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Enabling the design for circularity through circularity measures: breaking down the R-strategies into useful design measures

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Abstract

Implementing a product design that incorporates circular economy aspects is a highly intricate task. Its complexity stems from various aspects, such as the interdependent solution space and the challenge to evaluate the impact of circular design in early development phases. To facilitate informed decision-making, a support system is necessary that integrates product-oriented circular measures, and derives their effect on the product's design and its circularity. We present an approach for such a support system, including its evaluation on the design of an automotive center console.

Keywords: *circular economy, strategy, model-based systems engineering (MBSE), product development, automotive*

1. Introduction

Within the field of sustainable product development, there is an increasing focus on eco-design and similar approaches which give priority to early consideration of environmental impacts (McAloone and Pigosso, 2021). The Cradle-to-Cradle concept, which is characterized by completely closed material and energy cycles, provides even more extensive sustainability improvements (Braungart and McDonough, 2021). A feasible means to embody these principles can be found within the Circular Economy, an economic model that moves from linear to circular forms of value creation (Ellen MacArthur Foundation, 2013). Essentially, this approach aims to diminish resource depletion and waste production by endorsing infinite material use, sharing, and recycling within a closed-loop structure.

However, the design for circularity encounters various obstacles. This is due to its complex nature and the extensive range of solutions available, as well as the many interdependencies involved that can potentially hinder the realization of sustainable outcomes. Further the interdependencies between the physical product architecture, the methods of production and further product characteristics, strongly influence the potential and applicability of circular processes. The interdependencies can result in a chain reaction throughout the product based on a single applied measure to enhance circularity. Potting *et al.* (2017) identify ten possible strategies referred to as R-Strategies for closing energy, material, and usage cycles. These strategies can be applied to the system as a whole, a subsystem, or a specific component. It is possible to mix strategies and apply them sequentially, even in different orders, during the product's life cycle. Furthermore, the employment of circular strategies may lead to interdependencies. Remanufacturing a product could for example potentially decrease its recycling quality and hereby lower the overall sustainability of the product throughout its entire life cycle (Purvis *et al.*, 2019). Undesired side effects might occur, when strictly following certain strategies and measures. Consequently, it is required to document with which intention and why certain design decisions and circular measures were taken, to provide a rationale. Additionally, it should be possible to evaluate circular measures introduced into the product's design regarding their interdependencies and overall effects on the product's sustainability, to guide decision making in development.

Current approaches in product design either go for abstract guidelines (e.g., (Bovea and Pérez-Belis, 2018) or design principles (e.g., (Sassanelli *et al.*, 2020) to solve these challenges. However, they are not specific enough to support such complex decisions effectively (see Section 2). They only give hints and ideas for a circular design but do not support the designer, when making specific decisions regarding a certain product design. The designer must still apply, document, evaluate, and optimize his overall circular strategy manually. With respect to said interdependencies of applied methods and product characteristics and complexity in circular design, this is at least cumbersome and might at most lead to suboptimal design decisions. Thus, it is necessary to provide tangible and product-related definitions of possible circularity measures, which can be documented together with the product's design and subsequently analysed with respect to their impact on sustainability. Within this paper we propose such circularity measures, referred to as C-measures, and evaluate them in an automotive development project. The developed C-measures build upon the R-Strategies as defined by Potting *et al.* (2017). It was found that the solution effectively enables the designer to create concrete and tangible circularity strategies, which we refer to as C-Strategies, by including C-Measures directly into a products expected life cycle. The dynamic analysis of the effects of those C-Measures allows to optimize the developed strategy during the process.

2. Literature review

Life Cycle Engineering (LCE) describes engineering activities to develop and manufacture products with the goal of optimizing the product life cycle and enhancing sustainability (Jeswiet, 2014). Thus, enhancing circularity of a product is one part of LCE. LCE encompasses product development activities and decisions that prioritize certain product properties with respect to sustainability, while considering multiple product life cycles (Hauschild *et al.*, 2018; Hauschild *et al.*, 2020; Wanyama *et al.*, 2003; Laurent *et al.*, 2019). Typical product properties in this context are amongst others "Reliability", "Durability" or "Recyclability" (Potting *et al.*, 2017; Weck, 2011). Accordingly, Sassanelli *et al.* (2020) understands circular design as a set of "Design for X" approaches (DfX) and identifies a scheme of five DfX approaches fostering circular economy adaption (i.e., (Bovea and Pérez-Belis, 2018; Kuo *et al.*, 2019; Moreno *et al.*, 2016; Bhamra, 2004; Favi *et al.*, 2019). They suggest using a hybrid, unified DfX approach derived from these five approaches. However, this increases process complexity and information need to an extend not feasible for early phases of development. Furthermore, the DfX approaches address design criterions which are expected to have positive effects on circularity. Their real impact must be evaluated individually for each product under design as causality between the target of X and circularity cannot be implied. Furthermore, measures towards circularity are not documented in the product's design. Consequently, LCE in terms of DfX approaches is insufficient to solve the problems described in Section 1.

Bovea and Pérez-Belis (2018) offer a different approach and analyse existing products from a circular economy perspective. Design guidelines are derived, and approximate measures are defined to estimate possible effects on the product’s design. However, the challenge with all of the mentioned approaches is, that design guidelines only provide a set of criteria and advises, which can be used to identify better design options. They are not specific enough to support circular design decisions for complex products with many interdependencies, where one decision might have multiple side effects on circularity and sustainability (see e.g., (Ellen MacArthur Foundation, 2023; Block *et al.*, 2023). Similarly, Potting *et al.* (2017) offer a structured framework for circular economy implementation strategies. They distinguish material efficiency (recover, recycle), extended product life cycles (repurpose, remanufacture, refurbish, repair, re-use), and intelligent product development (reduce, rethink, refuse). The German Institute of Norms (DIN, 2023) introduces a similar approach aimed at aligning business processes with circular principles. These standards encompass various domains, including modular design, product simplification, toxic substance reduction, digital product passports, and information-sharing platforms. While these strategies offer at least concrete definitions of different approaches towards circularity, they also lack defined design and analysis guidance.

Therefore, other approaches to LCE propose Model-based Systems Engineering (MBSE) procedures, notations, and tools as an adequate foundation. Model-based Systems Engineering (MBSE) is the model-based and IT-supported application of systems engineering (Hillary Sillitto *et al.*, 2019) to optimize modeling and to promote a common understanding of the system under development (Dumitrescu *et al.*, 2021; INCOSE, 2021). As such, holistic approaches for MBSE typically consist of a method, a (software) tool and a (graphical) modeling language (Friedenthal *et al.*, 2015). This allows the system to be examined at various levels of abstraction, supporting the description and analysis of internal and external interdependencies concerning structure and behaviour (Weilkiens, 2014). Werner *et al.* (2023) for example highlight approaches to integrating MBSE and LCE, recognizing the essential focus of circular economy on the entire product life cycle. Numerous dependencies, spanning different life cycle phases (e.g., producibility, recyclability, or method of use) are considered in development (Werner *et al.*, 2023; Hauschild *et al.*, 2020). Halstenberg *et al.* (2019) propose a methodology for the development of Smart Services, which addresses circular economy strategies. Block *et al.* (2023) present a model to define individual and probabilistic system life cycles in system architecture models. This makes it possible to document and analyse different life cycle paths of specific, individual systems and their parts. Other methods, pointing in the same direction with MBSE for LCE, are for example (Bougain and Gerhard, 2017; Yvars and Zimmer, 2021; Cerdas *et al.*, 2018). A. Dér *et al.* (2022) for example take divergent, individual life cycle circumstances in LCE into account. Yet, their perspective is data focused and simulation driven. Overall, the mentioned approaches provide a well-founded bases for circular design because they aim to document different aspects of a system's life cycle in its model. However, none of the mentioned approaches provides the possibility to document and analyse concrete circular strategies and measures within the system model. Consequently, Sumter *et al.* (2020) find that methods and tools are missing which support the design for multiple use cycles while supporting circular impact assessment. Thus, our analysis led us to the insight that there is a need for tangible and product-related definitions of possible circularity measures, which can be documented together with the product's design and analysed with respect to their impact on sustainability. To the authors' understanding, this has not been covered by the findings proposed in literature so far.

3. Approach

The following chapter presents the developed approach to define tangible and product-related definitions of possible circularity measures. We call those measures C-Measures. C-Measures are atomic measures, introduced into the product. They are based on the R-Strategies defined by Potting *et al.* (2017). As such C-Measures aim to support the circularity of the system as a whole, a subsystem or a specific component of the product. Thereby, we follow a MBSE approach. We implement the idea of C-Measures into a metamodel to support the complex, circular-oriented development process. The metamodel establishes the foundation for a support tool and specific product models, comprising circular economy approaches. The sum of all C-Measures builds a Circular Strategy also referred to as C-Strategy.

3.1. The concept of C-Measures and C-Strategies

Our approach is based on the understanding that each product has its individual life cycle (see (Block *et al.*, 2023)). Figure 1 visualizes an abstraction of such an expected product life cycle on the left-hand side of the graphic. Within such a life cycle, critical states of the system or of components can occur. A critical state is scenarios where one would consciously decide the product should or could not be used as planned anymore. This might be a condition where the product is susceptible for undesirable or defective behaviour for example. Moreover, a critical state can be a condition where the usage of the product in its intended functionality at the time might be uneconomical. The developer can identify those critical states based on experience or statistics on the products performance. Consequently, the product may be replaced or sorted out in a conventional linear life cycle approach. However, for our approach, such states are the collar point for circular strategies. In case the product reaches a critical state, the aim is to transfer it to a state where the problem can be analysed, and necessary measures can be initiated to handle or dissolve the critical product state. For this purpose, we extend the model of the expected life cycle by a circular strategy (C-Strategy) depicted on the right-hand side of Figure 1. The

C-Strategy introduces the novel concept of undesired states. Undesired states indicate that the product can no longer be used as intended. Applying C-Measures like repair, reuse or remanufacturing allows to return the system or component to a functioning state within the expected product life cycle. Thus, they close energy, material, and usage cycles (Figure 1).

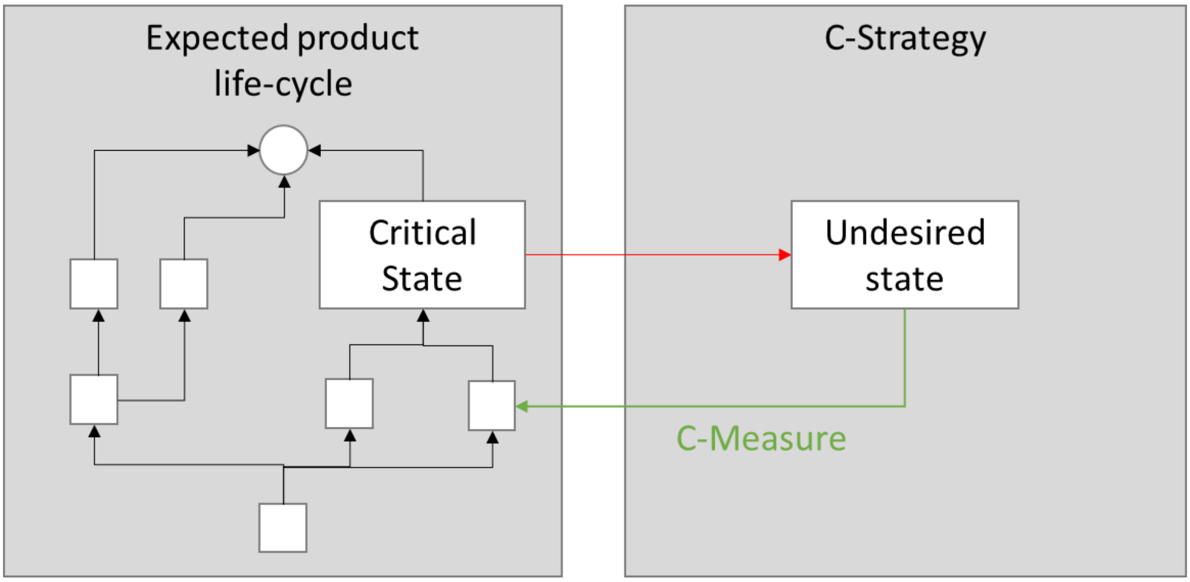

Figure 1. Critical states can lead to undesired states which can be dissolved through the application of C-Measures

Potting *et al.* (2017) identify ten possible strategies for closing energy, material, and usage cycles. They are commonly referred to as R-Strategies and are categorized as follows: “recycle”, “repurpose”, “remanufacture”, “refurbish”, “repair”, “reuse”, “rethink”, “reduce” and “recover”. The proposed approach to develop a support system for circular product design builds upon these strategies. C-Measures pick up the idea of R-Strategies and extend it by a definition of their effect on sustainability-relevant product metrics and associate the abstract R-Strategies with certain product components. The aim is to enable a designer to estimate the impact of integrating such an R-Strategy into a product's life cycle. The application of C-Measures can then be optimized and adapted based on the estimated impact on sustainability. Thus C-Measures adapt the notions and categorization of R-Strategies. Yet, C-Measures extend the R-Strategies and incorporate a relation to a specific physical component of the product and to its effects on sustainability. The first relation defines on which part of the system, the measure should be applied. The second one specifies, which effects on sustainability are to be expected when applying the measure. As such, C-Measures are design measures specifically applied to a system or component to escape an undesired state and leverage positive sustainability effects.

The application of several C-Measures may lead to interdependencies between them. Thus, we propose a higher-level hierarchy that goes beyond specific measures: C-Strategies. A strategy is the process of planning something or putting a plan that is intended to achieve a particular purpose into operation in a skilful way (Oxford English Dictionary 2023). As such, C-Strategies describe the combination of all applied C-Measures to one component or system. Consequently, C-Strategies enable a holistic analysis of the interdependencies and influences of different C-Measures. A C-Strategy combines the individual effects and handles the interrelations.

3.2. Using C-Measures and C-Strategies in a circularity aware development process

Our methodological approach to incorporate C-Measures and C-Strategies into a circularity aware development process is depicted in figure 2. It is composed of two phases. In the first phase the product architecture without circular considerations is modelled. The logical and physical structure of the product, its component's characteristics and metrics are defined. Furthermore, the estimated life cycle must be described, to identify the potential application of C-Measures (see Figure 1). Phase 2 comprises the modelling of circular economy related measures and effects. Firstly, the designer identifies the critical states of the product, based on the already defined life cycle. The critical states must then be dissolved in the sense of circularity. C-measures are introduced and further specified to close the loop. The measures transfer the component back into a useful state within the product's scope or any new state of purpose considering sustainability and circularity. In parallel, the effect on sustainability can be estimated based on the relationship between the C-Measure and its effects.

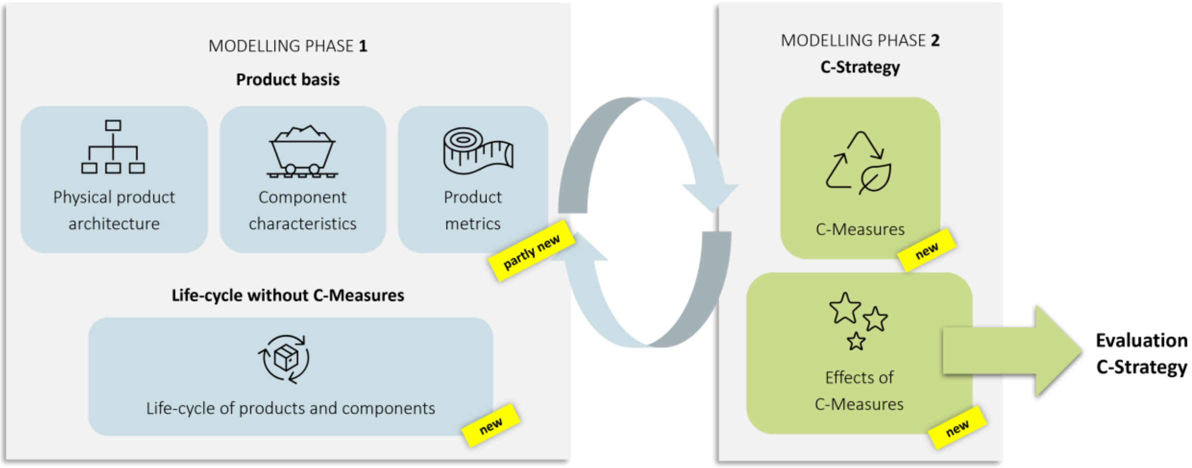

Figure 2. Circularly oriented engineering and design process

The two phases are not processed linearly. They are rather visited iteratively because the product is refined iteratively on each side based on the current level of knowledge and detail of the design. The evaluation of the developed circular strategy is enabled through the combination and relation between the individual modelling components. Utilizing the introduced modelling phases the designer can gradually navigate through a circular development process. Due to the complexity involved, a digital model as used in the MBSE approach is considered essential.

4. Implementation and evaluation

We evaluated the concept of C-Measures and C-Strategies within an automotive development project. A circular center console was designed. Due to the complexity involved, we firstly implemented the concept of C-Measures and C-Strategies into a software tool, to incorporate an MBSE approach and deal with the complexity.

4.1. Implementation

In the previous sections the concept to incorporate overarching C-Strategies into the development of a product was introduced. A software tool is developed to provide modeling capabilities, improve visualisation and documentation of the C-Measures and to automate analysis of circular system model. The implementation is realized as an extension to the open source systems modelling tool *Capella* (Eclipse, 2023a; Roques, 2018). The metamodel implementation is based on the *Eclipse Modeling Framework* (EMF) (Eclipse, 2023b). The metamodel is implemented as an orthogonal metamodel. It builds upon the existing metamodel for the product architecture and extends it with circular related aspects. Our orthogonal metamodel is based on the *Meta Object Facility* (MOF) (OMG, 2019).
The metamodel is divided into several dimensions. Together, these model dimensions allow for a holistic description of modules' or components' respective C-Strategies. The first dimension contains a Physical Base Model, defining circularity specific libraries to extend the physical model of a product. The central part of the physical base model is the C-Measures Library based on the preparatory work done by Potting *et al.* (2017). The C-Measures Library (see Figure 3) define the ten C-Measures "recycle", "repurpose", "remanufacture", "refurbish", "repair", "reuse", "rethink", "reduce" and "recover". They address potential effects of sustainability, such as influences on material or energy

consumption, that can be achieved when applying a measure to a specific physical part of the product. Those effects are in turn organized in a second extensible library, the C-Effects Library (see Figure 3). The possible associated effects on key performance indicators of the product were added based on a selection of previous works of several authors (Kadner *et al.*, 2021; Potting *et al.*, 2017; Watson, 2014). Adding specific effects to each C-Measures allows for a quantitative analysis of C-Strategies. At the center of Figure 3 an example is provided showing the relation of the C-Measure repair to a selection of C-Effects.

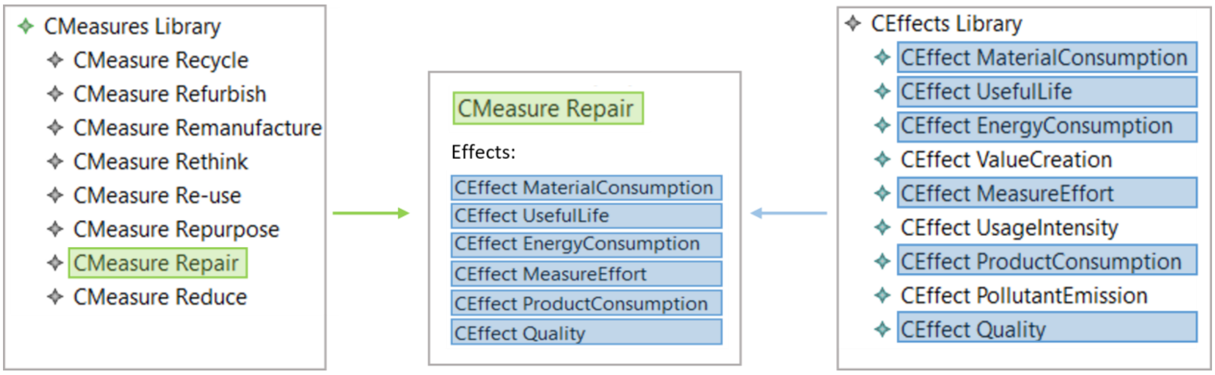

Figure 3. Exemplary implementation of a C-Measures and C-Effects Library and their relation to each other at the example of the C-Measure Repair

The Strategic Metric Model adds the second dimension to our metamodel. It aims to provide information enabling a strategic evaluation of the developed strategies at a higher level. The model enables the designer to define key performance indicators in order to evaluate the impact of respective C-Strategies. Finally, the formalized description of C-Strategies themselves is facilitated by the C-Strategy Model (Figure 3). It builds upon preliminary work by Block *et al.* (2023) and is specific to the product's architecture. The structure of the Strategy Model initially describes the product life cycle without C-Measures at component or product level (left hand side of Figure 3). With further progress, the designer defines a C-Strategy by integrating C-Measures into the specific phases of the life cycle and associates them with a certain component of the product.

Analyses in terms of requirements or interdependencies within the system's life cycle are then enabled by additional the metrics library which might trigger their own algorithms to estimate the effect on sustainability or use external tools such as a Life Cycle Analysis (LCA).

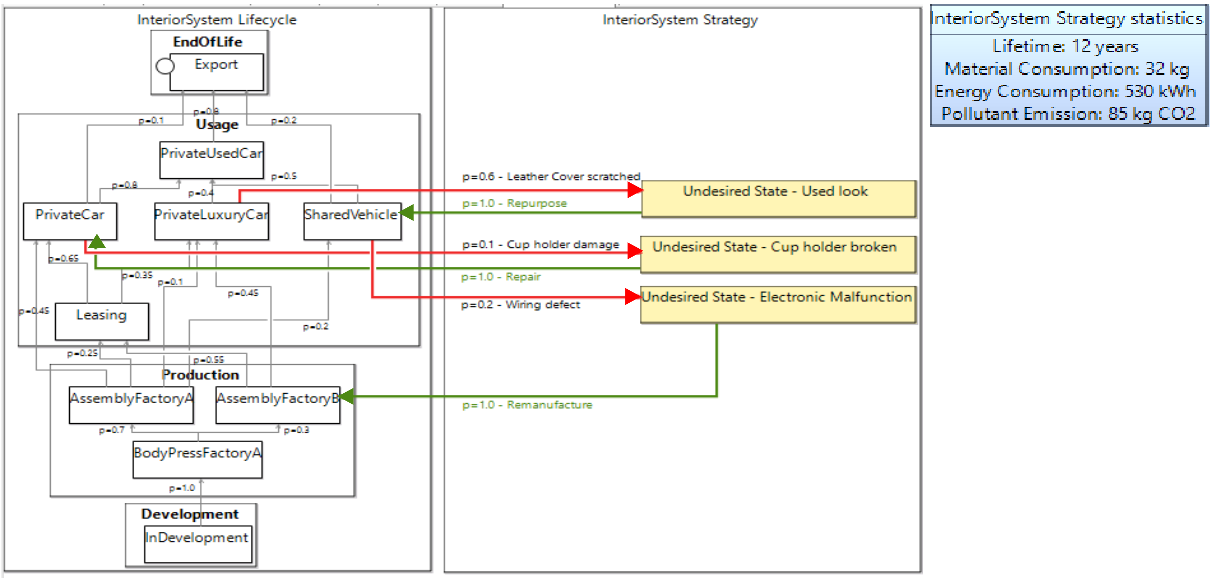

Figure 4. Implementation of the center console's life cycle and Circularity Strategy with probabilistic transitions and C-Measures

4.2. Evaluation at the example of an automotive center console

The evaluation was carried out within a current research project *Cyclometric*. An automotive centre console of a series vehicle was taken and further developed physically digitally to be more sustainable (Fraunhofer IAO, 2022). Firstly, the physical product architecture without circularity aspect was modelled in *Capella*. Thereby, the physical components were provided with parameters to define their characteristics, such as material or weight. Subsequently, life cycles were modelled for a set of chosen components of the physical product architecture. The modelled life cycles enable the designer to identify phases which are critical for the products circularity and can be resolved with the help of C-Measures. The identification of critical points which lead to undesired states is based on experience or statistical values about a similar products performance and functionality in the past. To test the implementation, approach an exemplary C-Strategy composed of C-Measures was modelled. Figure 4 shows a screenshot of the tool and a diagram to visualize one modelled life cycle on the left-hand side and the developed C-Strategy on the right-hand side. The red arrows originate from a state of the initial life cycle. They terminate in an undesired state. The undesired states are dissolved by the green transitions to useful states initialized by the application of C-Measures. Each C-Measure is by definition based on a specific R-Strategy and therefore defines which method is chosen to return the product to a useful state in the sense of circularity. The values assigned to the variable p on each transition depict the probability of the specific transition. The blue box on the right-hand side of the figure depicts a selection of product metrices which dynamically change depending on the effects of newly incorporated C-Measures.

During the application, the concept of C-Measures has proven to serve the purpose of providing a tangible and product-related definition of circularity measures. Building up the strategy on the basis of an expected life cycle without circularity considerations, allows for a tailored application of C-Measures at a very specific time during the product's life cycle. After modelling the product's architecture and the expected life cycle, the designer can follow a step-by-step process to develop C-Strategies. Circularity-critical states in the conventional product life cycle can be located and directly addressed. This includes undesired states. The tool then allows the designer to apply a C-Measure to dissolve the undesired state of its product.

Moreover, a significant advantage in contrast to previous methods is the ability to immediately analyse and assess a designed strategy and evaluate the application of a single C-Measure. The effects of the C-Measures allow a dynamic update of product metrics.

5. Discussion and conclusion

The aim of this work was to develop tangible and product-related definitions of possible circularity measures, which can be documented together with the product's design and subsequently analysed with respect to their impact on sustainability. For this purpose, our work introduces the concept of C-Measures. C-Measures are tangible definitions of circularity measures inspired by the definition of R-strategies. Our approach is based on the idea to understanding that each product has its individual life cycle (see (Block *et al.*, 2023)). Within such a life cycle, critical states of the system or of components can occur, which can be dissolved in the sense of circularity with the help of C-Measures. The combination of C-Measures applied to a specific component in a specific state during its individual life cycle creates a C-Strategy for the whole product under development.

The approach encompasses potential unwanted events throughout a product's life cycle and permits comparison of various solutions. Hence, the approach facilitates better identification and documentation of the impact of circular economy measures, leading to more informed decision-making. It is essential to furnish specific and product-oriented circularity measures definitions that are integrated into a product's design. This strategy enables the analysis of the overall product effects.

The approach was implemented using the open-source system modelling tool Capella (Eclipse 2023a; Roques 2018). The implementation of the approach for mapping C-measures and the associated creation and analysis of C-strategies was successfully completed. The tool allows the user to obtain a structured overview of the relationships between datasets. The tool is based on a domain-specific metamodel for circular economy aspects and is implemented as an orthogonal metamodel based on the product architecture and extended by C-related aspects. It is also possible to extend the orthogonal metamodel.

The C-Measures Library addresses the sustainability potentials that can be achieved, and the effects are organised in another library, the C-Effects Library. A Strategic Metrics Model adds further information to the metamodel, enabling strategic evaluation of strategies at a higher level. This allows the developer to define key performance indicators to evaluate the effects of the respective C-strategies.

However, the implemented approach is still subject to challenges arising from the complexity of the development process. The life cycles are already quite complex even before the extension by C-Strategies. The extensions further increase the complexity to an extend where an uncluttered visualization can be challenging. Further, the effort to create a holistic C-Strategy for a product highly depends on the complexity of the decomposition into subsystems and components. The current approach asks for the development of a C-Strategy for each component independently. It would make sense for future implementations to enable strategies created at a higher level to be transferred to subcomponents automatically. However, our approach lays the foundation for further developments in the area of circular oriented design.

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