions in colored labels (Figure 27). Each color belonged to an expert, and the blue color resembled the final configuration of the priority of the questions. The input provided by the experts was collected through note-taking.
The notes were analysed after the sessions and served as input to sharpen and clarify the formulation of the questions, and add or delete questions (Figure 28). Design considerations were documented following the example in Table 19.

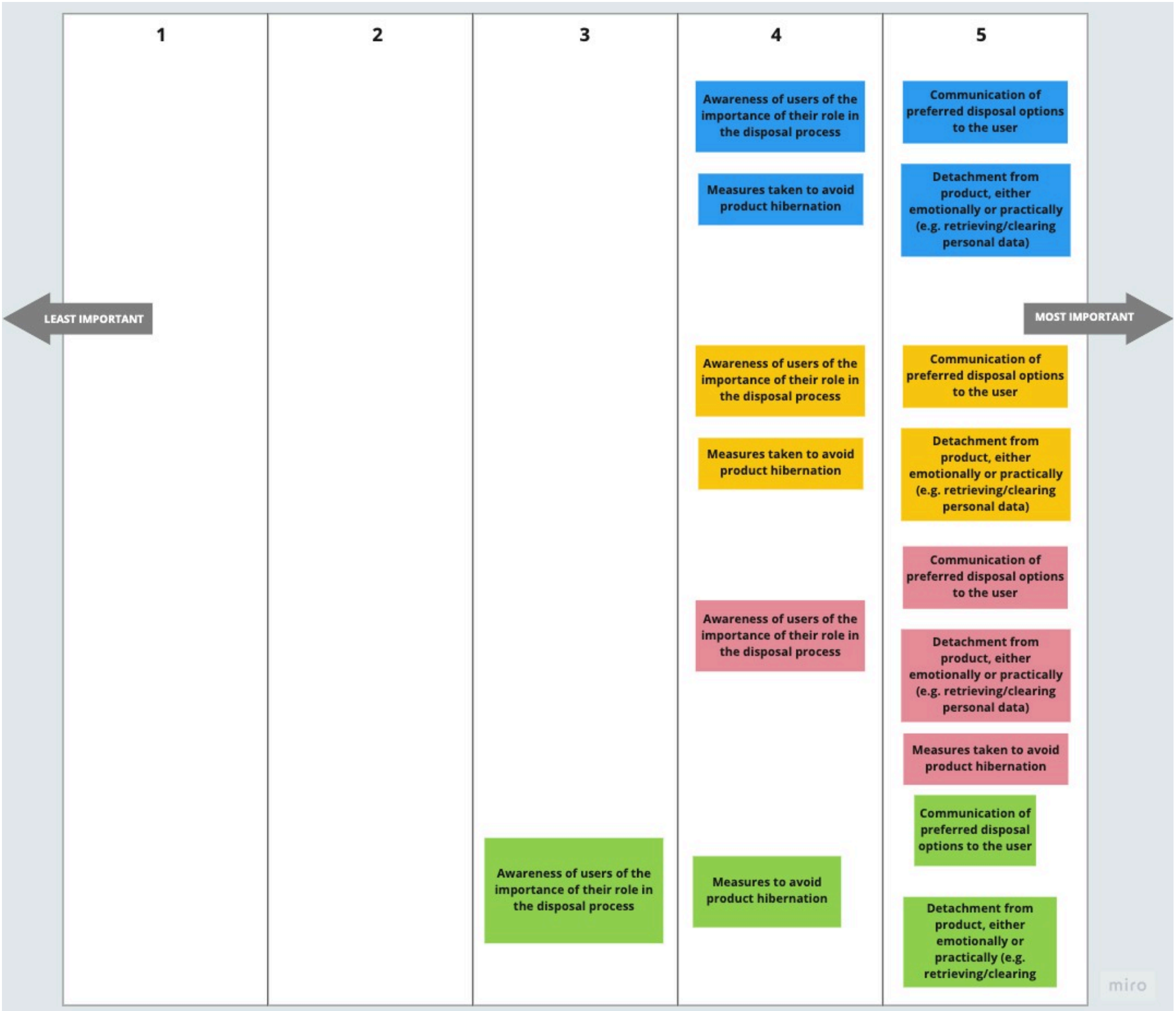

Figure 27 Miro-board structure used during the co-creation session (example of the outcome of the co-creation sessions about indicator number 10: On- & Off-boarding (Customer Experience & Care))

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Results

	Questions	Comments	Conclusions
1	Is the user informed about the preferred disposal options?	Disposal associated with products that have no worth, suggested: "end-of-use options"	**EDIT:** Is the **customer** informed about the preferred **end-of-use** options?
2	Is the user supported in detaching from the product, either emotionally or practically (e.g. retrieving/ clearing personal data)?	off-boarding instead of detaching	Is the user supported in **off-boarding** from the product, either emotionally or practically (e.g. retrieving/ clearing personal data)?
3	Is the user's role in the disposal process and its impact communicated clearly?	"obligations and responsibilities customer" ipv role	**EDIT:** Are the **customers' obligations and responsibilities** in the **end-of-use** process and its impact communicated clearly?
4	Are measures taken to avoid product hibernation (storage of unused products)?	You are asking about one specific "bad" end-of-use scenario	Leave out
	GENERAL	product off-boarding is needed but at the same time companies want to maintain a positive brand image	

Figure 28 Results of co-creation expert sessions about indicator number 10: On- & Off-boarding (Customer Experience & Care)

Table 19 Logbook of design decisions: Adjustments to the indicators and questions as a result of the co-creation sessions

Adjustments as a result of the co-creation expert sessions	- Move **standardization** from Strategy and planning to hardware and software // The experts expected this to be with the other circular design strategies that concern hardware. Even though, this indicator looks at product families and generations, it is still sufficiently hardware-related to join this theme. 30-09-2021 **- Branding** was taken out of the indicator overview // Branding does not link strongly enough to product design. 30-09-201 **- Servitization** was not adopted in the overview // From a resource and design perspective this is the ideal choice for closing loops, but the economic viability is not proven. 30-09-2021 - Indicator label: **Materials** OR Material Sustainability? OR Materials' circularity potential (old version: Material fairness) // **Materials** was selected to be the label of this indicator, to cover all the topics addressed and to keep a general focus. 30-09-2021 - For recycling of **Materials,** the parameter will be based on value (euro) instead of mass // This is more likely to capture small amounts

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	of valuable/ critical/ scarce materials instead of only focusing on the big amount of 'cheaper' materials. 30-09-2021 - **Product use intensity** was taken out of the overview // Product use intensity does not say anything about circularity in itself. 30-09-2021 - Product design is attuned to the needs of users in multiple use-cycles was changed into customer research attuned to needs in multiple use-cycles // To make a clear distinction to what is needed in value proposition design and what is needed prior to value proposition design. 30-09-2021 **- (RE)MOVE:** Is the use efficiency of consumables made future proof? In what way? // Difficult to assess. 30-09-2021

I.B Analysis of existing indicator frameworks

An analysis of indicator frameworks from (grey) literature was used to develop the framework for this design method. On the basis of the analysis of these frameworks (Table 4, Table 20, Table 21, Table 22, Table 23, Table 24) a collection of insights from the analysis of indicator framework was created (Table 5).

Table 20 A taxonomy of circular economy indicators (Saindani et al. 2019)

Themes	Indicators		
	Micro	Meso	Macro
Loops	Recycling Reuse/reman Maintenance	Recycling Reuse/reman Maintenance	Recycling Reuse/reman Maintenance
Performance	Intrinsic Impact	Intrinsic Impact	Intrinsic Impact
Perspective	Potential Effective	Potential Effective	Potential Effective
Dimensionality	Single Multiple	Single Multiple	Single Multiple
Transversality	Generic Sector-specific Computational tool	Generic Sector-specific Computational tool	Generic Sector-specific Computational tool
Format	Computational tool Textual format	Computational tool Textual format	Computational tool Textual format

Table 21 Categorisation of keywords based on commonly used definitions from literature (Kristensen & Mosgaard 2020)

Themes	Indicators
Re-principles	Refuse Rethink Reduce Repair Reuse Refurbish Remanufacture

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	Repurpose Recover Recycle Restore/regenerate Re-mine
Waste	Eliminate/reduce waste Waste as a resource Waste hierarchy Waste-to-energy Waste management
Efficiency	Resource-efficiency Eco-efficiency Cleaner production
Value retention (product)	Highest utility and value Product longevity Upgrade Servitization Value retention
Sustainability	Sustainable development Social benefits Economic benefits Environmental benefits
Resources	Eliminate toxic chemicals Preserve/enhance natural capital Cascading resource use Extend resource life Dematerialization
Design	Design (material, products, business models, systems) Eco-design
System perspective	Scale/levels (micro, meso, macro)
Energy	Renewable energy Energy efficiency
Cycles	Technical and biological cycles

Table 22 Themes and indicators of the MATChe platform (Pigosso & McAloone 2021)

Themes	Indicators
Organisation	Circular economy business cases Tools and processes for circular economy implementation Risks and investments Training programs
Strategy & business model innovation	Integration in long-term strategy Top management commitment and resource allocation New circular value propositions Marketing of circular offers Redefining revenue streams
Product & service innovation	Development and delivery of PSSs Design for lifetime extension Design for End-of-Life Design for shared use
Manufacturing & value chain	Partnerships to enable circular business Supplier engagement in circular initiatives Recycled/ renewable/ biodegradable material use Engagement in industrial symbioses
Technology & data	Product monitoring in use phase Technology use to extend product lifetime
Use, support & maintenance	Professional service and support during use phase Professional product repair Establishing and encouraging shared use and access
Take-back & End-of-life strategies	Establishment of take-back systems Disassembly and remanufacturing Value recovery processes
Policy & market	Market readiness for circular products

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	Market readiness for new business models Co-development of circular solutions Influencing of sectorial legislative frameworks Influencing of national or international legislative frameworks

Indicator frameworks from grey literature:

Table 23 Themes and indicators of the Circulytics indicator tool (EMF 2020)

Themes	Indicators
Strategy and planning	CEO's agenda Risks and opportunities Circular strategy Circular economy targets Circular economy implementation plan
Innovation	Leadership attuned to circular economy Project briefs attuned to circular economy Tools and metrics attuned to circular economy Collaboration in circular economy projects User-centeredness and system focus for circular economy
People and skills	Circular economy communication Circular economy training Functions dedicated to circular economy implementation
Operations	Suitable IT and digital systems Processes supporting circular economy Plant, property, and assets supporting circular economy
External engagement	Engagement suppliers Engagement customers Engagement policy makers Engagement external investors Membership/ Circular economy related initiatives
Products and materials	Annual mass inflow of products and materials Annual mass outflow Material sources Outflow to landfill and incineration Circular economy principles in product design Enabling customer improvement of circular economy performance Substances from certifications Percentage suitable for recirculation (reuse, redistribution, refurbishment, remanufacturing, recycling, nutrient recirculation Average use-cycle
Services	Service revenue from circular services Circular economy principles in services
Property, plant, and equipment assets	Type of assets Amount of assets Circular economy procurement approaches Percentage recirculation
Water	Water flow income/ outcome Water demand sources Plans/ processes to extract resources Water reuse
Energy use	Total annual energy usage and production Percentage of renewable resources
Finance	Percentage of circular alignment with: Lending Fixed income Private equity Listed equity

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Table 24 Themes and indicators of the circular economy transition diagnostic tool (Potting et al. 2017)

Themes	Indicators
Means	Mobilisation of means Knowledge development
Activities	Knowledge exchange Experimenting by entrepreneurs Giving direction to search Opening markets Overcoming resistance
Achievement	Circular design (Lifespan comparison; disassemblability; use of recycled materials; Recyclable) Production Consumption Waste
Effects	Circularity Environment Economy

I.C Theme and indicator development for the Circular Product Readiness method

With insight collected form the analysis of existing indicator methods, the first version of themes and indicators was further developed in several design iterations. The first version of themes and indicators did not contain all relevant design factors and missed a design-oriented structure (Table 25).

Table 25 Themes and indicators version 1 - November 2020 (prior to literature review)

Themes	Hardware	Software	Product recovery	User interaction
Indicators	- Durability - Reliability - Condition monitoring - Hardware upgradability	- Software upgradability -Secure and private data exchange and storage	- Reparability - Safe to handle - Remanufacturability - Recyclability	- Emotional attachment to product & brand - Ageing with dignity - Stimulate sustainable behavior

Based on input from the indicator framework analysis (Table 5) and by doing design iterations, the themes and indicators from Table 26 were defined. The structure of the themes is similar to the steps of a design process and product lifecycle, and is therefore more intuitive in use. The indicators were developed to have more detail and cover a wide range of factors contributing to circular design.

Table 26 Themes and indicators version 2 - February 2021 (after literature review)

Themes	Product planning	Products (Value retention)				Services
	Innovation strategy	During functional life	End of functional life	Customer Experience	Product support	Recirculatio n

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Indicators	- Use of circular product design milestones/ targets - Product requirements derived from business model, supply chain, and ICT - Customer needs and associated product requirements for products with multiple use-cycles - Product identity - Fairness (p. 57) - Product variety/ standardization as a result of innovation	- Longevity/ durability - Reusability - Maintenance & repair (e.g. safe to handle) - Reliability - Hardware upgradability	- Disassembly - Remanufacturing - Recycling	- Sharing, pooling and leasing platforms; - Product as service; Pay per service - Packaging reuse service - Warranty - Return options at End-of-Use - Contributing through sustainable behaviour - Software upgradability - Secure and private data exchange & storage	- Maintenance support service (technical support, spare parts distribution and customer care) - Warranty - Software: Condition/utilisation monitoring; Predictive maintenance systems; Materials/product utilisation tracking; Software upgradability; Secure and private data exchange & storage Servitization: Sharing, pooling and leasing platforms (Product as/ pay per service) - Packaging reuse service	- Buy-back and take-back management - Waste management service - Secondary market places

Further design iterations were done to improve upon the completeness of the themes and indicators, and to reduce overlap, until an optimal configuration was found (Figure 29). This resulted in the final set of themes and indicators which can be found in Table 6. The purpose of all indicators is included in this table as well.

Figure 29 Themes and indicators - a design iteration (June 2021)

I.D Development of the indicator questions

The improvements of the first set of questions had to do with clarity of how they were phrased (practical application), the ease with which they could be answered (in

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relation to the answer options), and the simplicity and accuracy of the content (avoiding compound questions) (Figure 28).

Table 27 Example set of early-stage indicator questions - June 2021

Indicators	Indicator questions
Disassembly	- To what extent is the product designed for easy disassembly?
Refurbishing	- Does the product's design allow for returning its state to satisfactory working and/or cosmetic condition by repairing, replacing or refinishing all major components?
Remanufacturing	- Does the product's design allow for returning its state to as-new product specification by fully disassembling, testing, replacing and cleaning components, to result in a new product with a warranty?
Recycling	- What percentage of the the product's materials can be recycled? (mass of recyclable content/total mass of product) - Does the product contain materials that are non-recyclable? - Is there an End-of-Use repurposing plan for the materials that are not recyclable? - Does the product disintegrate into separate homogenous and compatible material fragments during shredding? - Are the connections optimised for breakdown during shredding? - Is the amount of connections minimised?

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Appendix II

Circular Product Readiness – assessment questions

Circular Product Readiness method	
Themes and indicators	**Questions**
1. Circular Strategy	The questions in this section assess the commitment and the implementation potential of circular design within your organization.
1.1 Design budget	1.1.1 Has your company made a budget available for circular design? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0)
1.2 Know-how	1.2.1 Does your company have access to circular design expertise? *This could be circular design expertise internally or from an external party, such as advisors, consultancies, etc.* O Yes, we have access to either internal and/ or external expertise (1) O We are in the process of acquiring (additional) expertise (0.8) O We are planning to acquire additional expertise (0.4) O No, we do not have access to circular design expertise (0) 1.2.2 Does your company have channels to exchange product design information with stakeholders, like repair and remanufacturing technicians? O Yes, we have regular exchanges (1) O We are in the process of setting up channels for information exchange (0.8) O We are planning to set up channels for information exchange (0.4) O No, we do not have channels to exchange information (0) O N/A
1.3 Customer research	1.3.1 To what extent are the needs of customers not only considered in the first use-cycle, but also in the subsequent use-cycles of the product? O This is the norm (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A
1.4 Value proposition	1.4.1 Does the circular value proposition and its related service and product offer new benefits to customers? *For example, being part of a (like-minded) user community, being able to become more sustainable and fulfil sustainability aspiration.*

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	O Yes, there are new benefits to this circular value proposition (1) O We are in the process of adding new benefits (0.4) O No, there are no new benefits to this circular value proposition (0) O N/A 1.4.2 To what extent does value proposition design support high product quality not only in the first use-cycle but also in subsequent use-cycles for the products? O This is the norm (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0)
2. Hardware & Software Design	The questions in this section assess the implementation level of circular product design in physical products and their software.
2.1 Materials The following questions indicate the potential of a product to circulate in loops while maintaining high-quality, without harming the environment, and at the same time supporting fair production.	2.1.1 What fraction of the material value, by cost price, consists of recycled and/ or reused materials calculated over all use-cycles? *This can be calculated using the following formula: (cost price of recycled and reused materials / cost price of materials in total) x 100%. For products with multiple use-cycles, the average of this fraction over the use-cycles can be calculated.* O 0% (0) O 1 - 19% (0.4) O 20 - 39 % (0.6) O 40 - 69% (0.8) O 70 - 100% (1) 2.1.2 What amount of the material value, by cost price, consists of critical materials? *Critical materials for product designers are defined by Peck et al. (2015) as "elements from the periodic table of elements (metals/ rare earths) that may be at risk of price volatility and supply restrictions, [...] they are often present in small quantities in technology products, [..] substitution usually changes a product's properties and/ or performance." Examples of common critical materials to the EU are the following: Lithium, Beryllium, Magnesium, Scandium, Chromium, Cobalt, Gallium, and Germanium (Bauer et al. 2010).* O 0 € (1) O 0 - 0,09 € (0.8) O 0,1 - 0,19 € (0.6) O 0,2 - 0,4 € (0.4) O 0,4€ < (0) 2.1.3 What amount of the material value, by cost price, consists of conflict materials? *Conflict minerals refer to raw materials or minerals that come from a particular part of the world where conflict is occurring (i.e. those specifically associated with armed conflict, human rights abuses and corruption) that affect the mining and trading of those materials (Diemer et al. 2021). Examples of common conflict materials include the 3TG: tantalum, tin, tungsten, and gold.* O 0 € (1)

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	O 0 - 0,09 € (0.8) O 0,1 - 0,19 € (0.6) O 0,2 - 0,4 € (0.4) O 0,4€ < (0) 2.1.4 Does the product contain easily separable biodegradable or compostable components? O The product is fully biodegradable or compostable (1) O The product contains biodegradable and compostable components that are easy to separate (1) O The product contains biodegradable and compostable components that are hard to separate (0) O The product does not contain any biodegradable or compostable components 2.1.5 Does the product contain composite materials that are designed to last? *A composite material is a combination of two materials with different physical and chemical properties. Materials commonly used for composites are polymers, metals and ceramics.* O The composite materials used in this product are recyclable (1) O The product contains composite materials that are easy to separate and designed to last (0,6) O The product contains composite materials that are easy to separate, but not designed to last (0,2) O The product contains composite materials that are hard to separate (0) O No, the product does not contain any composite materials 2.1.6 Does the product packaging consist of recyclable, biodegradable, or compostable materials? O Yes, the packaging is fully recoverable (1) O The packaging is partly recoverable (0.8) O This is planned (0.4) O The packaging is not recoverable (0) O N/A
2.2. Longevity The following questions assess the potential for a product to last as long as reasonable from a profit, market and environmental perspective.	2.2.1 How does the total lifetime of the product compare to the market average? *Compare the expected total lifetime of your product to the market average* O Higher than average (1) O Equal to average (0.8) O Lower than average (0) 2.2.2 After what period of time will the user experience noticeable degradation of the product? *For example, degradation due to (cosmetic) wear, battery life, and corrosion* O From 100% of the expected lifetime (1) O Between 75-100% of the expected lifetime (0.8) O Between 50-74% of the expected lifetime (0.4) O Between 0-49% of the expected lifetime (0)

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<table>
<tr><td></td><td>2.2.3 Does the product indicate to customers what key components are critical to the duration of either the technical lifetime or the economic lifetime (relevance to the market)?
O Yes, all key parts are indicated (1)
O Only for a selection of key parts is indicated (0.6)
O No key parts are indicated (0)
O N/A

2.2.4 Does the product allow for enhancing a product's functionality and/or cosmetic condition throughout its lifetime?
For example, by having a modular or upgradable design.
O Yes, for all key parts (1)
O Only for a selection of key parts (0.6)
O This is planned (0.4)
O There are options for enhancement (0)
O N/A

2.2.5 Is the product designed to have a timeless aesthetic?
O This is the norm (1)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A</td></tr>
<tr><td>2.3. Standardization

The following questions indicate the level of product homogeneity that allows for sufficient volume of products to run viable recovery operations, i.e. standardization of interfaces, backward compatibility, etc..</td><td>2.3.1 Are Design for Standardization and (backward) compatibility applied throughout the whole product portfolio to support recovery options?
Design for Standardization aims for standardizing selected parts throughout the product portfolio and between product generations over time. Part compatibility is based on the interoperability between selected parts for multiple product types, and is dependent on, for example, part dimensions, energy uptake, interfaces, and software versions.
O This is the norm (1)
O This is the norm for a sub-set of products (0.8)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A</td></tr>
<tr><td>2.4 Maintenance & Repair

The following questions indicate the potential for a product to be repaired and maintained with the lowest possible effort, time and costs, relative to the function and value of the product.</td><td>2.4.1 Is the product designed for ease of maintenance?
For example, if the product requires regular cleaning, does the design of the product enable this?
O This is the norm (1)
O This is the norm for a sub-set of products (0.8)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A

2.4.2 Does the product come with information, like a manual, on how to take care of it?
O Yes, for all parts that require maintenance (1)
O Only for a selection of parts that require maintenance (0.6)</td></tr>
</table>

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	O No information about how to maintain the product quality is provided (0) O N/A 2.4.3 Does the product come with information, like a manual, on how to diagnose faults in key parts? O Yes, for all parts that could require repair (1) O Only for a selection of parts that could require repair (0.6) O No information on fault diagnosis is provided (0) O N/A 2.4.4 Does the product come with information, like a manual, on how to repair faults for key components? O Yes, for all parts that could require repair (1) O Only for a selection of parts that could require repair (0.6) O No information on the repair of faults is provided (0) O N/A 2.4.5 Does the product have visual or auditory design cues supportive of maintenance and repair by consumers? *For example, sound or light indicating faults and pictograms showing repair steps.* O Yes, for all parts that could require maintenance or repair (1) O Only for a selection of parts that could require maintenance or repair (0.6) O No, the product has no design cues for maintenance or repair (0) O N/A 2.4.6 Is the safety risk for customers minimized during repair of the product? *For example, by avoiding harmful substances* O *Yes, for all parts that could require repair (1)* O *Only for a selection of parts that could require repair (0.4)* O *No, the product is not safe to repair by customers (0)* O *N/A*
2.5 Software support The following questions indicate the extent to which the product's design facilitates software updates during the time that the product's function is in demand.	2.5.1 Does the product make use of any software? O Yes O No 2.5.2 Does software support form a bottleneck for products to live longer than the expected lifetime or for the extension of the product lifetime through re-use or remanufacturing? O Software support does not form a bottleneck (1) O Extending software support is initiated (0.8) O Extending software support is planned (0.4) O Software support forms a bottleneck (0) O N/A
3. Customer Experience & Care	
3.1 On- & offboarding	3.1.1 Are the obligations and responsibilities for access, use, and end-of-life of a product communicated to customers?

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The following questions indicate the extent to which the benefits of the product/ service are clear to the user, and the extent to which the procedure and responsibilities to access and disposal of the product/ service are clear and convenient. This is particularly relevant for products that are offered as a service.	O Yes (1) O No (0) O N/A 3.1.2 Is the onboarding process tested with customers on clarity and convenience? O Yes, this process is tested and provides clarity and convenience (1) O Only a limited amount of clarity and convenience are provided for onboarding (0.6) O The development of a clear and convenient onboarding process is in development (0.4) O No, clarity and convenience are not maximized for the onboarding process (0) O N/A 3.1.3 Is the customer supported in letting go of the product at the end of life, either emotionally or practically? *For example, by supporting them with clearing personal data from the product.* O Yes, the customer is supported (1) O Only a limited amount of support is provided (0.6) O No, the customer is not supported (0) O N/A
3.2 Use efficiency The following questions indicate the extent to which the product's function is maximized while the use of consumables, and the potential environmental harm, is minimized.	3.2.1 Does your product make use of consumables? This includes energy and water use. *Consumables are goods that are used up while using a product, such as ink, paper, and cleaning agents.* O Yes O No 3.2.2 Does your product maximize the use-efficiency of consumables, compared to the market average? *For example, by technologies and innovations that enable energy and water use efficiency.* O The use-efficiency is higher than the market average (1) O The use-efficiency is equal to the market average (0.6) O The use-efficiency is lower than the market average (0) O N/A 3.2.3 Does the product activate customers to opt for sustainable use options? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 3.2.4 Does the product require the use of consumables that contain critical or conflict materials? *For example, coffee beans that are obtained from conflict zones* O No, the customer can select alternatives that are free of critical or conflict materials (1)

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	O Yes, the customer is restricted to a selection of consumables that contain critical or conflict materials (0) O N/A 3.2.5 Does the product require the use of consumables that contain contents that can be hazardous to the environment in which they are discarded? *For example, the use of laundry detergents that contain hazardous chemicals* O For example, the use of laundry detergents that contain hazardous chemicals O No, the customer can select alternatives that are free of hazardous contents (1) O Yes, the customer is restricted to a selection of consumables that contain hazardous contents (0) O N/A
4. Product Support Services	
4.1 Warranty The following questions indicate the expected lifetime during which a product functions properly without unforeseen recovery activities.	4.1.1 Does the product's warranty period last longer than what is legally required? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 4.1.2 Are products that are returned by the customer as part of warranty repaired, refurbished or remanufactured? O This is the norm (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A
4.2 Professional support The following questions indicate the commitment and ability of a company to facilitate high product quality beyond the point-of-sale in terms of service.	4.2.1 Does your company, or partnered companies, offer in-warranty maintenance & repair services for the product? O Yes (1) O Only for specific defects (0.6) O This is planned (0.4) O This is not considered (0) O N/A 4.2.2 Does your company, or partnered companies, offer any paid maintenance & repair support service for the product? O Yes (1) O Only for specific defects (0.6) O This is planned (0.4) O This is not considered (0) O N/A 4.2.3 Is the customer informed about the professional maintenance and repair service? O Yes (1)

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	O No (0) O N/A 4.2.4 Does your company, or partnered companies, offer an upgrade service for your product? *Examples are upgrading the memory of a laptop and exchanging the armrest of an office chair.* O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 4.2.5 Is the customer informed about the possibility to upgrade the product? O Yes (1) O No (0) O N/A
4.3 Spare parts supply The following questions indicate the commitment and ability of a company to facilitate spare part availability beyond the point-of-sale.	4.3.1 Are the spare parts to support self-repair by customers affordable? O Yes (1) O No (0) O N/A 4.3.2 Does your company produce extra spare parts for recovery, to enable refurbishment or remanufacturing? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 4.3.3 Can customers return their used parts, that they have replaced, to your company? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 4.3.4 Are parts that are returned by the customer repaired, refurbished or remanufactured? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A
5. Recirculation service	The questions in this section assess the likelihood of retrieving products back from the market after use.
5.1 Return program	5.1.1 Does your company have a program to actively retrieve products from the market?

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	O Yes (1) O No (0) O N/A 5.1.2 What percentage of the sold products are returned to the company or to partnered companies? *This includes returned part from buy-back schemes and pay-per service models.* O 0% (0) O 1 - 9% (0.4) O 10 - 19 % (0.6) O 20 - 49% (0.8) O 50 - 100% (1) 5.1.3 Are customers informed about the product return options? O Yes (1) O No (0) O N/A 5.1.4 At what point are customers informed about the possible return options? O During product purchase (1) O During use, at end-of-use, or at end-of-life of a product (0.8) O N/A
5.2 Product retrieval	5.2.1 Does the company provide re-usable packaging for return options? *For example, in case the product requires protection during transport.* O Yes (1) O A non-reusable replacement packaging is provided (0.8) O This is initiated (0.8) O This is planned (0.4) O No (0) O N/A
6. Recoverability	
6.1 Disassembly This indicates the extent in which a product is designed to be taken apart in terms of safety, time, and costs.	6.1.1 Does your company list the key parts for disassembly? *Key parts that should be accessible for repair, upgrades, refurbishment and remanufacturing.* O Yes, all key parts are listed (1) O Only a selection of key parts is listed (0.8) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 6.1.2 Is product disassembly and reassembly optimised for time, cost efficiency, simplicity and tool availability? *For example, by optimizing the joints and connections, minimizing the risk of damage, minimizing tool and equipment complexity, and reducing the number of product components.* O Yes, for all key parts (1) O Only for a selection of key parts (0.8) O This is initiated (0.8)

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<table>
<tr><td></td><td>O This is planned (0.4)
O This is not considered (0)
O N/A</td></tr>
<tr><td>6.2 Refurbishment

Indicates the extent to which a product is designed to be remanufactured in terms of safety, time, and costs.</td><td>6.2.1 Does your company list what parts make the refurbishment operations feasible and viable?
O Yes (1)
O Only a selection of parts is listed (0.8)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A

6.2.2 Which fraction of the material value, by cost price, can be refurbished?
Calculated by dividing the cost price of the materials that can be refurbished by the total cost price of materials.
O 0% (0)
O 1 - 19% (0.4)
O 20 - 39 % (0.6)
O 40 - 69% (0.8)
O 70 - 100% (1)

6.2.3 Does your company provide refurbishment instructions and protocols to the relevant departments or third parties?
O Yes (1)
O Only informal instructions are provided (0.8)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A

6.2.4 Does your company have a clear diagnosis procedure for products returning from the market?
O Yes (1)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A</td></tr>
<tr><td>6.3 Remanufacturing

Indicates the extent to which a product is designed to be remanufactured in terms of safety, time, and costs.</td><td>6.3.1 Does your company list what parts make the remanufacturing operations feasible and viable?
O Yes (1)
O Only a selection of parts is listed (0.8)
O This is initiated (0.8)
O This is planned (0.4)
O This is not considered (0)
O N/A

6.3.2 Which fraction of the material value, by cost price, can be remanufactured?
Calculated by dividing the cost price of the materials that can be remanufactured by the total cost price of materials.
O 0% (0)</td></tr>
</table>

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	O 1 - 19% (0.4) O 20 - 39 % (0.6) O 40 - 69% (0.8) O 70 - 100% (1) 6.3.3 Does your company provide remanufacturing instructions and protocols to the relevant departments or third parties? O Yes (1) O Only informal instructions are provided (0.8) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A 6.3.4 Does your company have a clear diagnosis procedure for products returning from the market? O Yes (1) O This is initiated (0.8) O This is planned (0.4) O This is not considered (0) O N/A
6.4 Recycling Indicates the extent to which a product's materials are designed to be recovered while minimizing the use of non-recyclable or non-repurposable materials.	6.4.1 Which fraction of the material value, by cost price, can be recycled? *Calculated by the price of materials that can be recycled divided by the total cost price of materials.* O 0% (0) O 1 - 19% (0.4) O 20 - 39 % (0.6) O 40 - 69% (0.8) O 70 - 100% (1) 6.4.2 Does the product fall apart into separate homogeneous or compatible material fragments in the shredding process? O Yes (1) O Only for a selection of the parts (0.6) O No (0) O N/A 6.4.3 Are general recycling processes available for the materials in your product? O Yes (1) O Only for a selection of the recyclable materials (0.6) O No (0) O N/A 6.4.4 Is there an End-of-Use repurposing plan for the materials that are non-recyclable? O Yes (1) O Only for a selection of the non-recyclable materials (0.6) O No (0) O N/A

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Glossary

Composite material: a combination of two materials with different physical and chemical properties. Materials commonly used for composites are polymers, metals and ceramics.

Conflict minerals: This term refers to raw materials or minerals that come from a particular part of the world where conflict is occurring (i.e. those specifically associated with armed conflict, human rights abuses and corruption) that affect the mining and trading of those materials (Diemer et al. 2021). Examples of common conflict materials include the 3TG: tantalum, tin, tungsten, and gold.

Consumables are goods that are used up while using a product, such as ink, paper and cleaning agents.

Critical materials for product designers: "elements from the periodic table of elements (metals/ rare earths) that may be at risk of price volatility and supply restrictions, [...] they are often present in small quantities in technology products, [..] substitution usually changes a product's properties and/ or performance." (Peck et al. 2015) Examples of common critical materials to the EU are the following: Lithium, Beryllium, Magnesium, Scandium, Chromium, Cobalt, Gallium, and Germanium (Bauer et al. 2010).

Design for Standardization: This design approach aims for standardizing selected parts, which is constant for a product family. The remaining parts allow for flexibility to innovate. Recovery options are operations with the primary aim of reversing obsolescence (Den Hollander et al., 2017), such as repair, remanufacturing and recycling.

Part compatibility: The interoperability between selected parts for multiple product types, and is dependent on, for example, part dimensions, energy uptake, interfaces, and software versions.

Priority parts are necessary to assess the ability of a product to be repaired or upgraded, because not all parts will be equally relevant (CEN/ CENELEC 2020).

Product use cycle: the duration of the period that starts at the moment a product is released for use after manufacture or recovery and ends at the moment a product becomes obsolete (Den Hollander et al., 2017).

Product life cycle: consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal (ISO-Norm, 2006).

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Product lifetime: the duration of the period that starts at the moment a product is released for use after manufacture and ends at the moment a product becomes obsolete beyond recovery at product level (Den Hollander et al., 2017).

Recovery: this term describes any operation with the primary aim of reversing obsolescence (Den Hollander et al., 2017).

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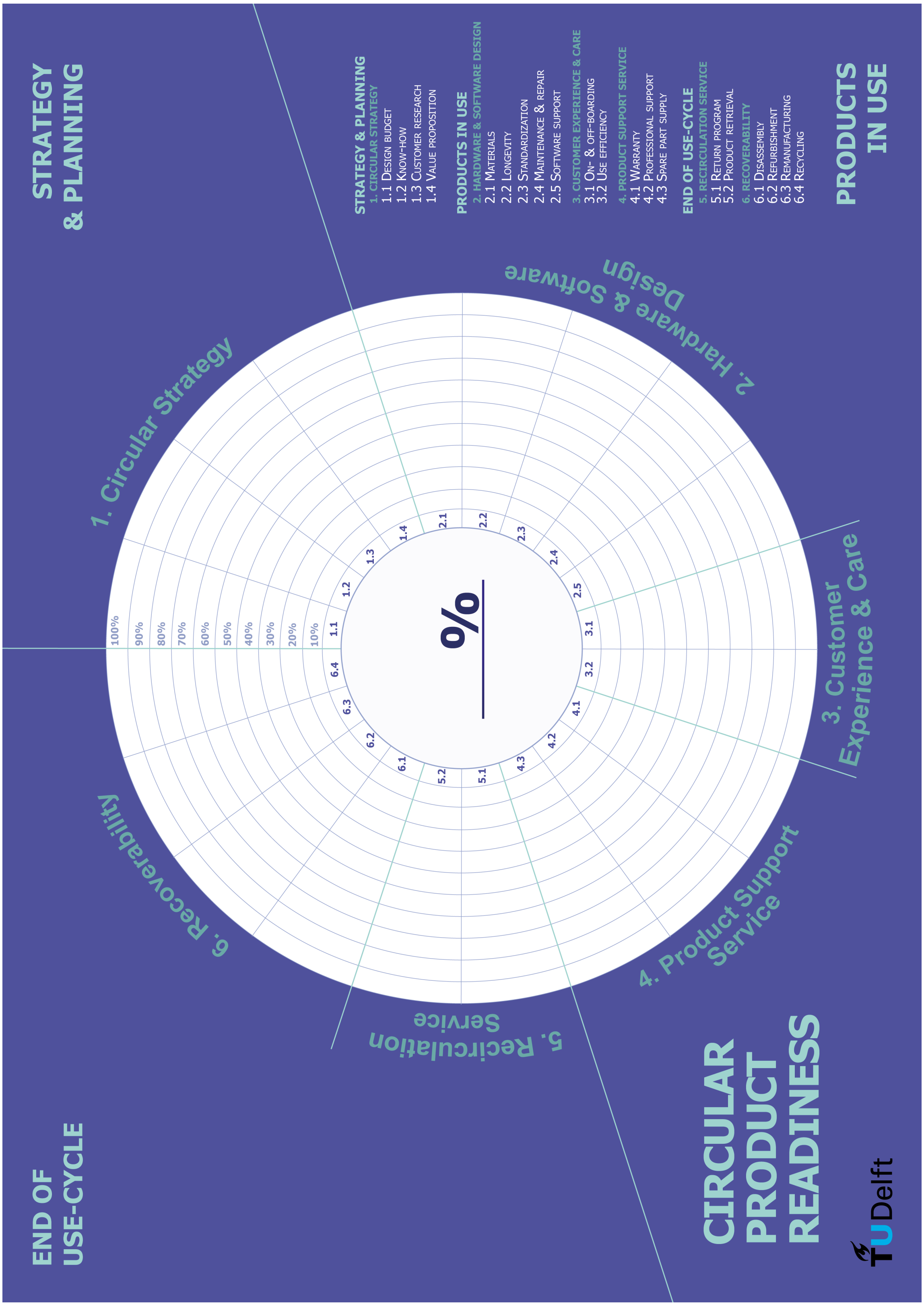
Appendix III



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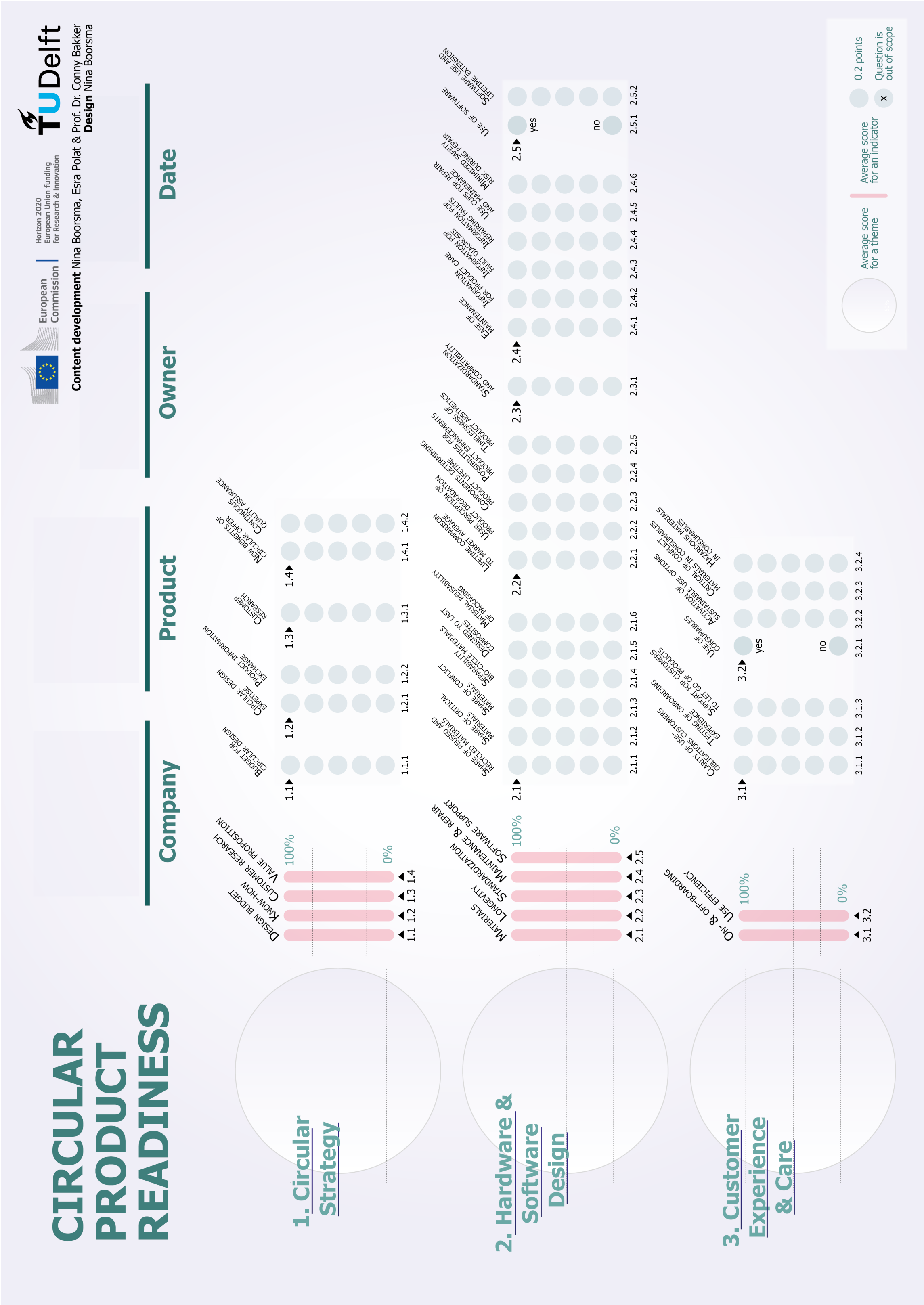

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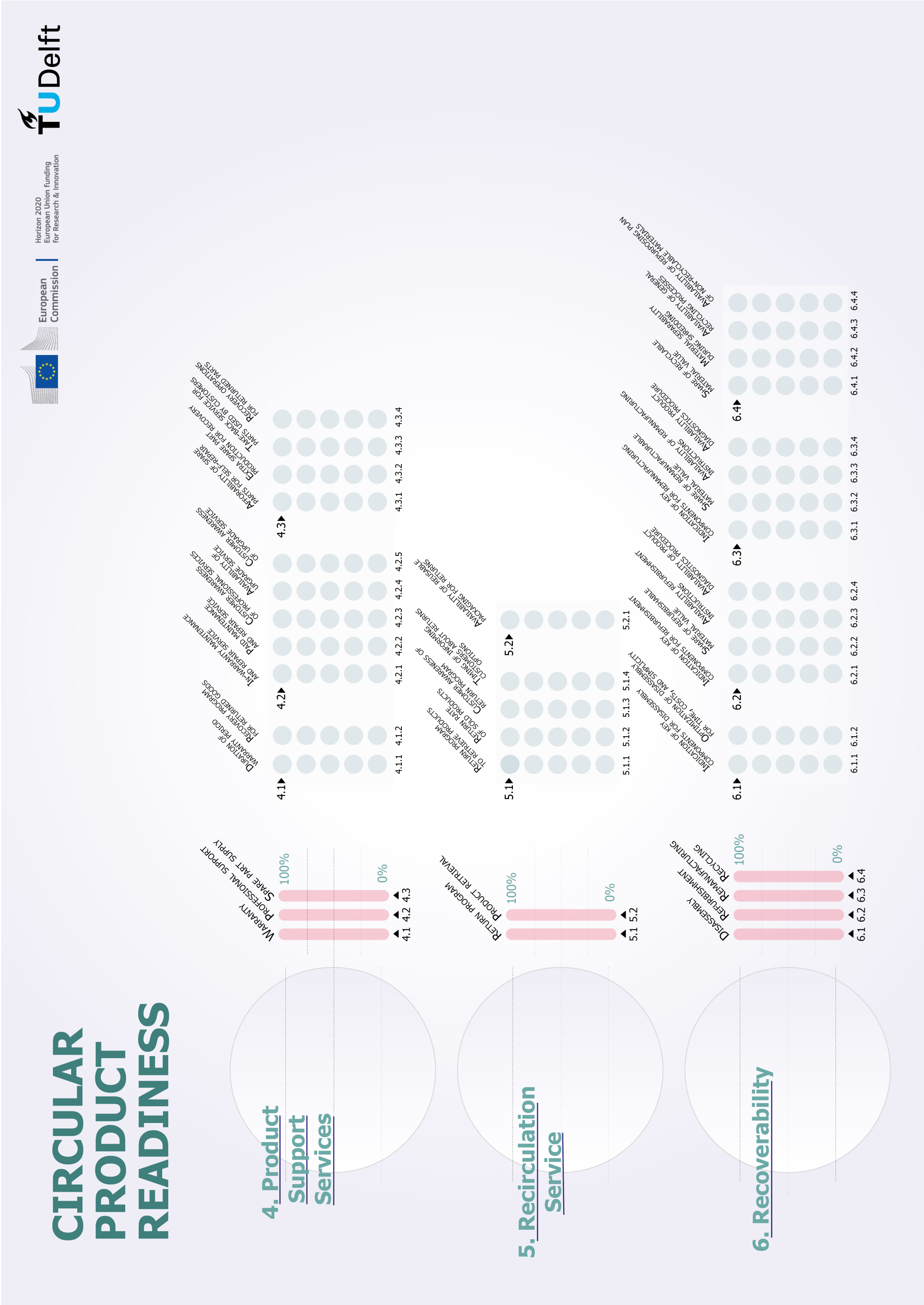

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Appendix IV

3.3.3 Learnings from concept development for the PJM

Case descriptions

Roetz: Bike rental system by the Nederlandse Spoorwegen (Dutch railway operator)
Roetz has the ambition to let their bikes last for three five-year use-cycles, with sustainability and convenient mobility as the spearheads. Their aim is to make a fully circular bike which is available to a wide audience.

Strekkar: industrial pushcarts for supermarkets by Castor Ventures
Castor Ventures is a Dutch company that specializes in the manufacturing of industrial pushcarts. These carts are used for logistics and distribution of goods by supermarket chains. At the moment, the carts have a life expectancy of 10 years. The company services the charts if they break down. The goal of the company is to extend the lifetime of the charts.

Gorenje: washing machines in a pay-per-use model
Gorenje is bringing 400 long-lasting washing machines to the market through a pay-per-use business model. The design goal is to have the washing machines last for three five-year use-cycles, supported by maintenance and repair. At End-of-Life, a third party will dismantle the machines and harvest parts that can serve as spare parts.

Learnings of Concept 1

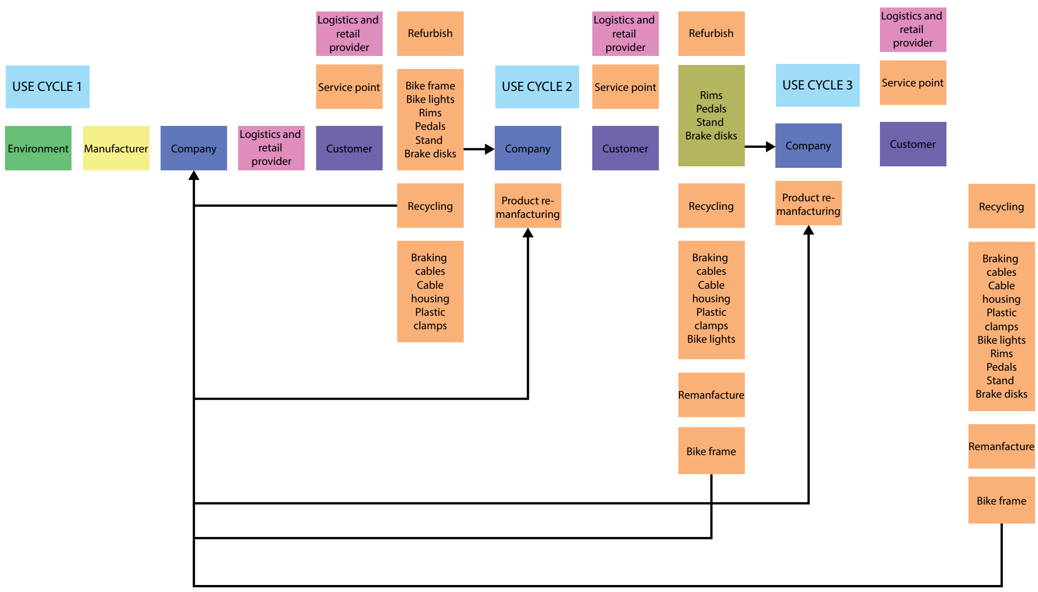

Figure 30 PJM - Concept 1a

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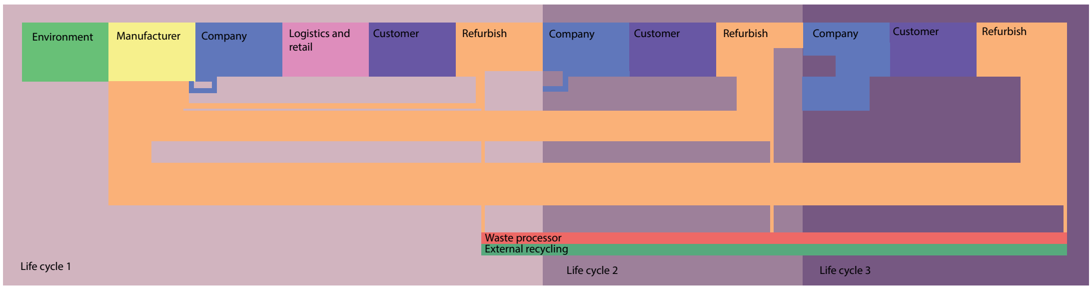

Figure 31 PJM - Concept 1b

Case: Roetz
Visualization techniques: Customer Journey Map, Sankey Diagram, and Bakker et al. (2017).
This concept has created a map of the currenty situation at Roetz, based on real data, to function as a basis for a redesign. It is also meant to highlight pains and gains. A common challenge in the designing of a product or service, is to design touchpoints or features that do not only function properly in isolation, but also work in synergy as a whole (van Boeijen et al., 2020). Hence another aspect of the CJM that can be integrated in the PJM, are the touch points on the vertical axis. Furthermore, the addition of stages can further aid the user in plotting the lifecycle of a product.

Learnings from Concept 2

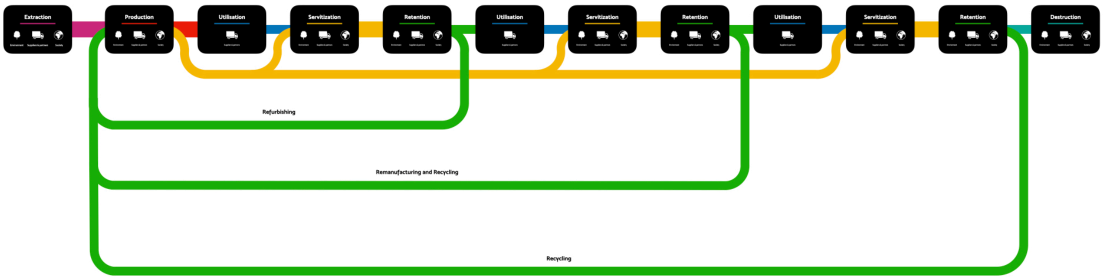

Figure 32 PJM - Concept 2

Case: Roetz
Visualization techniques: Butterfly Diagram by the Ellen MacArthur Foundation, Sankey Diagram, and Bakker et al. (2017).

From this concept multiple learnings were derived. First of all, using the black boxes did not communicate the information coherently and color coding used in the visualization was confusing. Furthermore, the addition of the touchpoints was not visualized at all.

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Secondly, it is not clear from the visual what the opportunities were. The outcome of a small-scale test conducted with industrial design students, was that it was unclear what the lines represented and the next concept should clearly identify opportunities.

In the same test, conducted with industrial design students, it was noted that the addition of icons greatly improved readability of the visualization. Therefore, this should be considered for the next concepts.

Learnings from Concept 3

Figure 33 PJM - Concept 3

Case: *Roetz*
Visualization techniques: Customer Journey Map and the Value Mapping tool (Bocken et al. 2013).

This concept demonstrated that a simpler visualization of the CO2 impact helps identify critical areas of the life cycle. This journey map includes stakeholder activities and can be therefore be used to find opportunities for improved stakeholder involvement. Improving collaboration throughout the stakeholder network, has a positive influence on the efficiency of the whole product-service-system. Nevertheless, this visualization does not provide information about the possible solution.

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Learnings from Concept 4

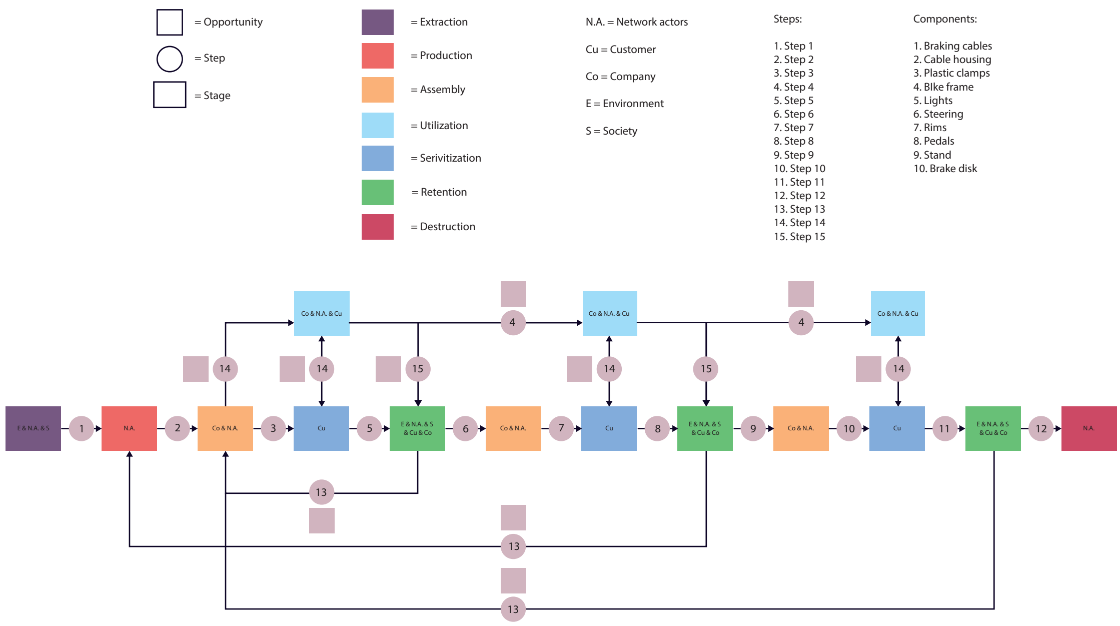

Figure 34 PJM - Concept 4

Case: *Roetz*
Visualization techniques: Disassembly Map (de Fazio et al. 2021) and Service blueprint

The visualization has clear rules for the set-up, and makes use of symbols to clearly structure the information. Nevertheless, it requires constant referral to the legend, which makes it was difficult to read. Additionally, the role of the stakeholders requires another form of visualization and integration. In this concept, they had standardized labels, which made their role too rigid.

Another insight from testing with industrial design students, was that the stages should follow from the steps, and not the other way around, since that was too standardized to represent a wide range of products.

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Learnings from Concept 5

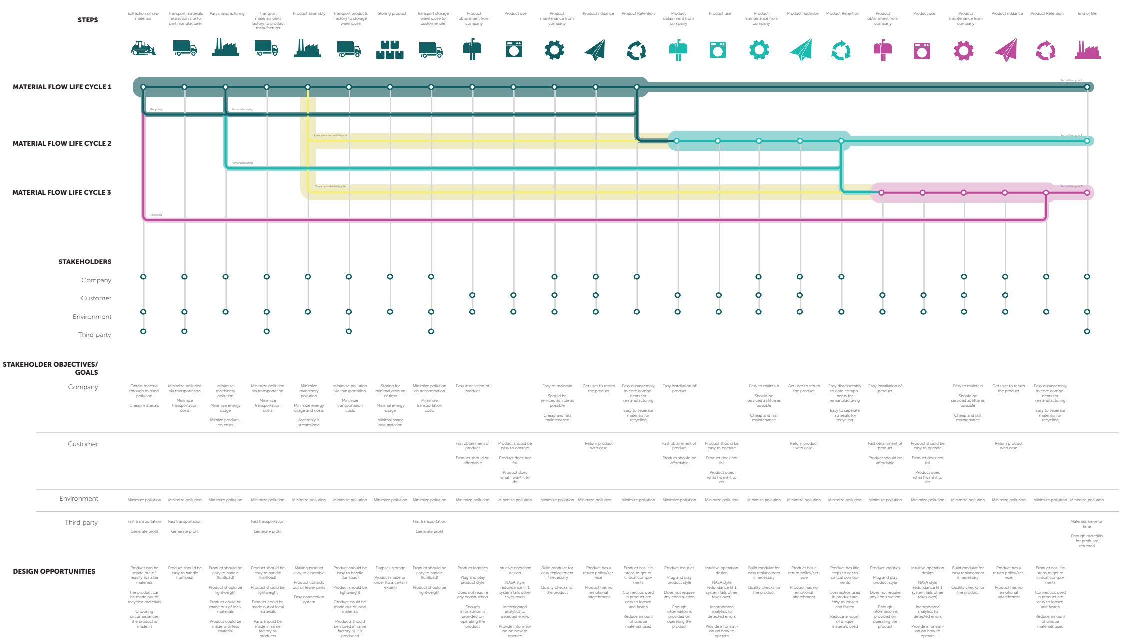

Figure 35 PJM - Concept 5

Case: Strekkar
Visualization techniques: Customer Journey Map and the Value Mapping tool (Bocken et al. 2013).

To include triple bottom line thinking was the main goal for this concept, which was done through adding the environment, the company, and customers to the 'stakeholder' section at the bottom of the visual. This map clearly shows the flow of the product and the link to different stakeholder needs.
Originally, the method was intended to be analytical, based on historical data. But during validation sessions with the company Castor Ventures, data confidentiality seemed to be a barrier. For this reason, the method was remodelled into a generative one, that deals with ideal scenarios. Another insight was, that the flow of parts, like spare parts, should have the correct departure point. It should be clear whether they come from inventory or production. The user should have the freedom to make easily such adjustments.

A final learning from this concept was, that adding or removing lanes/ rows to the y-axis, would allow the PJM to be used for different goals, for example, by zooming in to specific stakeholders, or adding a 'costs' lane.

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