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Investigation Into the Suitability of Existing Evaluation Methods for Application with Circular Product Architectures in Early Development Phases

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Abstract: The paradigm shift from a linear to a circular economy appears to be one promising way of countering the steadily increasing consumption of resources. Both circular business models and the methodical development of circular products pose a major challenge in this regard. This paper aims to identify requirements for research into potential methods that enable the evaluation of circularity in the early phases of the product development process. For this purpose, the impact of implementation of DfCE criteria on the product development process is compared with evaluation methods for early phases.

Keywords: Circular Economy, Methodology, Requirements, Product Architecture, Evaluation

1 Introduction and motivation

The circular economy (CE) is considered one of the most suitable ways to handle resource scarcity by separating resource consumption from economic growth (Bocken et al., 2016; Diaz et al., 2022). In the past few years, the exploration of the concept of CE has advanced in different areas ranging from its implementation in business models to the adaptation of supply chains. One key aspect is the circular product itself and how it is effectively developed while taking into account the relevant information. Such complex development goals can only be achieved with the help of a methodology that supports developers designing circular products. Previous studies have found that circular product development is currently only supported by a few methods – and support for developers in the early phases of the product development process (PDP) is still non-existent (Stoelzle et al., 2023a). Because decisions concerning the concept are taken in early phases, they have implications for the rest of the development process, making this phase very important (Bender and Gericke, 2021).

According to Pahl and Beitz (Bender and Gericke, 2021), the early phases of development are "planning and clarifying the task" and "conceptual design." The result of the early phases is the product concept and therefore the product architecture (PA), consisting of the function structure, the component structure, and the working principles that connect these two aspects (definition of PA according to Göpfert, 1998). Since it is common to pursue more than one product concept in this phase, the evaluation and selection of the proposed concepts also takes place at this point. There are countless methods for the evaluation of conventional non-circular products, with Bender and Gericke (2021) also providing methods for this purpose. While the evaluation of circular products and their architectures during the conceptual phases is still in its infancy, it does appear essential for expanding knowledge of what a circular product structure is. To gain knowledge of what a good circular product structure in regard to function structure, component structure and working principles may look like, there must be some kind of evaluation. This paper therefore reviews and investigates existing methods for performing evaluation in conceptual phases of product development, rating them in terms of their suitability for the evaluation of a circular product. The underlying research question is as follows: "To what extent are existing early-stage methods for product architecture evaluation suitable for circular product development?"

First, a systematic literature review was carried out to identify all relevant methods for an assessment of PAs in early development phases. These methods were then classified and compared with the development process requirements according to the Design for Circular Economy (DfCE) criteria. The requirements and the classification were based on previous investigations conducted by Stoelzle et al. (2023b). This comparison is intended to determine the suitability of these methods for the evaluation of circular PA and identify research gaps with respect to existing methods.

2 Methodology

The following subsections outline the methodology used for the systematic literature review of evaluation methods and explain the systematic classification of the evaluation methods.

2.1 Literature review

To find relevant methods for the evaluation of early product concepts, a systematic literature search was conducted in the two scientific databases Scopus and Web of Science. A search string consisting of a combination of synonyms for "evaluation," "methodology," "product architecture," and "product development" was used for this purpose:

Table 1. Search string

Component of the search string	Synonyms
Evaluation	assessment OR costing OR "decision-making" OR evaluation OR rating OR valuation
Methodology	approach OR framework OR guideline OR method OR methodology OR strategy OR tool
Product architecture	"product* architecture" OR "function* architecture" OR "physical architecture" OR "technical architecture" OR "function* structure*" OR "module structure" OR "part* structure" OR "working principle*" OR "working structure*" OR "function* principle*"
Product development	"product development" OR "product design" OR "engineering design"

All components were combined with the operator "AND" to generate the complete search string. Papers were searched by title, abstract, and keywords. Beyond that, no restrictions were imposed on the search itself or the search results.

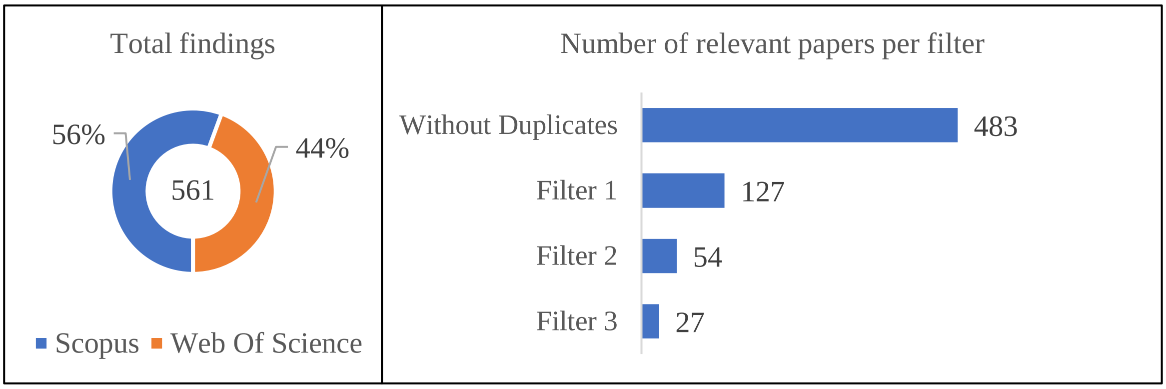

Figure 1. Results of the literature review and sorting procedure

All the results from this systematic research were filtered in three steps and examined for relevance. In the first step, the title of the article was read, in the second, the abstract, and in the third step the entire article. Standalone and independently published assessment methods for product architectures intended by the corresponding author for use in the early stages of product development were classed as relevant. Assessment methods published in conjunction with another method (e.g., a modularization method) were not considered.

Figure 1 shows the number of search results as well as the number after filtering. Ultimately, 483 independent contributions were found and investigated. 27 relevant papers and thus evaluation methods remained after step 3 of the filtering process and are considered in the following sections.

2.2 Classification of the methods

The investigation published in (Stoelzle et al., 2023b) serves as a basis for verifying the suitability of the identified methods. Results that have not been published but were generated in the course of the study by Stoelzle et al. (2023b) are also used. Stoelzle et al. (2023b) investigated the impacts on the PDP resulting from the implementation of DfCE criteria. Within the term DfCE, the paper examined in particular criteria for Design for disassembly, reassembly, remanufacturing, reuse, repair, refurbishment and recycling. Therefore, the PDP and the product itself were abstracted to formulate general impacts on different aspects of the PDP. Exact evaluation criteria were not derived. The extracted impacts on the PDP were used to perform a comparison examining whether the identified evaluation methods are suitable in principle for evaluating the circularity and circular aspects of products. The study establishes the suitability in principle of these methods for the evaluation of circular aspects of the PA but does not consider individual evaluation criteria. The procedure is illustrated in Figure 2.

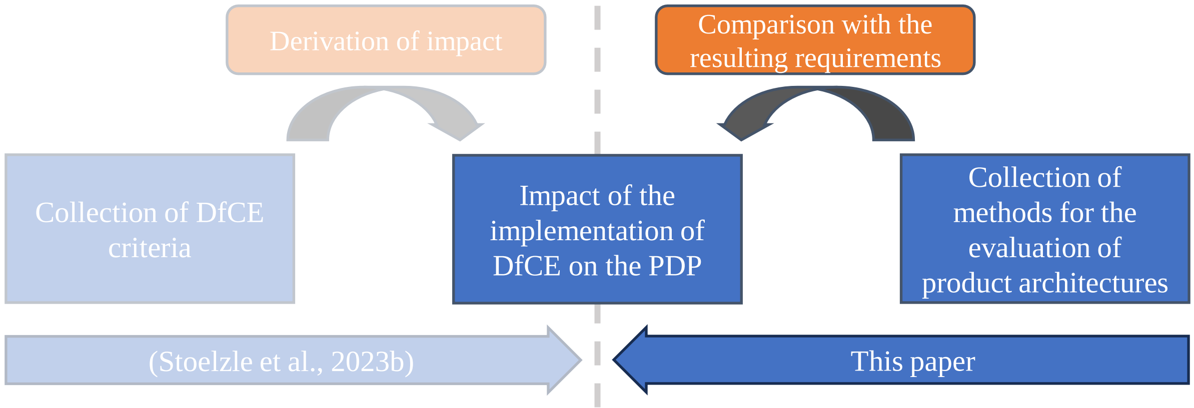

Figure 2. Graphic representation of the investigation methodology

Categories for the evaluation methods were introduced as an equivalent to the abstraction of the PDP. Both the categorization from Stoelzle et al. (2023b) and the corresponding categorization for this research are shown in Figure 3. The goal of the categorization was to have one category for every relevant aspect of the PDP. In order to consider temporal and procedural aspects, the PDP according to Pahl and Beitz (Bender and Gericke, 2021) was taken as the basis of the first two categories. The third category helps further understanding of the development-related challenges resulting from circularity. A division in this category should reveal the type of problem and eventually the type of solution needed for implementing circular criteria into the product and PDP. Category four provides the distinction between development for a subsequent product generation and new product development (NDP). To understand cross-linking in the development process, category five considers the flow of information from other phases of the product creation process that is needed to fulfil the respective DfCE criteria or execute the evaluation. Category six then considers how specific the DfCE criteria and evaluation results are: For example, it must be considered whether the criterion of not using a certain plastic is more specific than the criterion of product modularization for improving circularity. Since the latter criterion requires consideration of a large number of aspects, it is therefore more complex and cannot be implemented directly by the developer. The same principle applies to evaluation methods, as the "robustness" of a product concept is less tangible than aspects such as a calculated CO_2 equivalent. Categories seven and eight classify the application area of the methods. Finally, category nine links back to the circular strategies (R strategies according to Kirchherr et al. (2017)) and thus circularity itself.

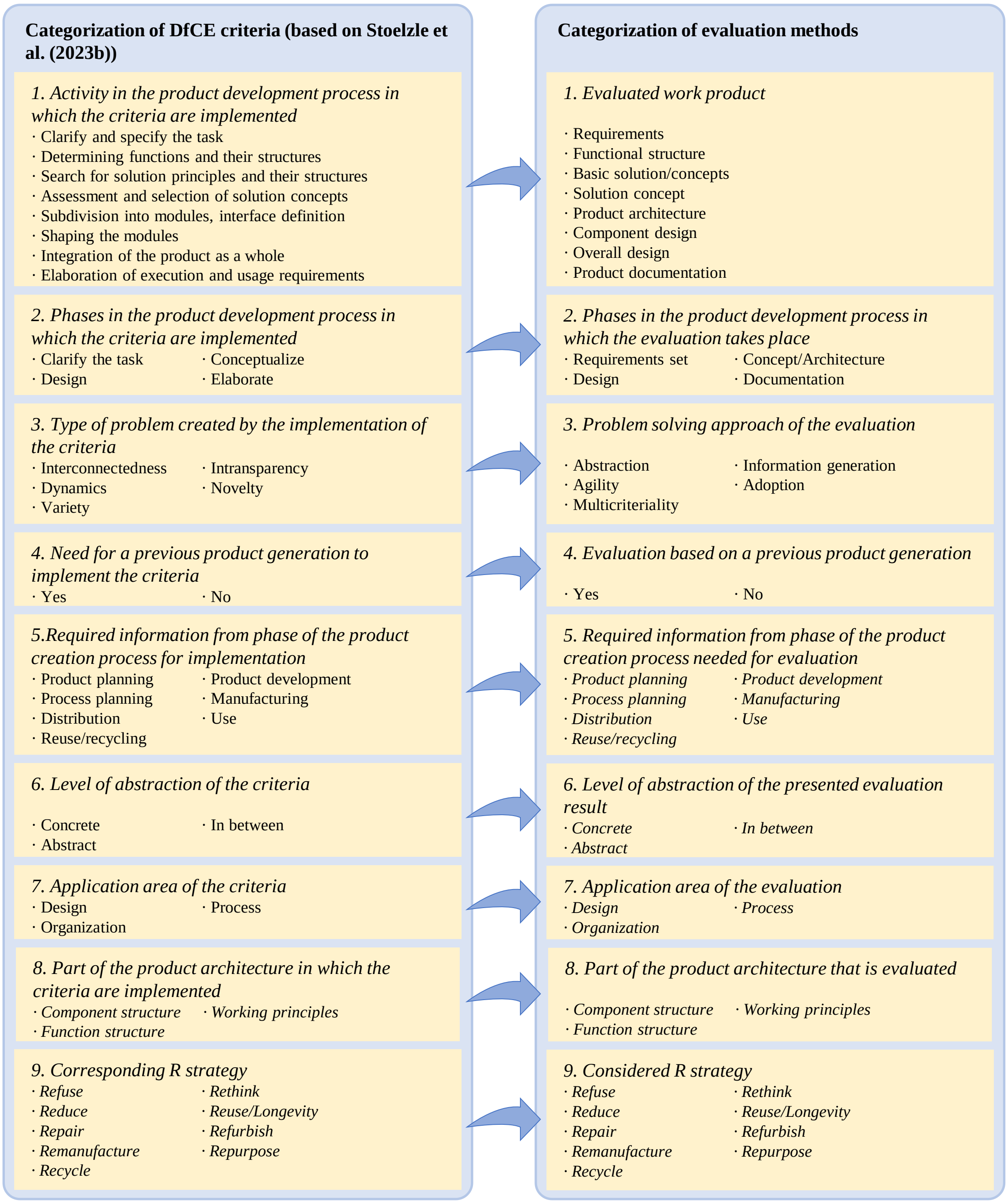

Figure 3. Categories of the abstracted PDP

The division of the methods into the categorization framework was carried out during workshops with product development experts in two appointments over the course of two weeks. Summaries of the identified evaluation methods were presented to the participants at each appointment. The participants were then required to categorize the methods based on a summary. No significant deviations occurred, and it was possible to categorize all methods after discussion. Participants were also able to classify these methods in multiple subcategories or none at all. A brief survey regarding the suitability of the given categories for the division of the methods provided further backing for the categorization itself.

3 Findings

The 27 methods identified via the systematic literature research can be divided into five main evaluation targets as seen in Table 2:

Table 2: Evaluation targets of the identified methods

Target	Methods	
Costing	Altavilla and Montagna (2019)	"A Product Architecture-Based Framework for a Data-Driven Estimation of Lifecycle Cost"
	Ripperda and Krause (2015)	"Cost prognosis of modular product structure concepts"
(Dis-) Assembly	Bouissiere et al. (2019)	"A method to assess manufacturing and assembly aspects of product architectures"
	Formentini et al. (2022)	"Conceptual Design for Assembly methodology formalization: systems installation analysis and manufacturing information integration in the design and development of aircraft architectures"
	Kim et al. (2016)	"A disassembly complexity assessment method for sustainable product design"
General	Chen et al. (2019)	"A Product Concept Generation and Evaluation Method Based on Knowledge"
	Fixson (2005)	"Product architecture assessment: A tool to link product, process, and supply chain design decisions"
	Jing et al. (2022)	"A quantitative simulation-based conceptual design evaluation approach integrating bond graph and rough VIKOR under uncertainty"
	Midžić et al. (2019)	"Energy quality hierarchy and "transformity" in evaluation of product's working principles"
	Qingchao et al. (2006)	"Multi-level fuzzy comprehensive evaluation based on NPD planning"
	Yamada et al. (2020)	"Decision support method for upgrade cycle planning and product architecture design of an upgradable product"
Modularity	Agua et al. (2012)	"Rules modification on a Fuzzy-based modular architecture for medical device design and development"
	Dambietz et al. (2023)	"Simulation-based performance analysis for future robust modular product architectures"
	Fukushige et al. (2009)	"Product modularization and evaluation based on lifecycle scenarios"
	Greve et al. (2022)	"Knowledge-Based Decision Support for Concept Evaluation Using the Extended Impact Model of Modular Product Families"
	Kim and Moon (2019)	"Eco-modular product architecture identification and assessment for product recovery"
	Recchioni et al. (2009)	"Supporting development of modular products utilising simplified LCA and fuzzy logic"
Robustness/ Risk	Brahma et al. (2023)	"Function driven assessment fo manufacturing risks in concept generation stages"
	Kissel et al. (2011)	"A methodology to evaluate the structural robustness of product concepts"
	Mamtani et al. (2006)	"Relative reliability risk assessment applied to original designs during conceptual design phase"
	Osman and Marjanović (2012)	"Matrix based approach in assessing optimum robust product architectures"

This section presents the results of the classification within the established categorization framework. All diagrams show the percentage (in proportion to the overall number identified) of the assigned methods (blue) as well as the DfCE criteria (light orange, taken from the studies by Stoelzle et al. (2023b)) in the respective subcategory. Absolute figures have been omitted for the sake of comparability.

3.1 Phases of the PDP

As expected, most methods are classified in the concept phase (cf. Figure 4) due to the focus of the search. Nevertheless, four methods were found that can be classified in the design phase. Only the methods of Borgianni and Rotini (2015) take place in the first phase of the PDP. Most of the methods evaluate the PA, which can be explained by the number of methods aiming for the evaluation of modularity. The methods classified under "component design" and "overall design" are used for concept evaluation but are strongly based on components of previous or comparable products. The remaining methods are distributed in the early phases of the development.

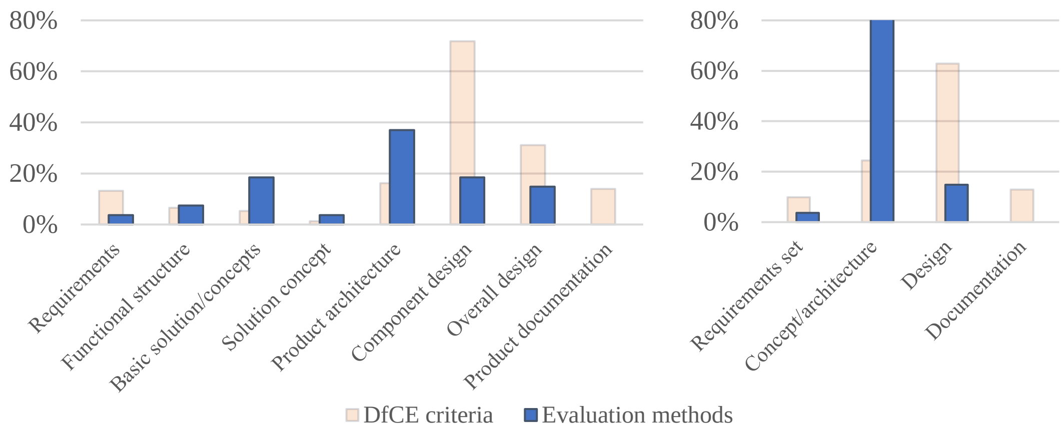

Figure 4. Categorization by activities and phases of the PDP

3.2 Approach to problem-solving

Most of the methods use abstraction and thus a simplification of the problem which can be solved. About half as many methods generate information during their execution, which can then be used as the basis for the desired evaluation. A small number of the methods follow the exclusive approach of multicriteriality by considering large datasets. As seen in Figure 5, no evaluation methods that follow the approach of adaption or agility were identified.

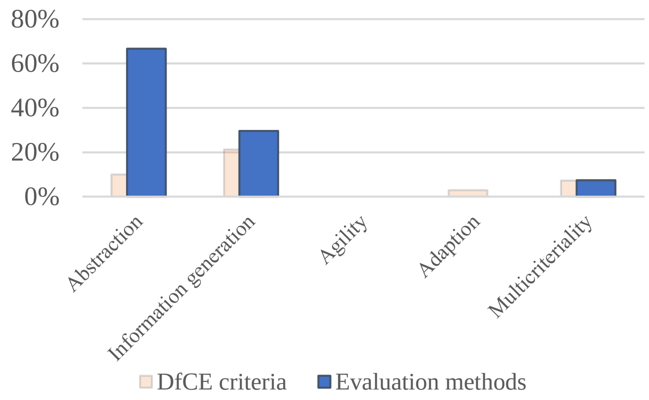

Figure 5. Categorization by the approach to problem solving

3.3 Information needed for execution

Just over half of the methods can be carried out independently of a preceding product and are therefore also suitable for NPD as seen in Figure 6. Most of the methods do not require information from other phases of the product creation process and are therefore based only on existing knowledge from the product development phase. If information on the later phases is required, this must be generated by predecessor products or knowledge catalogs. However, the methods with the focus on sustainability require data from the subsequent processes of the product development process. The same applies to the methods with a focus on cost evaluation. Neither of these findings seems surprising, since implications relating to sustainability and costs only arise in the subsequent phases and can therefore only be accessed later on. These methods therefore usually require information from a predecessor product. Methods that are not based on a predecessor product use data from databases.

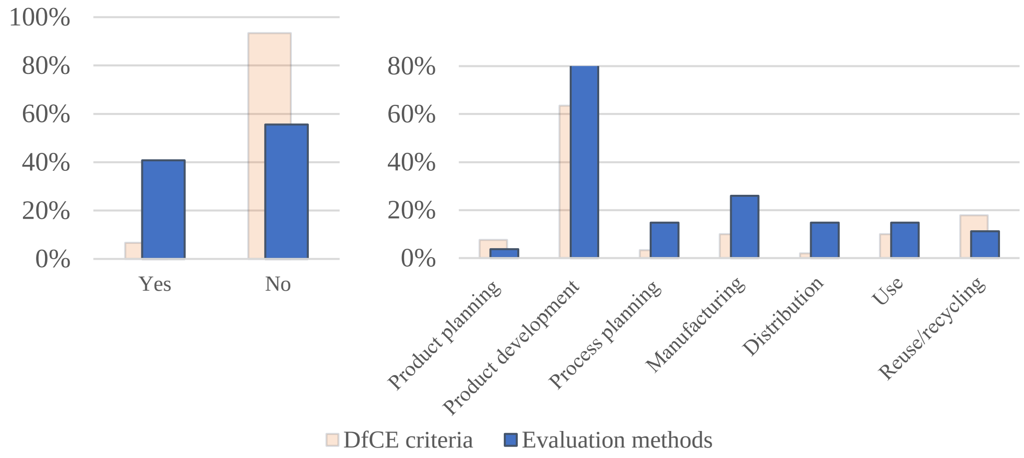

Figure 6. Classification by the information that is needed for execution (left: previous product generation required; right: phases of product creation process)

3.4 Area of application

Beginning with the application area of the respective methods, it is not surprising that most of the identified methods do indeed evaluate the product design as intended with the search parameters used in this research. However, one of the methods evaluates at least indirectly by acquiring data from underlying processes.

The results of the assessments are mostly in the range between concrete and abstract and use specially derived indicators for the assessment. About half as many methods are very concrete in their results and thus offer easier interpretability for developers. Only one method returns rather abstract results that are more difficult to interpret.

The classification into the different parts of the PA shows an accumulation of methods for the evaluation of the component structure. In this context, it is above all the methods assigned to the earliest phases of the PDP that evaluate the functions and their structures. On the other hand, an evaluation of the working principles takes place less frequently.

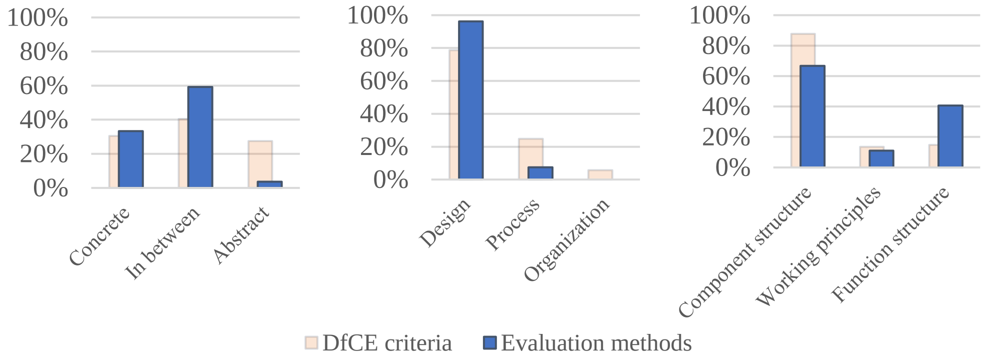

Figure 7. Classification by area of application

3.5 Assigned R strategies

Since the literature research was not specifically oriented toward the development of circular economy assessment methods, most of the methods could not be directly assigned to an R strategy. Only the methods with the evaluation goal of sustainability as well as assembly and disassembly could be assigned to the strategies accordingly. It should be noted that most of the methods that were categorized could be assigned to several strategies and not specifically to one strategy. Figure 8 shows the resulting evenly distributed number of methods across the different R strategies. The strategies "refuse" and "rethink" were not supported by any evaluation method.

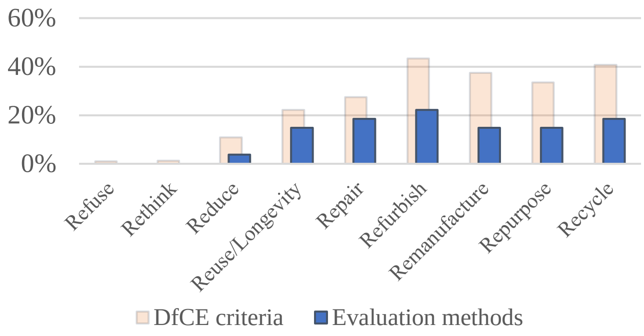

Figure 8. Classification by assigned R strategies

3.6 Discussion and link to the DfCE criteria

The evaluation of the assessment methods enables an estimation of how they fit into the PDP. Taken together with the classification of the DfCE criteria impact on the PDP, it is possible to make a statement on the basic suitability of the evaluation methods for evaluating circular product concepts in the early phases of development. It is important to emphasize that this is a comparison on an abstract level and that no statements on individual evaluation criteria within the methods can yet be made. The development of this knowledge remains the subject of subsequent investigations.

The comparison of the percentages across the PDP between the DfCE criteria and the assessment methods shows a difference in the distribution of the two (see Figure 4). On the one hand, this difference is due to the different focus of each study. While only evaluation methods for the early stages of product development were searched for, a restriction to specific stages of the PDP was not made when searching for DfCE criteria. On the other hand, the observation that the majority of DfCE criteria only become relevant in the later phases is interesting for the evaluation of circularity in the early phases of the PDP. This means that there are fewer DfCE criteria in these phases that could potentially serve as the basis for an assessment of circularity. Additionally, it can be observed that the criteria become more abstract and imprecise the further forward they are in the PDP. This observation cannot be confirmed for the evaluation methods.

Figure 5 shows that most evaluation methods are based on the principle of abstraction and generate a simplified model of reality to make the evaluation complexity manageable. A smaller portion tries to make an evaluation possible by collecting a variety of relevant data. The comparison with the classification of the DfCE criteria shows that they are distributed exactly the other way around. They mostly require a large amount of information from other phases of the product creation process. In this regard, most of the evaluation methods do not appear suitable for the evaluation of circular products.

Figure 6 seems to invalidate the preceding findings by highlighting the independence of the DfCE criteria from previous generations. However, closer examination shows that this peak is mainly caused by a high number of criteria for the later phases of the PDP. These phases contain many concrete criteria that are characterized by concrete design implementations independent of predecessor products. They are less relevant for evaluation in the early phases since their implementation cannot be evaluated accordingly at that point. However, the distribution of the required information about the product development process of DfCE criteria and evaluation methods is similar.

The comparison in the context of general application areas of the criteria and methods (Figure 7) shows an approximately equal distribution of the two in terms of the level of abstraction, the area of application, and the PA. It should be noted that there are more abstract criteria than abstract methods to be found. This is not surprising, since abstract ratings would defeat their purpose of providing usable information. Beyond that, there are more criteria in percentage terms that relate to processes than methods for that use case. This can also be explained by the focus of the search for the evaluation methods: No process evaluation methods were searched for or considered. However, there is potential for examining existing evaluation methods for processes to establish their suitability for circularity evaluation in the future. The classification into the different parts of the PA shows that there are more evaluation methods for functions than criteria for circular functions. An in-depth investigation and definition of product functions regarding their suitability for the cycle also could be the subject of future research.

The assigned R strategies in Figure 8 show a very similar percentage distribution of assignments. However, not all evaluation methods could be directly assigned to R strategies, which explains the lower percentages for the evaluation methods.

4 Summary and conclusion

To further understand the current research regarding methodology for circular development, this contribution investigates how existing evaluation methods designed for the early development phases can be used to evaluate circular products. A systematic literature review was conducted on Scopus and Web of Science. From a total of 483 independent papers found, 27 relevant evaluation methods for the early phases of PDP were extracted. The identified methods were classified into categories that reflect the PDP in an abstract form. The results of the categorization were compared with the impacts imposed by DfCE criteria on the PDP as explored by Stölzle et al. (2023b). Through the comparison, an appraisal could be made for each of the categories as to whether the found methods were also suitable for the evaluation of circular products in principle. However, there is no concrete approach to integrating Design for Circular Economy criteria into the evaluation methods.

The discussion of the comparison between the classification of the DfCE criteria and the assessment methods reveals the shortcomings of existing assessment methods, both in terms of their suitability for assessing suitability for recycling and in terms of the research gaps that result from this. Essentially, three areas requiring further research can be identified:

- The definition of circularity of products in the early phases of product development is currently not yet sufficient for an adequate evaluation in these phases. Functions and their working principles are defined in the phases of "clarifying the task" and "conceptual design." Knowledge of which functions and working principles are appropriate for circularity would make it possible to evaluate them in the early phases of the PDP.
- Existing assessments are based on the principle of problem abstraction or the creation of a simplified model. However, the comparison with the DfCE criteria shows that the development of information and data in the early phases in particular can contribute significantly to the development of cycle-compatible products.
- On a related note, the possibility of collecting information primarily from later phases of the product creation process and linking it to the work outcomes that result from the early phases appears to be a further step toward the evaluation of circularity in the early phases.

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