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Supporting circular economy strategies for design of sustainable mechatronic systems using MBSE

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Abstract

The paper investigates approaches for implementing circular economy strategies, such as designing mechatronic products for longer service life by replacing, upgrading, or remanufacturing subsystems. The research aims at applying MBSE to provide the necessary support for dealing with the complexity of these approaches. Requirements and challenges for the development of MBSE support in this context are examined. An example of an EV battery system model shows the benefits and challenges of comprehensive system modelling and traceability in the context of circular economy strategies.

Keywords: *circular economy, model-based systems engineering (MBSE), SysML, sustainability, mechatronic products*

1. Introduction

Technical products are developed to meet the specific needs of different stakeholders. For this purpose, the products must provide relevant properties such as functionality, but also aesthetics, ergonomics and much more. One product property that has become increasingly important in recent years is sustainability. Sustainability refers to all phases of a product's life, from material sourcing to manufacturing, use and recycling. Against this background, sustainability must increasingly be considered already in the planning and development of products. This means that sustainability must be included in all relevant decisions and analyses. This concerns decisions on the business model (should the product be sold, leased, offered as part of a service, etc.) and development decisions. Especially in the context of sustainability, the strategic direction towards circular economy plays a significant role (Geissdoerfer *et al.*, 2017). The focus is reflected, among other things, in the Circular Cars Initiative (CCI) (Valean *et al.*, 2021), a transformative movement, driven by the World Economic Forum, aimed at fostering a Circular Economy within the automotive industry.
From the viewpoint of the Circular Economy (CE), the strategy of closing the loop can be differentiated at three levels (Lee *et al.*, 2017), each with varying degrees of environmental impact.

- The first (best) level, which results in the lowest environmental impact, encompasses the processes of reuse, repair or upgrade (see also Figure 1). The primary distinction between reuse and repair lies in the condition of the whole product or its components; a repair is necessary if the properties of the product are no longer sufficient (e.g. due to damage, wear or ageing). A special form of repair is that the relevant components are replaced (e.g. the brake pads in a car).
- The second level of loop closure is characterised by remanufacturing. This process involves returning a used product to at least its original specification, as described in some literature (Nasr and Thurston, 2006), to an "As-New" state. The remanufacturing process requires several

preliminary steps, including disassembly, cleaning, inspection, and diagnostics. Following these steps, certain product elements may, during product reconditioning, be replaced with new, reused, or repaired product elements. To ensure a successful remanufacturing process, testing should be conducted post-reassembly to verify that all product specifications meet the original requirements.
- The third level of loop closure involves recycling. Material recycled from scrapped product elements should be utilised in the production of new components to achieve a complete loop closure.

It is important to note that these processes are labour-, energy- and resource-intensive and that the reverse logistics and acquisition processes face uncertainties regarding the quantity, quality, and timing of returned parts (Lee *et al.*, 2017). Potting *et al.* (2017) adapt and expand the already mentioned list of CE strategies (reuse, repair, remanufacture, recycle) by adding new concepts which should also be considered during the design process, thus making up the 10 Rs: refuse, rethink, reduce, refurbish, repurpose and recover.

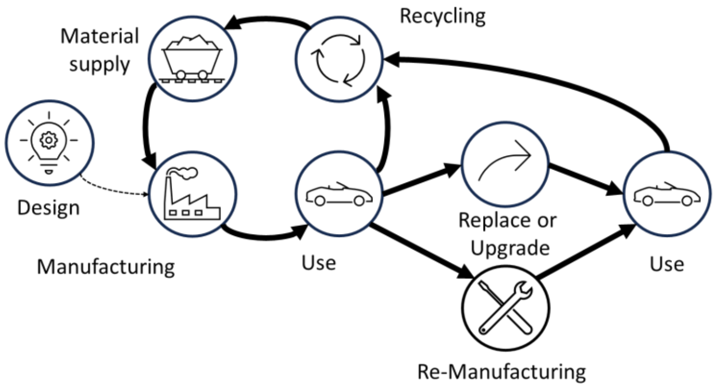

Figure 1. Circulation strategies and their combination (excerpt)

Many products today are mechatronic or even cybertronic. For the development of mechatronic or cybertronic products, it is recommended to describe them using Systems Theory. Accordingly, products are described as models of so-called mechatronic systems (systems are themselves models of the product, possibly in combination with processes). Introducing systems thinking involves decomposing the mechatronic system into subsystems (Pohl *et al.*, 2012; Höhne *et al.*, 2024). The decomposition of a system is in principle arbitrary, and different decompositions can be chosen for a product depending on the objectives and constraints (Ariyo *et al.*, 2008). One common approach is to break the product (model) down according to organisational structures or specific attributes, such as functionality (Browning, 2001).

From the point of view of this paper, it is relevant that mechatronic systems are usually existing on the upper system levels. The domain-specific components (mechanics, electrics, electronics/software) are developed at the lower system levels (Pohl *et al.*, 2012). For the realisation of circular strategies, targeted development decisions have to be made on all system levels. This paper focuses on the upper system levels, i.e. on the overall mechatronic system and the architecture incl. the mechatronic subsystems.

(Bocken and Ritala, 2022) propose three main loop strategies: narrowing loops, slowing loops and closing loops. Narrowing and closing loops is comprehensively addressed by EcoDesign guidelines (McAloone and Pigosso, 2017) this includes rethink, refuse, reduce from the 10Rs. Slowing loops plays a significant role at the mechatronic system level in addition to the domain levels, as loops can be slowed down through upgrades or refurbishment, reuse of existing subsystems or remanufacturing.

A widely used approach for the development and modelling of complex mechatronic products is so-called Model-Based Systems Engineering (MBSE) (Morkevicius *et al.*, 2017). The most widely used modelling language in MBSE is the Systems Modeling Language (SysML) (Friedenthal, 2014). SysML is a semi-formal graphical modelling language to describe products on the mechatronic system level(s) as well as the system context. MBSE models, realised with SysML, can additionally facilitate analysis,

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verification and validation activities on the design (Husung *et al.*, 2021). To a certain extent, they can also support development as a whole by continuous growth of the models along the process. Against this background, the question arises as to how MBSE can support the design of sustainable mechatronic products on the mechatronic system level.

2. State of the art - related work

(Faludi *et al.*, 2020) provide a systematic overview of the needs and gaps in sustainable design methods, the current state of practice and future research directions. Regarding the design process support for sustainable products and systems, different approaches have been proposed. In a document-based approach (Kwak and Kim, 2013), a sensitivity analysis is conducted to explore potential opportunities for improvement and reduction of environmental impacts. Similar to this approach, with the goal of narrowing loops, a SysML based design assistant has been developed (Bougain and Gerhard, 2017) to support sustainable design decisions. Another approach which uses SysML is the System Life cycle Management approach (SysLM) (Eigner *et al.*, 2017). This approach proposes methodological steps which include the definition of the analysis goal(s), the identification of components with high environmental impacts and the analysis of their behaviour. (Eigner and Zavareh, 2022) also describe the validation and verification of the approach, as well as the interpretation of results. Regarding the research of environmental assessment, several examples of connections with MBSE could be identified. One such example identifies the causes for the epistemic uncertainties in Life Cycle Assessment (LCA) and potential remedies with MBSE (Inkermann, 2022). In another example, the authors (Azevedo *et al.*, 2009) argue that SysML could be used as an interface between modelling and LCA tools, while also proposing frameworks for analysing the environmental impacts of multiscale complex systems and system of systems (SoS). For early design phases, evaluation methods for the assessment of product circularity have also been developed (Kamp Albæk *et al.*, 2020). In addition to the evaluation method, the authors also provide a summary of design guidelines and affected parameters for specific CE strategies. End-of-Life (EoL) strategy selection frameworks have also been proposed in the literature (Alamerew and Brissaud, 2019). The approach from (Mügge *et al.*, 2023), which is based on Digital Twin (DT) technology, facilitates information sharing among various stakeholders in the automotive industry, thereby enhancing EoL decision-making. A need for the evaluation of such strategies has also been identified in the literature. (Rossi *et al.*, 2022) propose a conceptual framework for the assessment of EoL strategies. According to the authors, there is a need to enhance the information base regarding the condition of the products for these assessments. Other research was also carried out with the intention of exploring the use of Digital Twins in the context of CE. In their paper, (Preut *et al.*, 2021) also give a general overview of CE information requirements for different life cycle phases and stakeholders while also revising the definition of the DT in the context of CE products and supply chains. Further research in the context of MBSE and CE strategies has been carried out by (Halstenberg *et al.*, 2019) with the focus on the development of smart Product Service Systems (PSS). (Halstenberg *et al.*, 2021) also point out the lack of CE knowledge in design teams and propose means for the transfer of this knowledge.
Based on the literature review provided in this section, it becomes evident that a wide range of MBSE- and SysML- based approaches exist with the goal of supporting the design of sustainable products. Additionally, a considerable number of document-based approaches can also be identified; it should be analysed whether they could also benefit of MBSE support. The research gap we aim to close in this paper arises from a lack of research addressing MBSE support for specific CE strategies (e.g.: upgrade, reuse, remanufacture).
Consequently, we have formulated the following research questions:

- How can MBSE systematically support product development activities in the context of CE strategies (focus: upgrade, reuse, remanufacture)?
- How to approach product and product life cycle modelling in SysML regarding CE strategy requirements? Which model elements and views should be experimentally explored?

In the following section we investigate the CE strategies which, in our view, could be supported with MBSE.

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3. Approaches to realise circular economy strategies

Based on Bocken's strategies (Bocken and Ritala, 2022), various concrete business models and thus design approaches for products can be derived. In the context of this contribution, particular approaches will be selected and addressed, which primarily have an impact on the mechatronic system level. Two selected approaches are:

- Products can be designed to have a longer service life by replacing subsystems or through upgrades (refurbishments), thus providing long-term value to stakeholders (Chierici and Copani, 2016).
- The remanufacturing and reuse of existing subsystems in new products supports the efficient slowing of loops.

The conception and design of products which implement CE approaches can be complex, since, among other things, different variants of subsystems in different product generations must be analysed (important especially in the case of replacement or upgrade) and/or uncertainties exist about the properties of remanufactured subsystems. MBSE can describe various information about the system (model of the product), subsystems or environmental systems, including their behaviour and relationships, through model elements, their parameters and relationships. Based on the model, analyses of this information are supported for specific questions (e.g.: what impact do specific changes to the properties have on the behaviour of the subsystems and the overall system?). Against this background, in the following sections necessary information is elaborated for individual selected approaches, the representation and analysis of which by means of MBSE can specifically support the conception and design of the product (current product including its components but also future upgrade, replacement or remanufacturing components)

3.1. Investigation of development of products for replacement or upgrades

When developing products the service life of which shall be extended by replacing or upgrading subsystems, various aspects must be considered and investigated. The basic prerequisite for the replacement or upgrade is that the modular architecture of the product, including its interfaces, permits this (Boothroyd and Alting, 1992). It must be possible to disassemble and re-assemble the new subsystems. The interfaces must support all subsystems (current and the planned new ones after replacement or upgrade), which is associated with many uncertainties, especially due to the time foresight of upgrades. Depending on the interface type, the description of the interfaces includes the static geometric, mechanical (e.g. transmittable forces), electrical (e.g. transmittable power), etc. specifications (Zerwas *et al.*, 2022) as well as the interface behaviour (e.g. update rate for signal interfaces).

The replacement and upgrade of subsystems can lead to the new or enhanced subsystems having changed properties; in the case of an upgrade, this is even intended for at least one property (e.g. in the case of a new drive, the mechanical power output and, associated with this, the undesired change in power loss due to heat output). The change in the properties of individual subsystems can have an effect on other neighbouring subsystems (e.g. heating or higher mechanical load) and the superordinate system as so-called emergent effects (Mittal and Rainey, 2015). The effects of the changed properties must be comprehensively investigated.

To support the conception and design of products for replacement and upgrade, an MBSE model should fulfil at least the following requirements:

- description of the modularisation of the architecture,
- static and dynamic (behaviour) description of the interfaces,
- description of the properties and their effects on the behaviour (also across the interfaces of the subsystems),
- description of the maturity level of the represented information.

3.2. Investigation of development of products for remanufacturing

When designing a product intended for remanufacturing, several design approaches must be considered (Sassanelli *et al.*, 2020). The decision regarding which components should undergo which value-retaining process could be based on information from previous product generations through an environmental impact assessment, such as LCA (Klöpffer and Grahl, 2014), or other MBSE-specific approaches for identifying potential reductions in environmental impacts, such as the System Life cycle Management (SysLM) approach according to (Eigner *et al.*, 2017). To mitigate some of the uncertainties inherent in the remanufacturing process, information from the product use phase is necessary. This information can be used to assess the degradation level of product components which supports the creation of predictive models (Garetti and Taisch, 2012) for estimating the end of the current product life cycle and the necessary beginning of the remanufacturing process. Research (Xia *et al.*, 2018) suggests that opportunistic scheduling for preventive maintenance can reduce environmental impacts. Two approaches have been identified for gathering relevant system information. One approach is based on the Digital Twin or Digital Shadow principle (Rojek *et al.*, 2021), where live information from the product is collected via sensors. The other approach relies on the maintenance process during the use phase within the life cycle. During the design phase, the appropriate methods for collecting this information must be considered, along with proposed methods of component identification (Nowakowski, 2018). It has been suggested to be represent this information by a health indicator number (Turner *et al.*, 2022). Given that the product specification needs to satisfy the original requirements, a system analysis should be performed to confirm that the reused or repaired component, with its changed properties, does not have undesired effects on the mechatronic system level and that all functions are tested against the initial requirements. Failure Mode and Effects Analysis (FMEA) approaches, which could be enhanced with MBSE (Korsunovs *et al.*, 2022), have also been proposed for this purpose.

MBSE can manage the raised complexity due to different product variations and also aid in the validation and verification of the remanufactured product. For this purpose, the MBSE model should define the processes for gathering information about the degradation level of components and store this information for further system analysis. Similar to the concerns mentioned in section 3.1., the impact of the deterioration of components and their interfaces needs to be analysed. For this purpose, an approach to describe the deterioration of system properties with SysML information in MBSE models is needed.

To support the conception and design of products for remanufacturing, an MBSE model should fulfil at least the following requirements:

- description of system element degradation and its effects on the system behaviour,
- description and maturity of gathered system health information,
- definition of component health indicators with temporal information for use in predictive End-of-Life models,
- original system specification validation results.

3.3. Combined approaches

In many practical applications, it is necessary to consider the combination of the replacement/upgrade of subsystems and the reuse/remanufacturing of subsystems within a single product. The combination of requirements from sections 3.1 and 3.2 results in several challenges. Both approaches involve the exchange of components with ones of different properties, requiring a thorough impact analysis to understand the effects of these changes on the overall system behaviour. The maturity level of information is a critical factor in both cases, although the sources of uncertainty differ. For upgraded components, uncertainties may arise from the forward-looking nature of upgrades, while for remanufactured components, uncertainties may stem from the variability in the current condition and performance of used components. In the next section, the MBSE support for the combined approaches is presented together with an overview of the SysML elements needed to satisfy the requirements.

4. MBSE support

Section 3 derived the requirements to be fulfilled by MBSE/SysML models so that they can support the considered approaches of CE strategies in the design of mechatronic systems. The SysML language is

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a semiformal specification language consisting of elements and relations with semantics and parameters. The elements and relations can be represented and modified in different diagrams. To find out how SysML can support CE strategies during system design, it is necessary to analyse what elements incl. their properties and relations are needed for modelling and how the modelling and analysis based on them should be performed. Background information: The SysML elements and relations define the language, the modelling methodology completes this with the grammar. In the context of the analysis presented here, modelling took place based on the MagicGrid methodology (Morkevicius *et al.*, 2017). The methodological basis for determining the SysML elements and relations is the analysis of the specific methods used for the approaches with regard to the necessary input, processing and output information and their relationships. For example, LCAs (Lipšinić and Pavković, 2023) are often carried out according to ISO 14040 with the methodological steps of defining the objective and scope, life cycle inventory, impact assessment and evaluation. The LCA analysis can be carried out with the help of analytical equations and thus in SysML with the help of parametric diagrams. Other methods support variant management (Weilkiens, 2016), change impact analyses (Hove *et al.*, 2009) to determine the impact of changes to properties or interfaces of subsystems, modularisation analyses (Dambietz *et al.*, 2021) and behaviour analyses (OMG, 2021). Table 1 shows a recommendation for the elements and relations of the SysML language that can be used for modelling according to the MagicGrid method in order to fulfil the requirements. It turns out that the requirements that lead to static descriptions are relatively easy to implement. This concerns e.g. the maturity level of information. The analyses can be performed by means of constraints blocks and analytical equations. The modelling effort increases for dynamic descriptions, e.g. the behaviour at the interfaces as well as degradation information, and for comprehensive analysis of relationships between the elements, e.g. the effects of the changed dynamic behaviour of the interfaces on the behaviour of neighbouring subsystems.

5. Example

In this section, the approach will be briefly described using the example of an electrically powered vehicle, in particular its battery (model is inspired by (Wennerblom; Barreras et al., 2018)). The battery is one of many subsystems (see Figure 2) and is subject to ageing, among other things. As explained in sections 3.1. to 3.3., various strategies are possible for realising Circular Economy approaches for the battery. To do this, different information must be represented in different variants (see Figure 2 with the variants "HV Battery current", "HV Battery upgrade" "HV Battery remanufactured" and other subsystems (indicated as "…" in Figure 2) with the utilisation of generalisation in SysML) in the SysML model and analyses carried out on this basis.

Table 1. Utilisation of SysML to meet the requirements derived in section 3

Legend: ↗ Allocate

Requirements	Relations	Aggregation / Composition	Generalization	Trace	SysMLElemente	Action	Activity	Block	PartProperty	ConstraintBlock	FlowProperty	InterfaceBlock	Port	ProxyPort	State	TestCase	Value Properties
Requirements		2		2		1	2	7	6	2	1	2		1	1	1	4
1 description of the modularisation of the architecture	1	↗			4			↗	↗			↗		↗			
2 static and dynamic (behaviour) description of the interfaces					6	↗	↗	↗			↗	↗			↗		
3 description of the properties					2		↗										↗
4 description of the maturity level of the represented information					3			↗	↗								↗
5 impact on the behaviour	2	↗		↗													
6 description of system element degradation					3			↗	↗								↗
7 description and maturity of gathered system health information					4			↗	↗	↗							↗
8 definition of component health indicators with temporal information					3			↗	↗	↗							
9 original system specification validation results	1			↗	3			↗	↗							↗	

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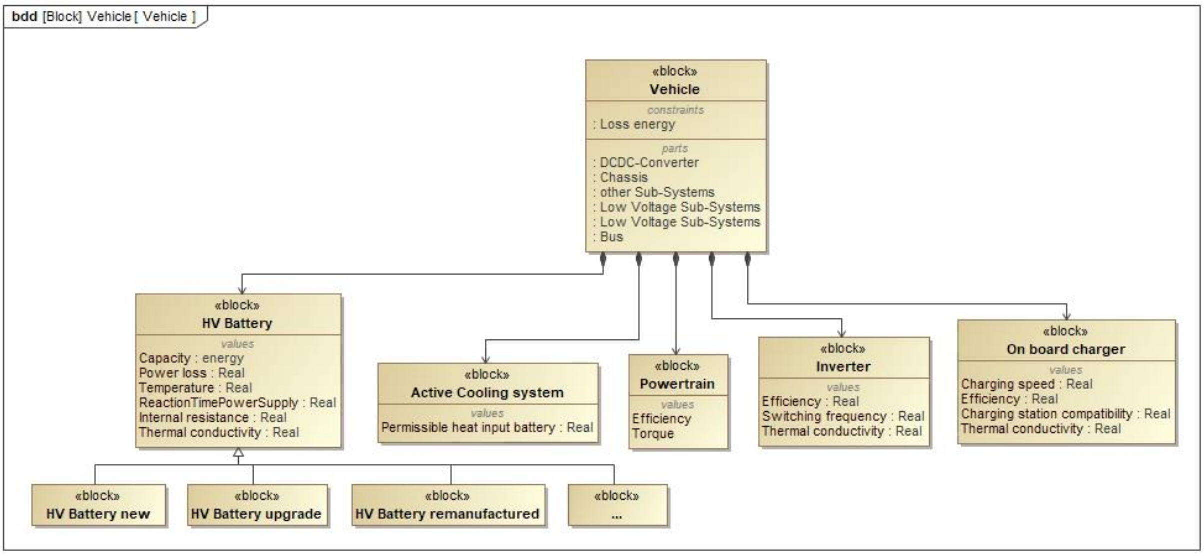

Figure 2. Diagram from the model of the vehicle with its breakdown (simplified model)

Static analyses for modularisation, including the interfaces, are relatively easy to perform. Analysing the impact of replacements or upgrades or changed properties through remanufacturing requires comprehensive linking of the affected model elements and more complex analyses. Figure 3 shows an example of the impact of changes to the properties of the battery - here via the power output in the derating state. For example, if the properties of the reaction time, internal resistance, etc. change after the battery has been replaced, remanufactured or upgraded, this can have an effect on the power output in the derating state (system state to describe the reduced power output) (see Figure 3). The impact of this change can be seen during the analysis of the model. Among other things, this affects the power that is output via the I_E_HV interface (I_E_HV means: "Interface" - "Electrical" - "High Voltage") and can therefore have an impact on other components, e.g. the inverter (see Figure 3). The possible change in behaviour can be evaluated conceptually (qualitative impact analysis based on the defined concept). Detailed analyses will become possible by linking to physical models (Zerwas *et al.*, 2022).

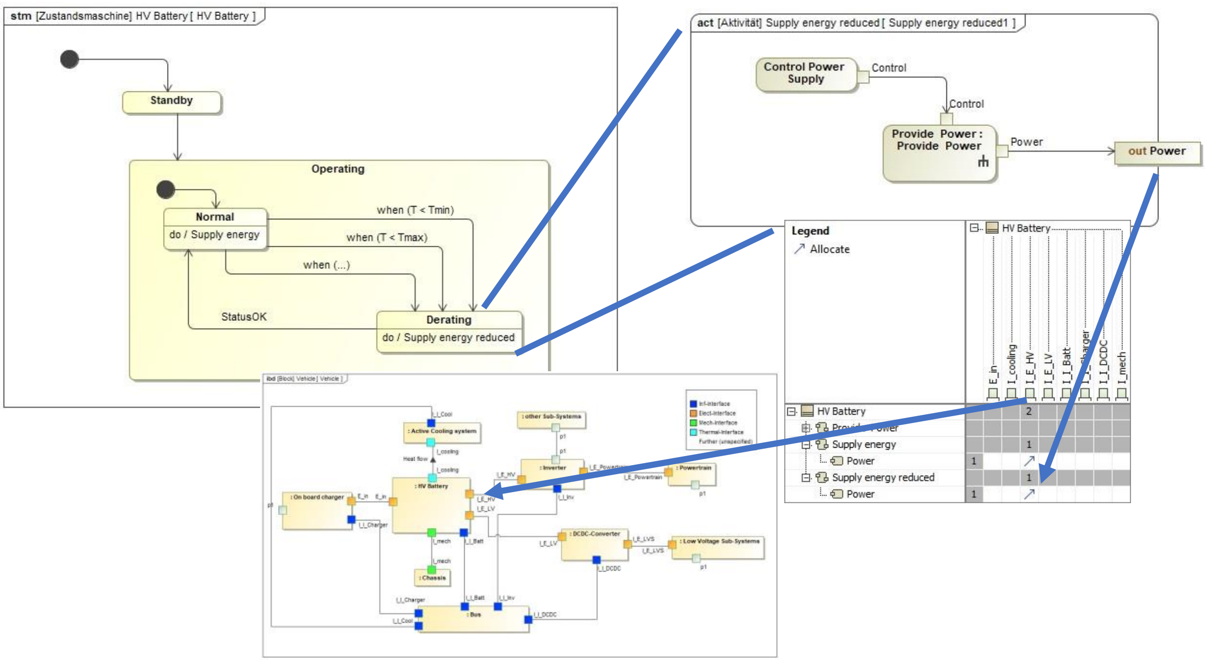

Figure 3. Diagrams from the model of the vehicle to illustrate the links between the elements (simplified model, inspired by (Wennerblom; Barreras et al., 2018))

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6. Discussion and conclusion

This paper investigates and discusses the possibilities offered by the current SysML language and its extensions to support Circular Economy strategies, based on the research questions in section XYZ. The presented example (section 5) offers insights in both the advantages and challenges inherent to the approaches described in sections 3 and 4. The most notable advantages are: the consistent and unified source for descriptions, which enhances clarity and overall coherence in system modelling, the comprehensive analysis options provided by SysML, and the capability of establishing traceability. On the other hand, the sheer volume of information contained within SysML is a major challenge, particularly when information is distributed across various heterogeneous models and tools during the development process. Creating and maintaining models under this approach may also prove to be exceedingly time-consuming, especially when managing connections between elements and dynamic behaviours for complex mechatronic systems. However, the successful managing of these connections and dynamic behaviour enables the impact analysis of property changes when components are replaced, upgraded, or remanufactured. These aspects should be considered as the main benefits of MBSE implementation via SysML, the challenge that remains is to balance the modelling effort with the gained benefits. Another issue with SysML models, that needs to be addressed, is the focus on characterising the mechatronic level concepts, which often lack detailed specifications and must be elaborately supplemented with profiles. This situation is expected to improve with SysML 2.0. The necessity to implement additional MBSE/SysML models above or beside the system model in order to capture neighbouring systems (or "X-systems" according to (Weber, 2007)) that actually do the replacement, upgrade or remanufacture is an additional challenge.

For further research we propose assessing the usability of these approaches, particularly the handling of life cycle data, e.g. from Digital Twins and maintenance activities. Another aspect worth exploring involves system safety analyses in the context of remanufactured subsystems. Products which include degraded components could introduce new potential failure modes. Asset deterioration information has yet to be successfully integrated in SysML-based MBSE approaches. Existing frameworks (Zhang *et al.*, 2018), based on probabilistic methods, e.g. Bayesian networks, should be considered for further development in this context.

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