CONSIDERING ENGINEERING ACTIVITIES AND PRODUCT CHARACTERISTICS TO ACHIEVE MATERIAL CIRCULARITY BY DESIGN

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ABSTRACT

To select design guidelines engineers have to identify relevant from a bewildering amount of design guidelines. In this paper, a rule-based method for selecting design guidelines for material circularity selection is presented. For this purpose, a generic Product Life Cycle model is detailed with regard to Multi Material cycles (gPLC-MM). The presented method is divided into four steps. Core of the presented method is the comparison of circular product strategies with product life phases and material recovery processes. Engineering activities and increments of the product architecture are used to identify design guidelines. The results show that through the material circularity-oriented design guideline identification method, the product architecture is designed for different processes and technologies, to recover materials. The method allows engineers to select guidelines in a more targeted and consolidated way in sustainability-friendly product engineering.

Keywords: Sustainability, Circular economy, Conceptual design

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Cite this article: Gräßler, I., Hesse, P. (2023) ‘Considering Engineering Activities and Product Characteristics to Achieve Material Circularity by Design’, in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.108

1 INTRODUCTION

Product engineering is confronted with increasing sustainability trends such as product life extension and material circularity (Isaksson and Eckert, 2020). With regard to material circularity, product engineering must consider the extraction of material from nature, the production, product use with resulting emissions and necessary operating material, as well as the decommissioning of End-of-Life (EoL) products (Gräßler and Oleff, 2022). Design frameworks and guidelines are needed so that engineers are able to design products correctly and reduce the solution space efficiently towards the final solution (Fiksel, 2009). A variety of different design guidelines with regard to material circularity exists in literature (Bovea and Pérez-Belis, 2018). Main challenge is to match design frameworks and guidelines to specific product engineering activities, and to identify relevant design guidelines for a specific product (Butenko et al., 2017). Within a great bandwidth of critical issues to achieve actual material circularity, intuitive and easy access to actionable knowledge is crucial for engineers. So far there is no sufficient approach that supports filtering of material circularity-oriented design guidelines with regard to both engineering activities and product characteristics.

In this paper, a rule-based method for the identification of material circularity-oriented design guidelines is presented. The method answers the critical issue of how products are designed for material circularity and how knowledge from EoL processes is integrated into the early stages of product engineering. Core of the presented method is the comparison of circular product strategies and engineering priorities with product life phases and material recycling processes. For this purpose, the generic Product Life Cycle and Multi-Material model (gPLC-MM) is presented. In addition, product creation activities and increments of the product architecture are used to identify relevant design guidelines. By using the presented method, relevant design guidelines are provided to engineers considering activity-related relevance. The result of the validation shows that by using the method, a given set of design guidelines can be reduced to an actionable sub-set using circular strategy, the key characteristics and the engineering activity. This reduces the number and variety of design guidelines in an iterative engineering process, relieves the engineer and reduces engineering time.

2 METHODOLOGY

In this work, the research procedure according to Ulrich is applied (Ulrich, 1981). The following questions are formulated as research questions (RQ):

- *RQ 1: "Which rule-based approach enables filtering of design guidelines in an activity-oriented manner?"*
- *RQ 2: "Which design guidelines are applicable for material circularity-oriented product design?"*

To determine the relationship between design guidelines and their impact, product and material life cycle models are examined in literature. Design guidelines are also examined with the goal of determining information content. Next, the product architecture and engineering process are examined using foundational literature to identify dependencies. Finally, using the dependencies, a rule-based approach is applied to identify material circularity-oriented design guidelines. These fundamentals are reflected by a structured literature analysis according to Machi and McEvoy (Machi and McEvoy, 2012). The platforms Google Scholar, Web of Science and Design Society are used to retrieve literature on supporting engineers in identifying and selecting relevant design guidelines. For the literature search, the keywords "design guidelines", "product design", "recycling", "categorisation", "classification" are used. According to this research, 13 papers out of 396 search results were identified as closely related work. The identified papers are incorporated in the method and used for the discussion of its application. The method is validated via a case study of interviews with students of the master's degree interviews.

3 FUNDAMENTALS AND RELATED WORK

The general use of design guidelines is justified to shorten the engineering time and to reduce the risk of solution alternatives that have to be discarded. Besides creativity techniques in virtual environments (Graessler and Taplick, 2019) and scenario based techniques (Graessler et al., 2017), design guidelines offer a reliable approach. Design guidelines are instructions for appropriate design of technical systems (Verein Deutscher Ingenieure, 2004). Instructions are understood to be recommendations, specifications, restrictions, if-then relationships and questions (Calkins *et al.*, 2000).

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The information content of design guidelines is formulated by attributes. An attribute represents information like characteristics, area of validity or description. In early stages of engineering, design guidelines such as "Place non-reusable parts in areas that can be easily removed" (Ijomah and Chiodo, 2010) are relevant. For example, the attribute "purposeful" refers to the appropriateness of systems with regard to life-cycle, process, technology and user so that the system performs the specified tasks with the best known and positive functions possible (Vajna, 2020; Itani et al., 2019).

In literature, there are different approaches to structure design guidelines. Challenges here are different designations such as Knowledge-Based-Engineering, design restrictions, design notes and design rules. Such differences complicate the understanding of relationships between design guidelines and their frameworks. Design for X (DfX) represents an example for a Framework. The X is equal to a variable and represents different product life phases, strategies, criteria, recommendations (Faerber et al., 2008). Additionally, DfX guidelines form subsets of each other on the one hand and are hierarchical to each other on the other hand (Bauer, 2003). A further structuring option (right) takes place via the detailing of the design guidelines (Faerber et al., 2008), which is accompanied by transferability (Freund, 2018) into disciplines and the system concretisation.

With regard to the focus on material circularity, there are approaches on the classification of design guidelines in terms of sustainability (Oh, 2017) and circular economy (Bovea and Pérez-Belis, 2018).

The life cycle of products or material is a set of successive and interrelated processes that recur cyclically (European Parliament). The life cycle must be distinguished from life span. The life span describes a product instance on its way from creation and delivery to decommissioning. Product life cycle models in literature take different perspectives and are suitable for different applications. The generic Product Life Cycle (gPLC) according to (Gräßler and Pottebaum, 2021) is characterised by the features inherent, circular, holistic, generic and adaptable and describes the product life cycle with a reference to the Circular Economy. Material circularity is included with reference to the circularity strategies by the 9R framework (Okorie et al., 2018). It links product life span to material life span by a multi-cycle approach. The material life cycle is described by the phases "mining", "material technology", "material production", "material evaluation", "material operation", "material treatment" and "material end treatment". Targeting material circularity according to the foundations of Circular Economy, product life cycle is subordinate to the material life cycle and is tangential to it in the phases "material assessment", "material operation" and "material treatment". Due to the technical perspective, the material life cycle in this work is considered from the product perspective. A material product consists of a conglomerate of material classes (metal, plastic, etc.) and types (plastic types: polypropylene, polyamide, etc.). Accordingly, the material life cycle from the product perspective is described as a multi-material life cycle. The intersection of material and product life cycle can be seen in the product life phase "decommissioning", which is detailed by the material life phases "material production", "material evaluation" and "material treatment". These three multi-material phases are structured by processes, as shown in Table 1.

Table 1. Detailing the product life phase decommissioning with relevant processes

	(Pan and Li, 2016)	(Mendes Campolina et al., 2017)	(Sarc et al., 2019)	(Chiu and Okudan, 2010)	(Phuluwa et al., 2021)	(Memon, 2010)	(United Nations Environment Programme, 2009)	(Soo et al., 2015)	(Alvarez-de-los-Mozos and Renteria, 2017)	(Chatterjee and Kumar, 2009)	(Milios et al., 2018)	(Hepperle, 2013)	(Sundin et al., 2012)	(Hribernik et al., 2011)
logistics		X	X			X	X		X	X			X	X
sorting	X	X		X	X	X	X	X	X	X	X		X	X
decomposition/ disassembly	X	X	X	X	X	X		X	X	X			X	
preparation/ production		X	X		X	X	X	X	X	X	X	X		X
evaluation									X	X				

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The processes are described in literature as follows:

- logistics: transferring the product from the customer to the recycler
- sorting: classification of the product (e. g.: product class, type of fasteners, material)
- decomposition/ disassembly: separate the product or subsystems into different disassembly depths
- preparation/ production: Industry-compatible preparation of material (a mixture from different end-of-life-products) and parts through e.g. primary shaping or cleaning
- evaluation: Measurement of material or part properties (physical or mechanical properties)

4 METHOD FOR SELECTING MATERIAL CIRCULARITY-ORIENTED DESIGN GUIDELINES

Design guidelines should be applicable in all engineering tasks like clarification, conceptual design, embodiment design and detail design (Pahl et al., 2007). In addition, the presented method is integrated into the generic Product Life Cycle extended by Multi-Material processes (gPLC-MM). By using the gPLC-MM, circularity-oriented strategies are enriched with information about stakeholders, process, technology, etc. This answers the critical issue of how products are designed for material circularity and how knowledge from the EoL processes is integrated into the early stages of product engineering.
The method for the identification of material circularity-oriented design guidelines is shown in Figure 1. The presented method combines different roles of the product creation and enables engineers to design products for the processes of circularity in order to consider economic and ecological compatible feedback in product engineering. First, a product manager determines the impact of circular product strategies and technical priorities using the gPLC-MM model (step 1). They are detailed by the preferred product property and the associated product key characteristics in the end-of-life. Second, key characteristics are specified following steps from functional decomposition to logical system architecture design (step 2). Having defined key characteristics, related activities of the generic product engineering process can be filtered (step 3). Finally, design guidelines are identified by rule-based selection according to product characteristics. The developed catalogue of design guidelines is derived from literature (see chapter 3) and can be extended in companies. The rule-based identification is provided by a software tool. For the purpose of validation, MS Excel is used in the paper at hand.

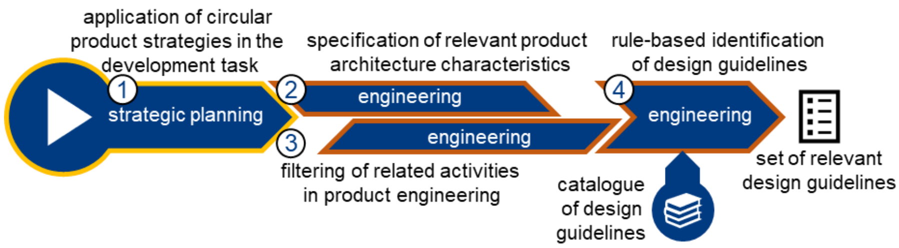

Figure 1. Method for identifying relevant material circularity-oriented design guidelines

4.1 Application of circular product strategies in engineering task

As a prerequisite, product strategies with regard to material circularity (represented by the 9R framework) and corresponding engineering priorities have to be set in strategic planning. Circular engineering priorities can be derived from applying sustainability strategies in the gPLC-MM (see highlighted step 1 in Figure 2). Such sustainability strategies are graphically arranged around the relevant product life phases and decommissioning processes. Relevant phases and processes are those in which the engineering priority (Diaz Tena et al., 2021) is implemented and realised in the product and in which the desired product properties generate the aimed benefit. This offers the possibility to consider recycling processes already in product engineering in more detail. Material is considered in early phases of the product cycle through their digital representation (e. g. mechanical properties) before they physically appear in prototypes in the phase engineering. The gPLC-MM extends the product perspective by including the processes of the material life cycle phases "material production", "material treatment" and "material evaluation". The phase "material treatment" covers the product life cycle. It should be noted that identified processes can be run through several times and in different order. For instance, consideration of sorting is relevant before, but also after decomposition into parts or even base material. In multi-material life cycle, no distinction is made between

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material classes and types. Only at the end of material recycling, when the product form is dissolved, the different material types enter a new product life. The gPLC-MM takes into account primary recycling in production, secondary recycling of products and tertiary recycling of material (Rolf-Dieter Weege, 1980). The circular strategies of 9R framework which are used are: R2-Reduce, R3-Re-use, R4-Repair, R5-Refurbish, R6-Remanufacture, R7-Repurpose, R8-Recycle and R9-Recover (van Buren et al., 2016). For example, by embedding circularity strategy R8-Recycling, statement can be made that the process of "decomposition/disassembly" is relevant. Detailing this process through technologies in turn leads to the possibility of identifying desired properties and product key characteristics. The technologies used are shredding (geometrically indeterminate, destructive separation) and disassembly (non-destructive separation) (Bilitewski et al., 2018). Derived engineering priorities are input for step 2.

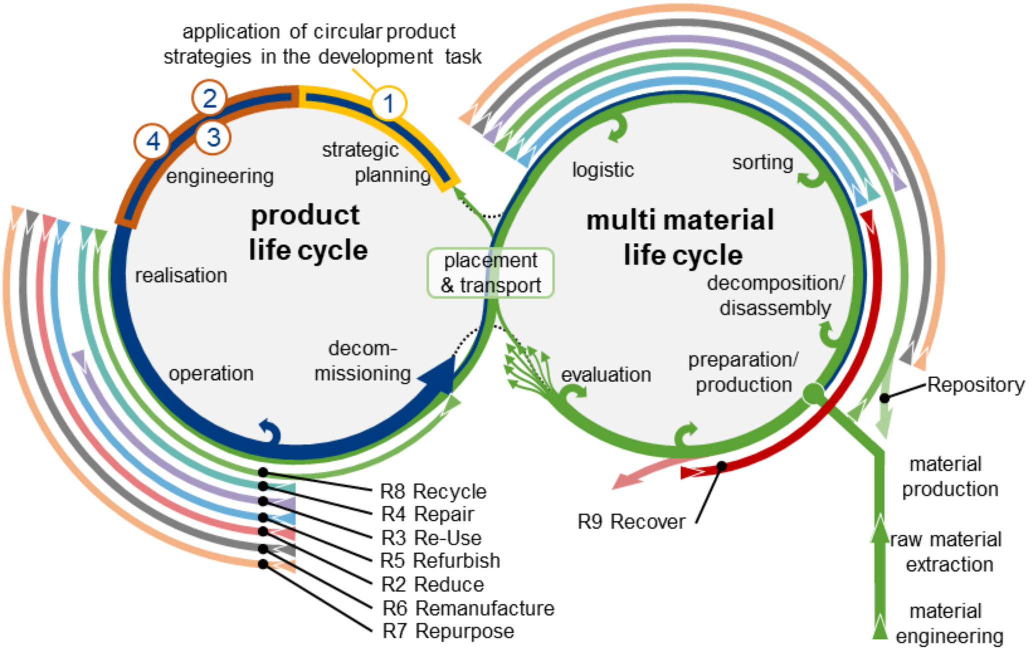

Figure 2. Circular strategies with generic product life cycle and multi material, according to (Gräßler and Hesse, 2021)

4.2 Specification of relevant product architecture characteristics

Detailed product architecture characteristics are classified by using key characteristics. The identified key characteristics are to be taken into account in engineering activities. The key characteristics are aligned with the role of the product manager and are superordinate to more detailed characteristics (e. g. key characteristic "surface"; detailed characteristic "surface roughness") in an advanced engineering activities. To determine key characteristics, the product architecture is considered (Figure 3).

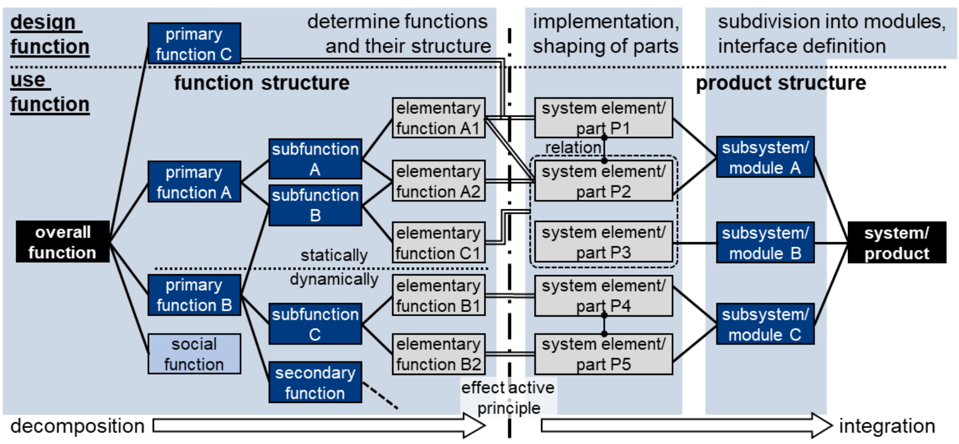

Figure 3. Product architecture, based on (Krause et al., 2021; Calkins et al., 2000)

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The functional structure (left) describes which functions a product shall fulfil. The overall function is detailed through primary functions and sub-functions (functional decomposition, (Matthiesen, 2002)). The subdivision into sub-functions leads to functional groups that form the basis for modules within the product structure. The product structure (right) represents the interconnectedness of parts, system element and subsystem (the modules) within the entire System (Ponn and Lindemann, 2011). In process, the form is generated from a subsystem (subdivision into modules, interface definition) to subordinate subsystems (shaping of modules) and parts (integration of product as a whole) (Calkins et al., 2000). By using the product architecture, following key characteristics can be defined on a systemic level as an input for subsequent engineering steps:

1. material (integration of product as a whole and shaping of modules)
2. modularisation (shaping of modules and subdivision into modules, interface definition)
3. part design (integration of product as a whole)
4. fasteners (integration of product as a whole and shaping of modules)
5. surface (integration of product as a whole)
6. function & socio-technical interaction (determine of functions and their structure)

By setting this focus, relevant types of engineering activities can be identified. Established engineering methodologies with corresponding activities are used as a reference activity set in the subsequent step.

4.3 Filtering related activities in product engineering

To select the relevant and sufficiently detailed design guidelines, the key characteristics are combined with the engineering progress. The engineering progress is described by engineering activities that need to be determined. The checkpoints of VDI/VDE 2206 (Verein Deutscher Ingenieure, 2021) offer the possibility to identify the current engineering activity (Graessler and Hentze, 2020). This ensures a sufficient by manageable amount of design guidelines. A large number of different detailed activities are described in literature (Sim and Duffy, 2003; Faerber et al., 2008; Zimek and Baumgartner, 2017). In this work, the detailed activities of mechanical engineering methodology VDI 2221 are used (Verein Deutscher Ingenieure, 2019). As a methodology for mechanical systems, VDI 2221 can be embedded in the higher-level and interdisciplinary V-model (Gräßler, 2017). In comparison to other methodologies, the V-Model offers potential in interdisciplinary engineering (Gräßler et al., 2016) and adds the main feature list (Gräßler et al., 2018) to the engineering process. It is relevant that the interdisciplinary engineering is thought together with the production and recycling system (Gräßler and Yang, 2016). In Table 2, the key characteristics of Step 2 (see section 4.2) are enlisted in column headers. They are mapped with the engineering activities from the VDI 2221 (rows in Table 2) (Welp and Lindemann, 1998; Dowie, 1994; Go et al., 2015).

Table 2. Basis of the identification of activity oriented design guideline selection

activities	**material**	**modular-ization**	**part design**	**fasteners**	**surface**	**function & socio-technical interaction**
clarification of problem or task						
determination of functions and their structures		X	X			X
search for solution principles and their structures	X	X				X
assessment and selection of solution concepts			X			
subdivision into modules, interface definition	X	X		X	X	X
shaping of modules	X		X	X	X	X
integration of product as a whole	X		X	X	X	X
elaboration of execution and usage requirements			X	X		

4.4 Rule-based identification of design guidelines

To determine relevant attributes, material circularity-oriented design guidelines literature are considered (see Figure 4 on the right). Attributes are identified especially based on (McAloone and Pigosso, 2021) and (Shahbazi and Jönbrink, 2020). Design guidelines consist of attributes containing numbers and letters. For example, "characteristic", "characteristic value" and "image" are an attribute

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of a design guideline. The characteristic type such as "wall thickness" with additional characteristic expression (incl. SI base unit e. g.: meter and SI prefix e. g.: centi) and expression type (<, ≤, >, ≥, ≈, =, ≠) enables the targeted description of the product characteristic. The product characteristic forms the central element via which design guidelines can be linked to the gPLC-MM (see section 4.1), product characteristics (see section 4.2), engineering (see section 4.3) and in a rule-based manner. The grey line describes the link between the life cycle, the product characteristics, engineering and design guidelines. Filtering according to product properties, key characteristics and engineering activities is implemented by rules according to which the relevant design guidelines are selected. For example, IF process "decomposition/ disassembly" AND IF key characteristic "fasteners" AND IF engineering activities "subdivision into modules, interfaces definition" THAN relevant design guidelines from the database will be given. Thus, this means an initial answer for RQ 1.

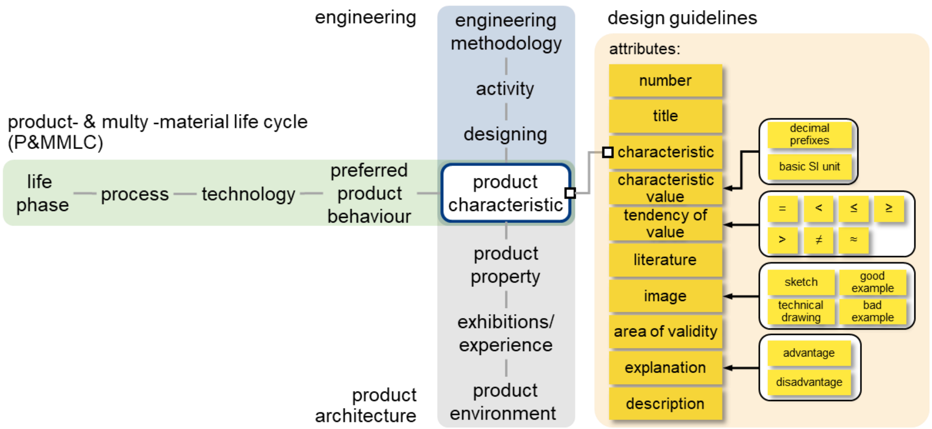

Figure 4. Interrelationships of the PLC, Engineering process and the product

5 VALIDATION

To validate the rule-based method for identifying design guidelines for material circularity, it is applied in a case example to answer RQ 2. Given is a Remote Controlled Car (RC-Car) (Figure 5, left). The RC-car is designed as a research object which is configured for comparative design studies. In this case, it includes weaknesses which are introduced intentionally with regard to all key characteristics (see section 4.2). The RC-Car should be optimised with regard to material circularity. The process is shown schematically in Figure 5. The engineering process is shown horizontal and the validation of the method is shown vertical. For the validation of the method, five students of the mechanical engineering master's programme are given an engineering order for the adaptation design of the RC-Car. They receive the following as tools in the validation: a concept environment (whiteboard), a CAD workstation with the software SOLIDWORKS and a catalogue of design guidelines.

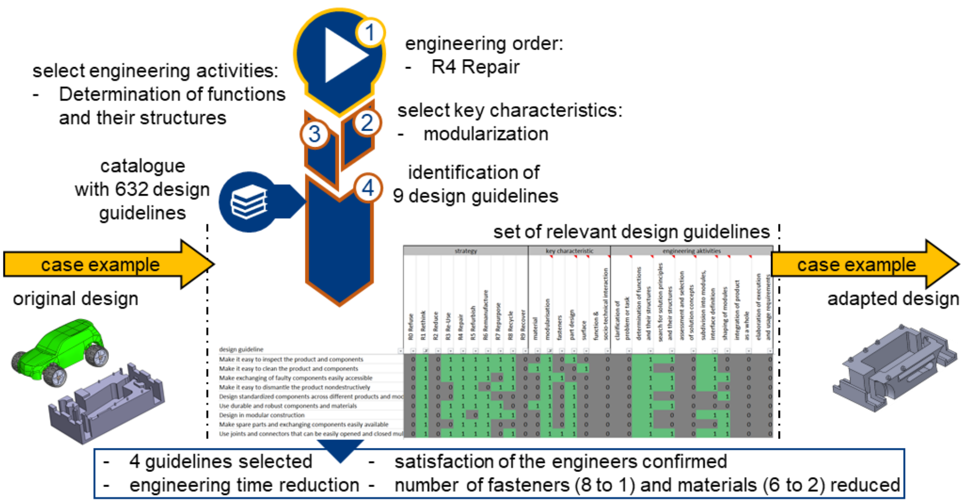

Figure 5. Selecting design guidelines using the identification method

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The catalogue is provided via the software tool MS-Excel and comprises 632 design guidelines. The engineering order specifies the R4-Repair circularity strategy of the 9R framework. The strategy R4-Repair to identify relevant life phases and processes by using gPLC-MM (see Figure 2) is used. Using the created overview of life phases and processes, relevant key characteristics are discussed. Then, the key characteristics "modularisation" is determined by using the key characteristics given in the method (see section 4.2). By entering these inputs (R4-Repair and modularisation) into the MS-Excel tool of the rule-based method, 9 out of 632 design guidelines were recommended for the engineering activity "determination of functions and their structures". In the case of variation of the engineering activity, other design guidelines are presented to the users. Finally, 4 out of the 9 design guidelines are selected based on relevance for the engineering order to implement this in the function structure. Subsequently, the adapted design solution was realised. The original and the adapted design were dismantled and sorted using EoL processes. In contrast to original design, the disassembly and sorting time is reduced. Even though measurements have to be treated carefully due to the limited number of probands, it can be stated that the adapted design has a more reasonable behaviour compared with the original design. This is indicated by a) solving all known weaknesses of the original design and b) initial measurements showing that the material can be identified and extracted from the product much faster. The interview with the students indicates advantages of activity-oriented recommendation of the design guidelines. Through the method, iteration and engineering time are reduced. Furthermore, inexperienced engineers are able to design products strategically without experience in sustainable engineering. This recommendation enables the inexperienced engineers to create sketches and modules as a basis for the subsequent engineering of the final design. The classification of strategies and product characteristics in the gPLC-MM also raises awareness for further processes in life cycle such as production and recycling.

6 CONCLUSION

In this work, the selection of material circularity-oriented design guidelines is addressed. A rule-based method is proposed to solve this critical issue of sustainability-friendly engineering. Main users of the method are engineers in concept and design. The method places circular product strategies and engineering priorities (exemplarily integrated by the 9R framework) into the product and multi-material life cycle and thus enables the targeted investigation of the life phases and processes. For this purpose, a life cycle is presented that summarises the product and material life cycle (gPLC-MM). Based on the life phases as well as the processes, the product characteristics and the engineering activities, design guidelines are identified in a targeted and efficient way.

The validation of the method by means of a case example shows that the activity-oriented and rule-based provision of relevant design guidelines leads to a clear identification and application of these and thus answers RQ 1. The method presented provides a factual sequence for identifying design guidelines and has to be tailored to the chosen engineering methodology. The adapted design carried out shows an improved disassembly behaviour compared to previous variants, confirms the design guidelines used and thus answers RQ 2. The method is to be enriched in further research by dependency investigations of design guidelines among each other to simplify the decision in the context of an applicable compromise solution. It is also conceivable to embed the method in approaches of Model-Based Systems Engineering (Gräßler et al., 2021). In addition, templates for the direct assignment of characteristics to the life phases and processes will be created in the sense of the principle of data accumulation.

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