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CLASSIFICATION OF METHODOLOGIES FOR DESIGN FOR CIRCULAR ECONOMY BASED ON A LITERATURE STUDY

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ABSTRACT

Global resource consumption is steadily rising. One option for stopping this upward trend is to reduce material consumption in general. With economics built for growth, this is not a practical path to pursue. Another recently explored alternative is the paradigm shift from a linear economy to a circular economy. The most common concept among practitioners and academics comprises the 6R's: Reuse, Repair, Refurbish, Remanufacture, Repurpose, and Recycle. In addition to business cases and supply chains that have been adapted to the circular economy, the products themselves must be circular. Developers face the challenge of developing novel products without appropriate experience from previous tasks.

This paper takes up the challenge of gathering relevant methods in the context of circular product development. A classification with regard to the required input data and use case shall help users effectively and efficiently find development methods suitable for their given development task. With the categorization via a product development framework it is pointed out in which phase existing methods support users and where a lack of support occurs.

Keywords: Circular economy, Design methodology, Design guidelines, Literature review, Design for X (DfX)

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1 INTRODUCTION

Circular economy (CE) is considered a promising way to counter the steadily rising pressure on primary resources (Diaz *et al.*, 2022; Bocken *et al.*, 2016). The gradual depletion of different materials, for example rare-earth elements, requires a transition from a linear economy with a "take, make, dispose" approach (Albæk *et al.*, 2020) to a circular product life cycle. The so-called "R-strategies" are the established methodical implementation of circular economy in product life cycle models. Reuse, repair, refurbish, remanufacture, and repurpose extend the lifespan of products and parts, whereas recycling processes materials at a product's end of life (EoL) after it has been used (Potting *et al.*, 2017).

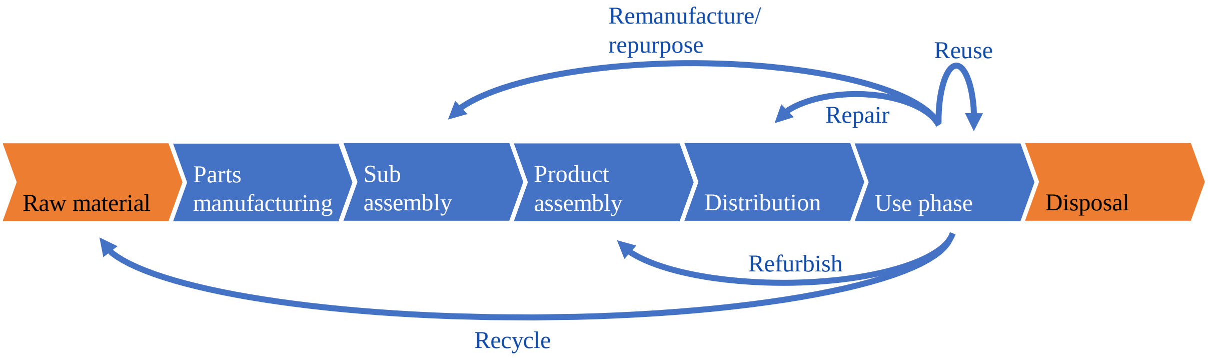


Figure 1. Production life cycle and "R-strategies" based on Potting et al. (2017)

A few companies have already found ways to implement circular economy in their business models and products (Skärin *et al.*, 2022). However, there is still a lack of basic understanding that would help bring the understanding of circular principles to a broader industrial audience. At the same time, the advantages of a circular economy are not purely environmental, as e.g., enabling a sustainable product life cycle leads to energy and material savings (Haziri *et al.*, 2019), but also to economical advantages. Estimates point out that adapting to a circular economy can save up to $100 billion in material costs in the EU alone (Asif *et al.*, 2021). Furthermore, the production costs are generally lower compared to a conventional linear product in the context of remanufacturing (Soh *et al.*, 2014).

Existing research focuses on the development of circular business models (Bovea and Pérez-Belis, 2018) and the understanding of CE as a whole. The prerequisite for inclusion is the mention of a circular product. Investigations into circular product design are mostly limited to design guidelines and synoptic overviews (Sassanelli *et al.*, 2020; Berwald *et al.*, 2021; Pozo Arcos *et al.*, 2018) but lack the exploration of methodological support for the product developer in order to solve problems occurring during the development of products suitable for a circular economy. These guidelines are often based on a certain Design for X (DfX) approach and attempt to help the developer by providing "design advice" on what is needed to develop a circular product. Because of this broad scope, these guidelines fail to support the practitioner in solving specific design problems. A common example is the advice to modularize products for circular economy. However, there is no suggestion on how this modularization should be carried out. Apart from that, there is no common definition of design for circular economy and therefore practitioners are faced with the challenge of finding suitable design methods among a variety of different designations and application areas.

This paper is intended to serve as an orientation for academia to identify methods regarding circular product development and research gaps alongside. The objective is to find methods that are marked specific for the development of circular products by the author. To allocate the field where a lack of methods designed for developing circular products occurs, the methods may be mapped to either aspects of the product itself (parts, links, structure, functions, etc.) or the product development process. Latter seems more sufficient in the context of finding development methods. This leads to the research question: In which phases of the development process of circular products do existing methods support the user and in which do they not?

A systematic literature review is carried out to identify relevant development methods. The relevant literature is filtered and classified via a commonly used product development process model.

Classification should help improve the accessibility and therefore applicability of existing methodological support. The article concludes with a discussion of the results and an outlook concerning possible future research.

2 RESEARCH METHODOLOGY

A systematic literature review was carried out to identify relevant product development methodologies for circular products. The scope of the search was restricted as little as possible in order to enable the identification of all relevant scientific papers within the research field of circular economy, product development, and methodology. Definitions and terms in the research field are not established yet and literature is fuzzy. A further constrain of the literature search would limit potential findings. The Table 1 shows the cumulative search string which was used on two different scientific databases:

Table 1. Breakdown of the search string

Component of the Search String	**Synonyms**
Part 1: General research field	Circular Economy
Part 2: Engineering field	design for, product design, product development, engineering design
Part 3: Method	methodology, approach, framework, procedure, strategy, guideline, tool, technique, practice
Overall search string	circular economy AND (design for OR product design OR product development OR engineering design) AND (method OR methodology OR approach OR framework OR procedure OR strategy OR guideline OR tool OR technique OR practice)

The literature search was carried out on two databases: Scopus and Web of Science. To obtain an extensive collection of relevant literature, the titles, abstracts, and keywords of the papers were searched. Further restrictions such as the year, subject area, or source type of the publication were not used. The three filters that were applied to sort the identified publications are listed in Table 2. The initial read-through only considered the title and keywords of these papers. Papers that were still viewed as relevant after reading the full article were considered for classification.

Table 2. Filters for literature sorting

Filter 1:	Reading of the title and keywords
Filter 2:	Reading of the abstract
Filter 3:	Reading of the whole paper

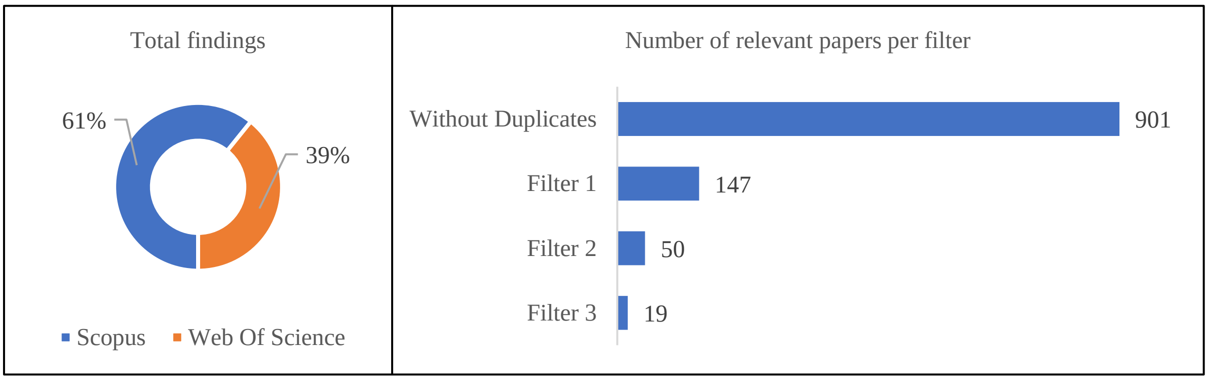


Figure 2. Results of the literature review and sorting procedure

Ultimately 1276 scientific papers were found across both databases, with 61 % on Scopus and 39 % on Web of Science. After eliminating duplicates that were found on both databases, a total of 901 independent sources remained. Reading the titles and keywords filtered out a large portion of these. 50 papers remained after the abstracts had been read, of which 19 were relevant methods in the field of circular product development. Figure 2 shows the visual representation of the findings. Relevant methods were defined as ones that provide development support in the form of procedures that can be incorporated in an individual development process. Providing checklists and design guidelines without actual implementation of methods for achieving corresponding design goals was not sufficient.

3 CLASSIFICATION FRAMEWORK

A classification of methodologies for product development can only be accomplished within a superordinate product development process (PDP) framework. To provide an effective and efficient collection of methodologies, it seems rational to perform classification based on the development phase in which a potential user is situated. The classification is based on the product development cycle according to Pahl et al. (2007). With their view of the PDP, the authors provide a comprehensive framework for the development of technical products. Figure 3 shows the different development phases into which the PDP is divided.

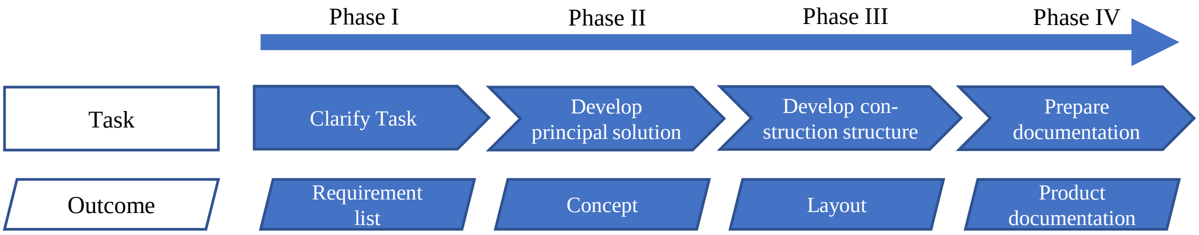


Figure 3. Product development cycle according to Pahl et al. (2007)

These subdivide the PDP into four different phases. The first phase applies general requirements to the product. Requirements arise from the internal product definition as well as external issues resulting from products or from competitors. The outcome of the first phase is the requirement list. The development activities of the second phase connect to the first one. Data from the requirement list are used and meet at the establishment of the function and effect structure of a product. This rather theoretical structure of the product is transferred into a physical structure in phase three. The construction structure of the product consists of the individually developed parts of the product. The entire product documentation is created during the fourth and last phase, containing aspects such as the assembly and additional production information for the developed product.

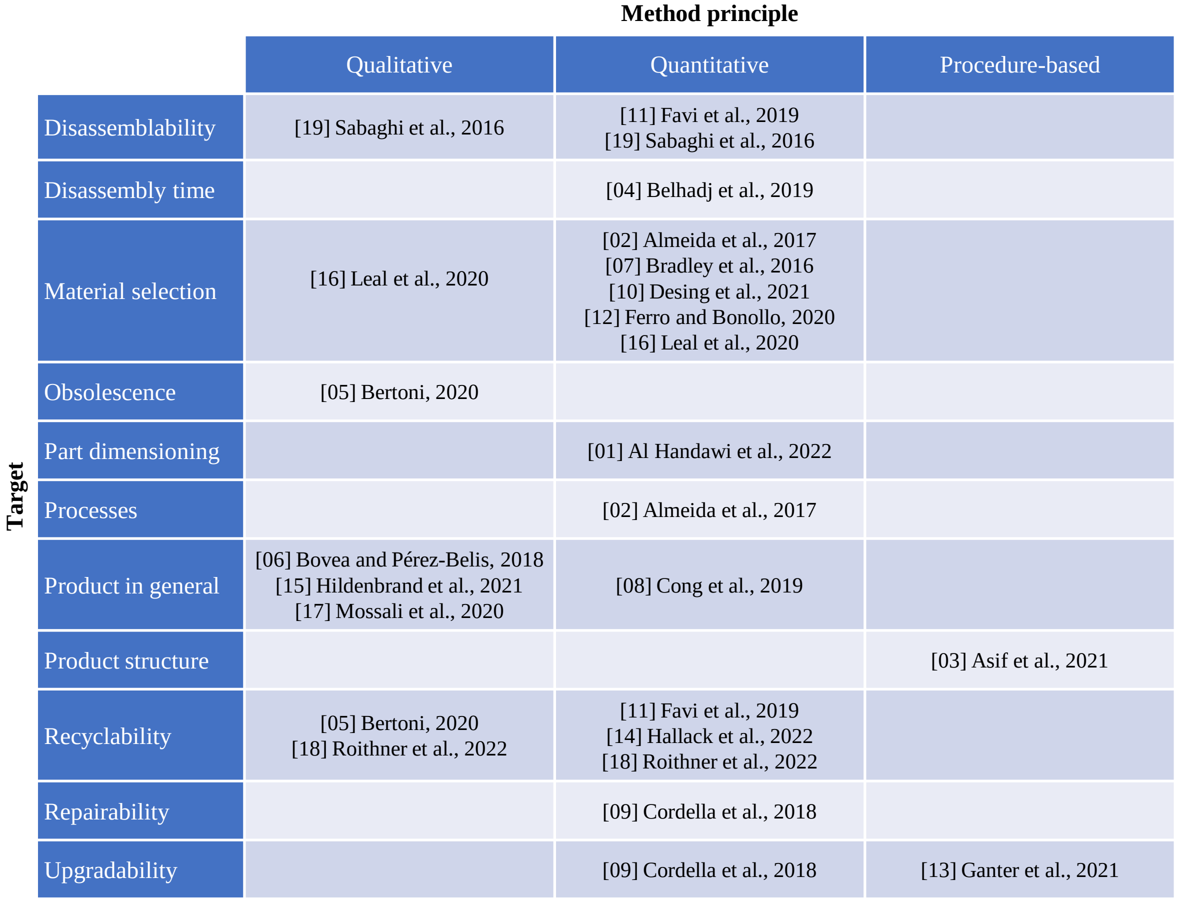
The first and most fundamental characteristic of a product development method is whether it is suitable for New Product Development (NPD) or the adaptation of an existing product (Pahl *et al.*, 2007). The technical product development process of both development tasks differs in terms of the application of a fundamentally new circular product or the "circularization" of existing products. The suitability of a certain method for either of the mentioned development tasks depends on the information required in the product development phase in which the method is located. If information and data from later phases are required, the method is technically unsuitable for NPD. Although the consideration of data from existing in-house or competitor products seems possible in theory, the lack of transparency in terms of available data and the overall demand for simplicity in classification means that this is excluded from the approach of this paper. To map existing and detect a lack of support, the identified methods are classified in this scheme by stating the development phase in which the respective method is applied and by stating the information and data needed to execute it. Additional information about the underlying working method and the targeted design aspect makes the selection process even more efficient.

4 FINDINGS

The results of the systematic literature research presented above suggest that there is no consistent definition of circular product design. In most of the papers that were identified, however, circular product design is represented by several different existing DfX approaches. Go et al. (2015) provide an extensive overview of this. There are rather general approaches such as design for disassembly, design for multiple life cycles, or design for longevity (Go *et al.*, 2015), while others are more specialized in terms of their focus on the respective R-strategies (Fegade *et al.*, 2015) as an example for remanufacturing). Much of the identified research focuses on design guidelines. The following subsections describe methodologies relevant to product design and subsequently classify these by product development phase.

4.1 Product development methodologies

Reviewing the methods identified, it can be seen that there are three basic principles according to which they operate. *Qualitative* methods are mostly based on design guidelines where individual product properties are compared to ideal conditions in order to match the needs of circularity. *Quantitative methods are based on a calculation which assesses a certain product property*. *Procedure-based methods are* not based on an ideal condition or comparison to the as-is state, nor are they based on calculated indicators. For easy access and synopsis, Figure 4 presents an overview of this information. In the first column, all authors are listed alphabetically. The right side of the figure shows the basic principle used in the method (Column 2 - 4). The left side shows the target which is to be adjusted to satisfy circular product design. Shown methods are further described in the following paragraph.



Method principle

Target	Qualitative	Quantitative	Procedure-based
Disassemblability	[19] Sabaghi et al., 2016	[11] Favi et al., 2019 [19] Sabaghi et al., 2016	
Disassembly time		[04] Belhadj et al., 2019	
Material selection	[16] Leal et al., 2020	[02] Almeida et al., 2017 [07] Bradley et al., 2016 [10] Desing et al., 2021 [12] Ferro and Bonollo, 2020 [16] Leal et al., 2020	
Obsolescence	[05] Bertoni, 2020		
Part dimensioning		[01] Al Handawi et al., 2022	
Processes		[02] Almeida et al., 2017	
Product in general	[06] Bovea and Pérez-Belis, 2018 [15] Hildenbrand et al., 2021 [17] Mossali et al., 2020	[08] Cong et al., 2019	
Product structure			[03] Asif et al., 2021
Recyclability	[05] Bertoni, 2020 [18] Roithner et al., 2022	[11] Favi et al., 2019 [14] Hallack et al., 2022 [18] Roithner et al., 2022	
Repairability		[09] Cordella et al., 2018	
Upgradability		[09] Cordella et al., 2018	[13] Ganter et al., 2021

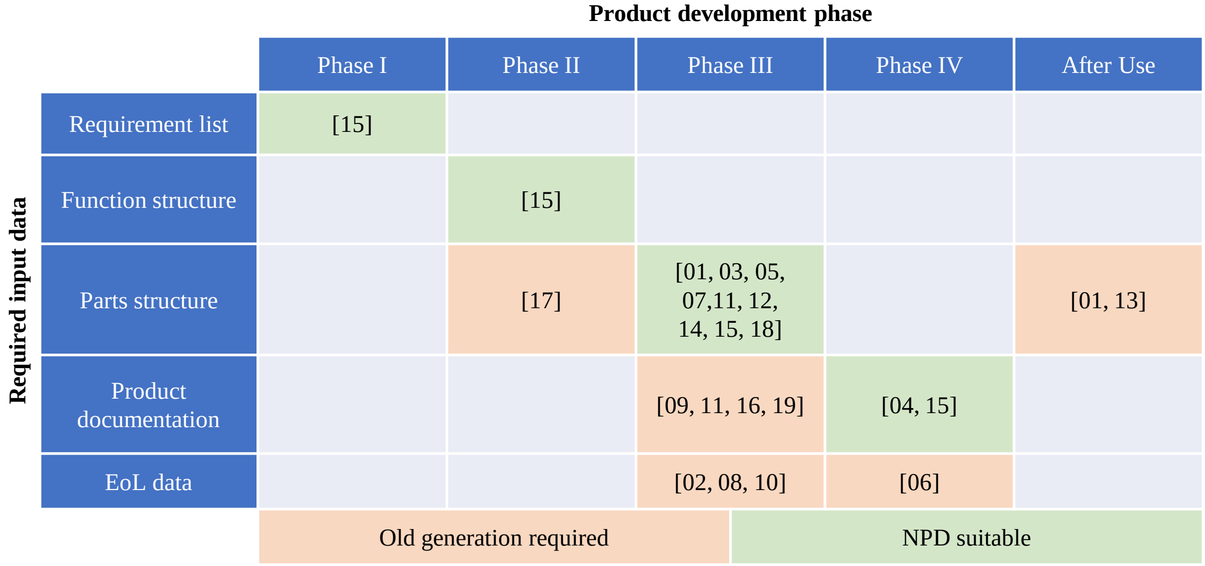
Figure 4. Classification of the identified methods via basic principle

Al Handawi et al. (2021) [01] develops a set-based design method to support product design in cases where requirements have not been fully determined. This makes it useful either for early design stages at the beginning of phase 3 or for remanufacturing processes that may feature changing requirements. The author refines this method for explicit application in remanufacturing scenarios (Al Handawi *et al.*, 2022). A set of design decisions can be obtained and refined through additive manufacturing to meet second life requirements. Almeida et al. (2017) [02] support the developer with a method for enhancing the reusability of a product. This is based on Life Cycle Assessment (LCA) and an exergy assessment. Exergy data regarding industrial processes and materials is therefore used for decision-making in relation to whether or not a subassembly is suitable for reuse. Knowing the end of life makes it possible to derive use actions for optimizing the product design. Asif et al. (2021) [03] present an approach for designing products across multiple life cycles. The method is based on Modular Function Deployment (MFD) by Erixon (1998) and focuses on modular product design to serve desired end of life scenarios like reuse, remanufacturing, upgrading, and recycling. Belhadj et al. (2019) [04] develop a method for estimating the disassembly time of product modules containing wear parts. The estimated times of different disassembly operations are obtained from industrial practice. A digital mock-up of the product is needed. Bertoni (2020) [05] presents the Circularity Impact and Failure Analysis (CIFA) which is based on the Failure Mode and Effect Analysis (FMEA). To raise awareness of potential risk in the development of circular products, the author adds consideration of component obsolescence and system recyclability to the FMEA. Bovea and Pérez-Belis (2018) [06] present a method that is based on design guidelines for circular products. The authors assess existing products in relation to circular properties that were identified via literature research regarding design guidelines. Development actions can be derived by evaluating the relevance and the level of implementation of these design guidelines. Bradley et al. (2016) [07] develop an assessment framework for design decisions regarding material selection. During the first stage, data relating to material properties, costs, LCA results, and social performance indicators are gathered. In the second stage, a 6R-based life cycle cost model is used. In the third stage, a genetic algorithm processes the provided data. Cong et al. (2019) [08] focus on disassembly bottlenecks. The authors investigate existing product designs in order to improve on joint design, material incompatibility, and product architecture. The method is based on modelling end of life value recovery. Cordella et al. (2018) [09] present an approach for assessing the repairability and upgradability of energy-related products. The method consists of a qualitative, a semi-quantitative (point-based system), and a quantitative assessment of the product with regard to repairability and upgradability. Desing et al. (2021) [10] try to reduce pressure on primary resources by calculating the resource pressure. The method considers product mass, product lifetime, manufacturing losses, primary material content, recyclability, and cascadability. The authors derive design guidelines based on these six parameters. Favi et al. (2019) [11] develop a method and an associated tool to assess disassemblability and recyclability of mechatronic products. The main elements of the analysis are identifying target components, precedencies, liaisons, and properties as well as disassembly time and costs. Ferro and Bonollo (2022) [12] introduce a material criticality index. Calculations with this index regarding material efficiency, recycling, and material substitution show the suitability of a certain material. Ganter et al. (2021) [13] present a method for upgrading single components within refurbishment through additive processes. The authors apply a design approach that is developed from modular product architecture and conventionally describes assemblies on a single component. Individual functions of a component are mapped to parts of the component. This component/function architecture features four possible refurbishing options: keeping/restoring, removing, improving, and adding new functions. Hallack et al. (2022) [14] aid the developer with a systematic design approach concerning design for recycling. The method specifically addresses automotive exterior plastics and targets the reduction of different plastics as well as dismantling challenges that lead to worse disassembly performance. Hildebrand et al. (2021) [15] provide two tools. The "Recirculation Strategies Decision Tree" identifies and redesigns the end of use and end of life scenario which is suitable for the given product and is based on the criteria of circular design guidelines. In addition, the "Eco Strategy Wheel" supports developers in all development phases by means of 8 basic guidelines. Leal et al. (2020) [16] approach a circular design with design for recycling and design from recycling. First, a product's recycling performance is assessed via guidelines (for recycling). Second, the convenience of using recycled materials from a technical, economic, and environmental standpoint is evaluated (materials from recycling). Mosalli et al. (2020) [17] use a house of quality approach to highlight the connections between engineering specifications and redesign requirements, which are guidelines for the end of life scenarios reuse, remanufacturing, and recycling. This allows developers to identify engineering specifications which are relevant for a certain end of life design. Roithner et al. (2022) [18] present a recyclability assessment method which incorporates material composition and product structure. The method is based on statistical entropy and evaluates the distribution of materials in products. Redesign actions regarding material use and distribution can be derived. Sabaghi et al. (2016) [19] introduce a disassembly index considering accessibility, mating face, tools type, connection type, and the quantity and variety of connections. It is therefore a guideline-based method from which redesign actions can be derived.

4.2 Classification according to the product development phases

Figure 5 shows the classification matrix of the identified methods according to the PDP. The columns indicate the four phases of the PDP plus an additional "after use" phase which is needed to classify all identified methods correctly. In this phase, products that have already been used are developed further. The mapping to the different phases happened according to the phase intended by the author. The rows show the required input data which is needed to execute the proposed method. All methods introduced in chapter 4.1 are sorted into this scheme accordingly and are numbered as shown in Figure 4.

Methods that are filled underneath the diagonal of the matrix need data that is not yet available in the product development phase for which the method is intended. This means that the information relies on previous product generation or on estimations. Those methods are therefore unsuitable for new product development. Methods on the diagonal of the matrix use exactly the information of the PDP that is present for this phase. The development of new products is possible because there are no estimations and the information that is needed can only be gathered from previous products. Methods above the diagonal are also unsuitable for NPD because they assist the developer with redeveloping existing products.



Product development phase

Required input data

	Phase I	Phase II	Phase III	Phase IV	After Use
Requirement list	[15]				
Function structure		[15]			
Parts structure		[17]	[01, 03, 05, 07,11, 12, 14, 15, 18]		[01, 13]
Product documentation			[09, 11, 16, 19]	[04, 15]	
EoL data			[02, 08, 10]	[06]	

Old generation required

NPD suitable

Figure 5. Classification of the identified methods via product development phase

4.3 Discussion

When examining the result of the literature search, it is noticeable that the number of product development methods is relatively low, although more than 900 papers were found. Only 19 different circular product development methods were identified. Figure 5 shows the distribution among the different product development phases. It can be seen that even though most of the papers state that their method takes place in "early development" phases, most methodical support takes place in the third product development phase, where the products are already constructed. Quantitative methods in particular focus more on design aspects than on early development tasks. Little methodological support can be found in areas such as requirements definition and function deployment in early development phases. Most of the methods found were based on a quantitative approach, of which a few also used qualitative techniques and were thus semi-quantitative. Only two methods were neither qualitative nor quantitative and were based on dedicated procedures. Based on comparison of the product development process and the required input data, only nine methods are suitable for developing new circular products that are not based on a previous generation.

Considering all methods found during the literature research that were subsequently eliminated, it can be said that there are lots of qualitative methods. But all of them lack methodical support for product development itself as they do not provide a dedicated procedure that supports proposed product changes. Generally, the border between methods that only provide an assessment and methods that support the user with an additional procedure to modify the properties found through the assessment is rather soft.

Figure 4 shows that most of the methods that support circular product development are based on quantitative and qualitative methods. The design guidelines behind the qualitative methods are derived from existing DfX approaches for different R-strategies such as design for disassembly in general, upgradability in the case of refurbishing, remanufacturing, or recycling. These guidelines were found through literature research and are not newly developed. But guidelines are only thought-provoking in a general sense. They fail to provide support in terms of how to implement and improve certain advice. Furthermore, there is no clear distinction between different DfX approaches. They intersect in different areas, which makes it difficult for users to summarize important aspects of each.

5 CONCLUDING SUMMARY

This paper provides an overview of existing development methods for circular products to help users identify a suitable development method for their specific use case. As a first step, a systematic literature review of development methods for circular products is conducted. From 901 independent scientific papers found on Scopus and Web of Science, 19 methods were extracted that support the development of circular products. The methods found were summarized and categorized by working principle, target, and the product development phase in which they are supposed to be used. It is to be noted that sole development methods in connection with the keyword "circular economy" were considered. An investigation of subcategories (remanufacturing, refurbishing, etc.) independently was not carried out.

Three different working principles were identified during analysis. Qualitative methods were mostly based on existing DfX guidance, such as design for disassembly in general, upgradability in the case of refurbishing, remanufacturing, or recycling. Quantitative methods incorporated assessments to identify potential design parameters for optimizing circularity. Procedure-based methods went one step further and methodically supported the optimization of a certain design parameter. Targets of the methods were recyclability, disassemblability, repairability, upgradability, material selection, and the general product. Despite the common allocation by the authors to "early phases," most of the development methods support the user in the third phase of the development process according to Pahl et al. (2007) and thus in the component design. There is no support for creating the requirements list (phase one) or a function structure suitable for CE (phase two). The information required to execute the methods differs in terms of information from the same development phase and information from later development phases. Since the latter must build upon a previous product generation, such methods are not suitable for new product development.

In general, this paper provides potential users with an easy way to find product development methods that are appropriate for their specific use case. Two matrices give a visual representation of the available methods and their application.

6 OUTLOOK

Methodical support for circular product development in early phases of the development process could not be found. In these development phases in particular, 80 - 90 % of the cost optimization for circular products can be achieved (van den Berg and Bakker, 2015). Herein lies the potential for academia to develop support for these phases of the product development process. The prerequisite is the extraction of requirements of circular products on the product development process and related phases and methods. Findings from this investigation should further clarify what existing methods (not labeled for developing circular products) lack or do not lack in regard to their application in development of circular products.

Besides the time of execution, many of the methods are not suitable for new product development. An investigation into whether existing products and product architectures are at all suitable for the transition to a circular economy is yet to be performed. Given the lack of development methods in the early phases, during which the product architecture is defined and set, this consideration should be implemented.

The variety of labelled methods and guidelines most likely is overwhelming from the user's point of view. To narrow the available selection of guidelines in the field of circular product development, comparative research can be conducted. Furthermore, the overlap between different approaches such as design for disassembly, remanufacturing, or recycling has not yet been investigated. It would be interesting to see how product requirements for these different EoL scenarios differ or whether they are actually the same.

To extend beyond academic viewpoints, interviews should be conducted with industry representatives and experts in the field of circular product development: This would enable investigation of the actual need for methods in this field. The mapping of challenges with the development of circular products in practice and support from academia is fundamental for achieving better matching and developing better support.

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