NORDDESIGN CONFERENCE
REYKJAVIK, ICELAND, 12-14 AUGUST 2024

Fostering Circular Life Cycle Strategies in Model-Based Systems Engineering

Lars Everding[1], Anja Cudok[2], Christian Raulf[2], Thomas Vietor[1]

[1]Institute for Engineering Design, Technische Universität Braunschweig
[2]Volkswagen Commercial Vehicles, Volkswagen AG

Abstract: This research paper focuses on integrating circular economy principles into a system model for the automotive sector. The central research question relates how an existing vehicle system model can be supplemented with characteristics of a reuse strategy. For this purpose, the so-called CE model is presented, which can be seen as an addition to a vehicle system model. The CE model inherits circular economy strategies by showing circular product loops with different stakeholders involved. An electric vehicle battery is used to show an example of second-life reuse application. By implementing the CE model, the approach led to an understanding on what stakeholders could be relevant after the primarily usage phase and which requirements could arise. The investigation aims to make a contribution to sustainable development in the automotive industry by focusing on extending the value lifetime and utilization intensity of products, components and materials.

Keywords: Circular Economy, Model-Based Systems Engineering, Vehicle Development, Requirements Engineering

1 Introduction

Today, technical products are frequently used for a limited period of time before being discarded due to reasons such as inferior performance or functionality, outdated appearance and aesthetics compared to newer products. This period, known as the value lifetime, often falls short of the maximum possible period, known as the physical lifetime. To prevent further resource waste, it is necessary to develop and consider approaches and concepts throughout the entire life cycle of a product. This includes questioning the development, manufacturing and deployment of products in the first place. Additionally, efforts should be made to minimize resource consumption and maximize resource recovery during both use and end-of life phases. This involves considering potential updates and upgrades of products to maintain their appeal and longevity, as well as transitioning from a linear to a circular economy. It is essential to establish the necessary services and processes to facilitate the provision and retrieval of resources including whole products, parts, materials, as needed. The aim of developers and providers of products should be to correspond precisely to the characteristics mentioned above of the Circular Economy (CE) and to offer products that can last and to ensure that these products will last. To be precise, it must have a maximal value lifetime, intensity of use and high resource efficiency. To reach these goals, a holistic view on a product's life cycle is a basic requirement that has to be taken into account when planning, developing, implementing, and taking it back. (Cudok et al., 2017)

However, the shift towards circular systems is associated with an increased complexity of the considered systems. The "Engineering of systems will play a central role in addressing the SDGs [formed by the UN]" (INCOSE, 2022) and therefore serves as an integrator for such challenges. Changes are needed to address a related broader set of elements when expanding the life cycle of a system (INCOSE, 2022). Product features such as modularity are becoming more critical, and processes relating to the product need to be established and implemented. This potentially adds further stakeholders with growing expectations regarding sustainability to the original structure (INCOSE, 2022). Especially when it comes to extending the useful life of products or individual subsystems through closed-loop management (second-life concepts), the interlinking of processes and stakeholders with domain-specific concepts plays a significant role (David et al., 2024). This lead to an increase in system complexity. Model-Based Systems Engineering (MBSE) enables handling complex and highly connected systems, which is essential for contemporary products, as they have a higher degree of complexity due to an increased software component and increasing cross-linking with their environment. Based on systems engineering fundamentals, a system model is always at the centre of the considerations in different methods. This enables system properties and behavior to be captured and information to be provided in a domain-appropriate manner through different model views. The mutual relationships between the system model elements are retained, which positively influences the traceability of changes across all departments involved in the development. (Friedenthal et al., 2015)

This research paper focuses on integrating circular economy principles into an MBSE method. To this end, CE principles and relevant MBSE methods are examined and highlighted in Chapter 2. In order to define the research gap, Chapter 2.2 reviews current MBSE methods for taking into account CE principles and strategies. Furthermore, current efforts to implement CE strategies in the automotive sector are listed. Based on the identified gaps in existing methods, a solution approach called the CE model is presented in Chapter 3. The question of how a system model in the MBSE context can be expanded to include the characteristics of a circular economy is pursued. Chapter 4 shows the application of the CE model in the field of automotive development. It can be seen how the model-based linking of a vehicle system model with strategies and measures for ecological sustainability in product development can be realised. The evaluation is based on the case of a vehicle system model that is intended for use in the context of the automotive sector. The Reuse-strategy is analyzed, and individual aspects are checked for possible model integration. This is followed by the extension of the model, the derivation of specific requirements for the battery system assembly and the cross-linking of the respective artefacts. The overarching goal is to extend the product service life and maximize the intensity of use. The results obtained are discussed in Chapter 5, and limitations are explained. Finally, further questions are raised in the form of a brief outlook.

2 State of the art and basic principles

2.1 Circular Economy

In today's era of heightened environmental awareness, the Circular Economy concept has become a significant factor in a paradigm shift towards sustainability. Unlike the traditional linear 'take-make-dispose' model, a circular economy aims to keep resources in use for as long as possible, extracting maximum value while minimizing waste and environmental impact. Circular economy principles emphasize designing products, systems, and business models prioritizing longevity, reuse, and resource conservation throughout their life cycle. By promoting regenerative practices, the circular economy offers a holistic resource management approach, promoting both economic growth and environmental protection.

The following collection of design principles shows an excerpt from the variety of possibilities to address a product's properties in terms of its circularity, introduced, e.g., in various case studies by the EllenMacArthur Foundation (EllenMacArthur Foundation, 2024):

Product as a Service (PaaS) / Product/Service Systems: Shifting from ownership to service-based offerings (e.g. pay per use or pay per hour) where products are leased, rented, or shared instead of being sold offers new business models to manufacturers. In many cases, the resulting lower use of resources enables a similar or equally high value for the users.

Design for Disassembly and Reuse: Products are designed with the intention of easy disassembly into components or materials that can be reused or recycled at the end of their life cycle. This principle involves selecting material, fastening methods, and standardized interfaces to facilitate easy separation of parts. An essential related aspect is planning reverse logistics and take-back programs as well as the organization and engagement of stakeholders (such as suppliers, manufacturers, consumers, collection centres, and waste managers) to be able to implement the CE approaches.

Design for Modularity and Standardization: Designing products with modular components or standardized parts that can be easily replaced or upgraded, extending the product's lifespan. This facilitates repair, maintenance, and adaptation to evolving needs, reducing waste.

Design for Minimal Environmental Impact: This involves optimizing manufacturing processes and transportation, as well as considering energy requirements during product use. It also includes material selection regarding the conservation of finite resources, longevity, reusability, recyclability, and toxicity.

Another collection of strategies developed and published by organizations like the Netherlands Environmental Assessment Agency (Potting et al., 2017) are the so-called "re"-strategies. These strategies primarily focus on the fundamental pillars of circularity: **Reduce**, **Reuse**, and **Recycle**. Reduce: Reducing resource consumption and waste generation aligns closely with CE's goal of minimizing the use of virgin resources. Strategies here involve minimizing material use, energy consumption, and waste production in product design, production, and consumption phases. By adopting efficient processes and innovative design, the aim is to reduce the overall environmental impact. Reuse: Reusing products, components, or materials promotes a circular approach by extending the lifespan of items. Instead of discarding products after use, reusing them in their original form or after refurbishment or repair helps conserve resources and reduce waste. CE emphasizes designing products with reusability in mind and establishing systems that support reusing materials or products. Recycle: Recycling plays a crucial role in the circular economy by converting waste into valuable resources. It involves collecting, sorting, and processing waste materials to produce new materials or products. CE emphasizes the importance of creating closed-loop systems where materials can be recycled and reintroduced into production processes. Further "re"-strategies mentioned are refuse, rethink, repair, refurbish, remanufacture, repurpose and recover. A closer look into their definition is given, e.g. in (Potting et al., 2017)

One model describing a product's circularity in practice is the so-called Comet Circle, founded by the Ricoh Group in 1994 (Ricoh, 2024). It propagates the flow of resources in the ecosystem of their products, taking forward and backward logistics and the relevant stakeholders into account. Materials suppliers provide resources harvested from nature, which transform into products reaching end-users. Unlike in a linear economy, where used products end up in landfills, the circular approach involves collection and recycling centres that process used products or components, and returning them to the production cycle. Parts unsuitable for reuse, repair or refurbishment are recycled into materials. The different paths of this closed-loop approach can be traced with the Comet Circle

The implementation of CE in product development can be complex and pose various challenges, such as traditional (linear) thinking, prioritization of economic factors, and lack of awareness, education or collaboration as mentioned in (Cudok et al., 2017). A whole ecosystem surrounding their products needs to be initiated by organizations, as proposed by Konietzko et al. (Konietzko et al., 2024). Bocken et al. (Bocken et al., 2023) propose design thinking tools to catalyse sustainable circular innovation. A discussion on guiding principles, strategies, and methods can be found e.g. in a paper from den Hollander et al. (den Hollander et al., 2017), improving the understanding of terms and stating the necessity of product design within a CE.

2.2 CE strategies in Model-Based Systems Engineering approaches

Modern products are characterized by a high degree of complexity triggered by an increased level of cross-linking. This can arise from within, through enhanced software involvement, as well as through interconnection with the product environment and potential surrounding systems. New methods and tools are needed to meet product development's changed challenges when ideating and designing such cyber-physical systems. (Şahin et al., 2021a)

Systems Engineering (SE), as a cross-domain approach, promises to handle the development of highly complex systems and is based on the theory of system thinking. Suppose an overarching, coherent meta-model, which documents the information of the individual elements and their relationships across domains, is at the centre of the considerations. In that case, this is termed **Model-Based Systems Engineering (MBSE)**. The successful implementation of an MBSE concept requires equal control of the trilogy of language, tools and methods. The graphical **Systems Modeling Language (SysML)** has been established as the leading language within SE. Methods generally consist of a series of interrelated activities, techniques and rules which, when executed, lead to implementing one or more specific processes. An MBSE method accordingly aims to implement the systems engineering process or parts of it. The main result of this is the structure of the system model and, in particular, the system architecture. (Friedenthal et al., 2015)

The system model can be generated from different views. SysML supports this through the four pillars: requirements, behavior, structure and parameters. (Friedenthal et al., 2015) Most approaches follow the path from an abstract representation of the overall system through a more concrete description of the individual subsystems to a detailed representation of individual components across the individual views. Examples include the MBSE Grid (Morkevicius et al., 2017) or the RFLP approach, which stands for Requirements, and Functional, Logical, and Physical system architecture (Krog et al., 2022).

The specific steps for designing the system model are documented using a variety of methods. The life cycle of the system of interest (SOI) is more or less emphasized via different sources. The **ISO15288:2023** states that the SOI progresses through the following stages during its life cycle: Concept, development, production, utilization, support and retirement. (Walden et al., 2023), (ISO/IEC/IEEE15288:2023). Although there are iterations and recursions, especially in the parallel process steps "development" and "support", this is certainly not a closed-loop model.

The **International Council on Systems Engineering (INCOSE)** promotes the **Object-Oriented Systems Engineering Method (OOSEM)**, which has as a declared objective to capture information about the entire life cycle of the system to be developed, to serve as a basis for specification, analysis, development, verification and validation (Walden et al., 2023). However, OOSEM also refers to a linear life cycle, in analogy to the previously mentioned stages of developing, producing, deploying, operating, supporting, and disposing (Friedenthal et al., 2015). Friedenthal et al. recognize the need to consider enabling systems to develop capabilities that support the entire system life cycle. These must be considered early in the development process to avoid adverse effects and high costs. However, its scope is limited to systems required to manufacture, maintain or verify the system. (Friedenthal et al., 2015)

OPM (Object-Process Methodology) is another method and modelling language developed by Dov Dori and documented in ISO 19450. Like SysML, it allows the modelling of the complex systems' function, behaviour and structure. It is based on a minimal ontology with two types of things: Objects that can have different states and processes that transform objects. (Dori, 2016) Although the OPM claims a high degree of universality and enables a solid representation of the object stages and processes, no tendencies towards supporting a circular economy in the SE are recognizable here either.

Use cases describe the interaction of a stakeholder with the system. A scenario described in this way makes it possible to derive requirements based on the described interaction processes. (Haberfellner et al., 2019) In his **SYSMOD** method, Weilkiens describes the modelling of use cases as an initial abstract description of the system behaviour. According to this, a use case can include several secondary use cases. (Weilkiens and Soley, 2014) However, a secondary use case in this example describes an inherent component of the primary use case. It does not extend the system's intended use phase - in the sense of a second-life concept (cf. Chapter 2.1).

Once the system context, stakeholders and use cases are known, the stakeholders' needs and requirements can be derived from these (cf. Friedenthal et al., 2015). The persona method can be used to understand the needs of individual stakeholders and their thoughts and motivations. This procedure can also follow a model-based approach. (Raulf et al., 2021) In the MBSE methods mentioned above, the interaction of stakeholders with the SOI is always addressed. Naturally, the known stakeholders at this point are the users. However, secondary use cases are also considered outside of the actual usage to consider requirements originating in production, for example. Since the focus is always on a conventional linear life cycle and the primary use case, i.e. the intended use of the system, the associated stakeholders need to be more sufficiently considered. Analysing a closed-loop life cycle model beyond the intended use phase implies a changed stakeholder structure and requires a dedicated examination of their needs and requirements for the SOI. An extended MBSE method is required to consider CE strategies (see 2.1) in product development. Stoewer points out that an SE approach and the underlying system thinking theory provide an appropriate base for implementing CE strategies (Stoewer, 2023).

2.3 Automotive trends facing circular economy

In recent years, next to other trends like automated driving or connected vehicles (Kuhnert et al., 2017), there has also been a significant trend towards greater sustainability and resource efficiency in the automotive industry. Several factors, including growing public awareness of environmental issues, stricter environmental regulations and consumer demand for greener vehicles drive this trend. The industry has recognized that sustainability is an ethical commitment and an economic requirement to remain competitive and meet changing market demands. (Opazo-Basáez et al., 2018)

Efforts to achieve greater sustainability can already be found in the automotive industry today, as seen in the following examples. Toyota is implementing circular economy principles within its manufacturing processes, for example, “Battery 3R” which means Reduce, Rebuilt/Reuse, and Recycle. Their efforts include recycling materials from end-of-life vehicles and reducing waste in production. (Toyota Motor Corporation, 2023)

In Germany, the partners Daimler AG, The Mobility House AG, GETEC and Remondis SE have joined forces to build a second-life battery storage system with a total battery capacity of 13 MWh. The energy comes from 1000 batteries that were originally used in the smart fortwo electric vehicle model. (GETEC, 2016)

Volvo has a robust remanufacturing program for components like engines, transmissions, and gearboxes. They refurbish and restore used components to a like-new condition, reducing the need for new parts and minimizing waste while providing cost-effective solutions for consumers (Volvo, 2024). To recycle used water in water-consuming production processes, Volvo introduced the "silane-based technology" (Opazo-Basáez et al., 2018).

In 2013, BMW launched the i3 model, an electrically powered vehicle which, according to the manufacturer, is 95% reusable. (Opazo-Basáez et al., 2018) In 2021, BMW presented the electrically powered vehicle concept called “i Vision Circular”. This concept shows a vision of BMW for 2040, where the design principles “Secondary First” and “Design for Circularity” will be the focus of development. Related activities for development are summarized by BMW’s own abbreviated “4Rs” labeled RE:THINK, RE:DUCE, RE:USE, RE:CYCLE. (Seidel, 2022)

3 Approach – The life cycle model

The increasing digitalization of vehicle systems is leading to a rise in development complexity. The commitment of car manufacturers to greater sustainability (see examples in Chapter 2.3) confronts them with additional challenges. The fact that the vehicles to be developed are perceived as part of a circular system further increases the degree of complexity. MBSE methods offer a solution here, as engineers are able to capture highly complex systems with a better understanding of parties’ involved and also point out the interactions between the SOI and its environment, including relevant stakeholders.

MBSE already offers a large range of well-established methods (see Chapter 2.2), but these do not focus sufficiently on the whole product life cycle. Although it is possible to model accompanying processes in addition to the intended use case, this is only used to represent part of the product life cycle. This means that CE methods and strategies can only be mapped to a limited extent. In addition, none of the relevant methods show a closed loop cycle as a permanent artefact - if at all, only linear product life cycles are used. One of the critical research questions in this thesis is the potential for a system model in the MBSE context to be extended to include the characteristics of a circular economy. In addition, the question is addressed which pillar (requirements, behavior, structure or parameters) can be used to integrate the influences of the CE into the MBSE-based approach.

The first step is to choose a life cycle model that is as universal as possible and suitable for representation in standard MBSE frameworks. At the same time, however, it must be specific enough to the particular branch to be transferred to the framework conditions of the automotive industry.

The Comet Circle (seen in chapter 2.1) is chosen for that, as breaking down a product to life cycle stages and provide the related views on a high level are the strengths. This should make complex systems as well as the complexity of circularity better manageable. At the same time, model building based on the Comet Circle is easy to understand and therefore suitable for integration into the product development process.

It includes stakeholders, processes, and different stages of the system of interest (SOI). These can be ideally linked to the MBSE artefact from the behavior pillar, describing issues with a process-related character, like the interaction between stakeholders and the system. Furthermore, it supports the idea of structuring the system via several degrees of abstraction.

In this approach, the Comet Circle contents are modelled ina use case diagram [uc] in SysML. The individual use cases are divided into SOI-related use cases, parts-related use cases and use cases on material level. The corresponding stakeholders can also be integrated into the diagram. Figure 1 shows a section of the Comet Circle Diagram. The case "Usage of the System (SOI)" by the user, previously known as the primary use case, claims the cycle's starting point on the left-hand side of the diagram. This is followed by the individual loops of the comet, each of which includes the associated use case and the responsible stakeholder. However, the object of consideration is always the SOI. When parts are mentioned, this refers to the components that make up the SOI, which, in turn, can be broken down to a material level.

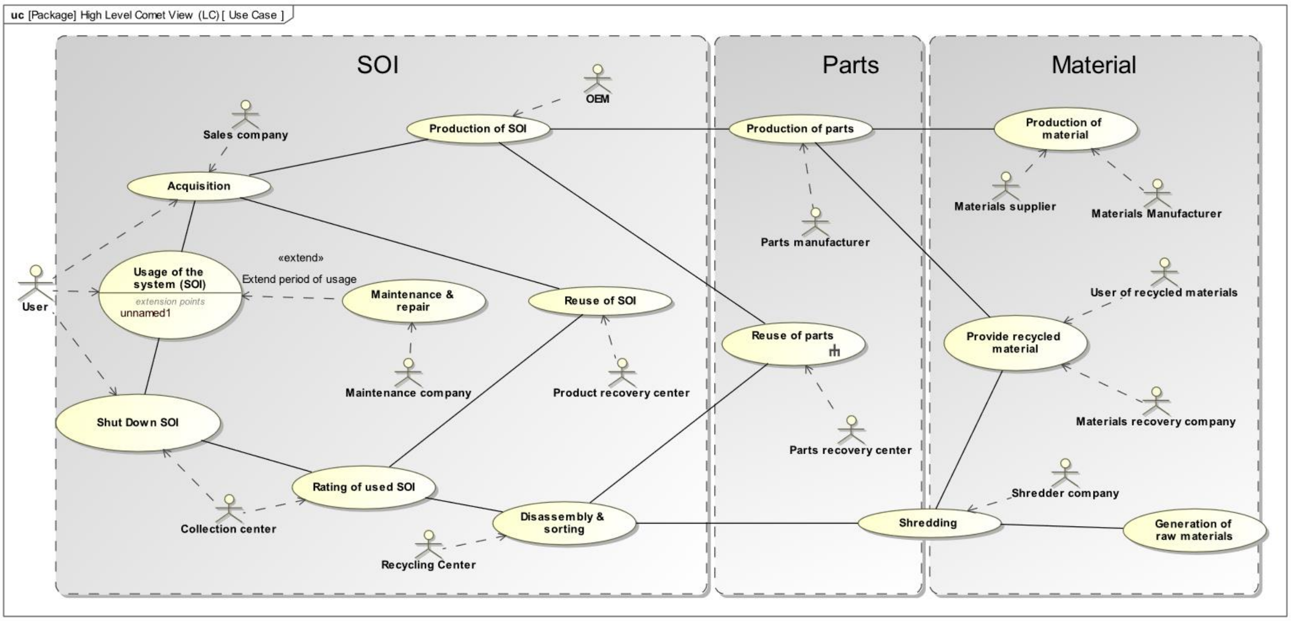

Figure 1. Detail of the Comet Circle SysML model

The insufficient consideration of secondary use cases in the closed-loop life cycle described here means that the associated stakeholders are also not sufficiently examined. In order to understand the needs of the individual stakeholders more deeply, a further description based on templates can be utilized as an inherent part of the model. (Raulf et al., 2021) This persona description can be mapped and linked directly within the model, ensuring enhanced traceability from the source of the user needs, through the use cases, to the SOI and its parts or even the used materials.

The Comet Circle Diagram can be regarded as a high-level view of the life cycle and is so abstract that it is valid for many usage scenarios within vehicle development. In order to use it to optimize system models, it makes sense to implement the contents first in the form of this separate model. For this purpose, the CE model is designed independently of the vehicle system model. Finally, the relationships and traces between these two models must be established in order to relate them to each other. A significant advantage of this approach is that it is not necessary in a first place to make any major changes to an existing vehicle model. Existing working methods and conventions of the model architecture are retained, which should positively effects the acceptance of the procedure by all parties involved in the development.

The CE model builds on the understanding of the mentioned literature (chapter 2) and propagates the integration of CE strategies and values into product development using MBSE. The approach should serve as a theoretical concept for analysing and updating an existing model but also for supporting the development phase of a new product model. Different stakeholders that could be relevant for a second-life phase can be identified, different strategies or measures can be simulated in detail (e.g. material substitution, product take-back schemes, or redesign) and, subsequently, evaluate impact on circularity metrics before implementation. Those aspects found and implemented in the CE model can be linked to a base product model. By that, potential benefits of extending the lifetime of parts in a product can be found early on and the process of preparing a product more plannable for a next life cycle phase is supported. A new base of requirements can be build and parts of an existing system model can be checked if they can fulfil those requirements or if adaptions are necessary. By that, a new system model can be created and existing parts that are appropriate can be used for that.

Modelling with the CE model can detail different secondary use cases from the closed-loop life cycle context and derive the stakeholders' needs. Those associated and derived CE requirements are not captured consistently enough in existing approaches and only find their way into current vehicle projects with difficulty and often in an incomplete form. In the following chapter, the requirements derivation step is carried out based on a specific application example and the linking of the CE model and the vehicle model is demonstrated afterwards.

4 Application and result

The system model represents the basis for the consideration of all MBSE approaches. It serves as an information repository, a so-called "single source of truth", and enables domain-oriented access with the ability of consistent cross-linking of the contents. Şahin et al. describe a system model that is divided into three pillars: requirements, behavior and structure. (Şahin et al., 2021b) Through different degrees of abstraction, the system can be described via a black box perspective, a white box perspective and the solution level, resulting in a matrix of 9 panels. This model was used to develop dynamically configurable autonomous vehicle concepts and was extended and validated by Raulf et al. for further automotive applications. (Raulf et al., 2021) This study will also use the modelling framework in an abbreviated form for the application of the proposed CE model. This paper discusses the second-life (SL) use of traction batteries from battery electric vehicles (BEV) as an application example. The battery usually accounts for up to 40 % of the total costs of an electric vehicle, which makes it particularly interesting to extend the lifespan and gain the most profit out of the supply chain (Shahjalal et al., 2022). Next to that, there is the European Union's goal of achieving net-zero greenhouse gas emissions in 2050 (European Union, 2024) and consequently banning the registration of new combustion vehicles that emit CO2 during operation from 2035 (Bundesregierung, 2023). By this, and the social trends towards more sustainability described at the beginning, the number of BEVs on the road is steadily increasing, so there is a potential rising in the amount of used batteries at some time.

The technical requirements for the batteries of BEVs may not be met over the entire possible usage time of the vehicles, which means that either the batteries of these vehicles must be replaced or the entire vehicle must be taken out of service. Usually there is a critical battery capacity limit of a minimum 80% in the automotive sector (Shahjalal et al., 2022). If these batteries are replaced, the replaced and aged ones can be used for other (SL) applications where the load profiles are less severe and, therefore, the batteries are reusable. Such SL applications can be stationary or mobile energy storage systems for power producers, grid operators, private households, industrial companies or service providers, for example. These energy storage systems could then be used, for example, to maintain supply obligations, provide balancing power in the grid, provide emergency power, manage peak loads or as a power buffer for charging stations for BEVs. This potentially results in a reduction in greenhouse gas emissions and resource consumption, generating additional revenue and saving costs. (Fischhaber et al., 2016)

Therefore, there is a need to investigate the development of battery electric vehicles and the impact of new stakeholders on SL applications for batteries. In this case, a MBSE vehicle model for a BEV will be extended with the invented CE model to consider the additional stakeholders and resulting requirements for the battery reuse, based on the Comet Circle. The resulting requirements out of this scenario, then have to be compared between the base vehicle system model and CE model to show what product adaption or changes could be necessary in further engineering phases for a more second-life fair battery development with the vehicle system.

According to the concept of the Comet Circle, the CE model includes stakeholders from different stages of the product life cycle. For the SL battery application scenario, there are different stakeholders potentially involved. This scenario is based on the process description for SL usage of batteries from a study by Fischhaber et al. in 2016 and is an excerpt of related processes in such a project.

First, there is the OEM of the vehicle, who withdraws the vehicle from the customer after the first-life usage. This life cycle station is similar to collection, recycling, and parts recovery centres in the Comet Circle. Next, there is a company that specializes in producing energy storage systems, here called "2L battery power company", which in this case uses discarded batteries from the OEM. The energy company can be compared with the station of a product manufacturer in the Comet Circle. These two companies are modelled as actors in a use case diagram in the CE model. Between these two entities, another stakeholder is relevant and must be considered. A company capable of transporting batteries from the OEM to the energy company must be involved. The detailed steps of what has to be done with the vehicle at the OEM first, and then with the battery or single battery modules at the energy company afterwards, are modelled in activity diagrams. The activity diagrams are related to a corresponding use case in the main use case diagram indicated by the "fork" symbol. Figure 2 shows these correlations in the "Reuse battery" use case diagram.

According to the activities done by the different actors in the shown use case, requirements for the processes in general, like “Removing the battery damage-free”, and also specific requirements for the technical system that is the battery like “Min. SoH for Reuse” can be derived by either looking at the modelled activities or the previous modelled requirements. The requirements are connected to a corresponding use case to trace the source and, therefore, allow the handling of any upcoming changes or new aspects of the system. The CE model will ensure that further handling these requirements is always comprehensible for involved persons in the development. All the information discussed is implemented into the use case diagram that is shown in Figure 2. The circular loop for the battery example is closed, and stakeholders involved are described. Corresponding use cases and activities are connected with specific requirements that arise from the stakeholders’ needs and actions.

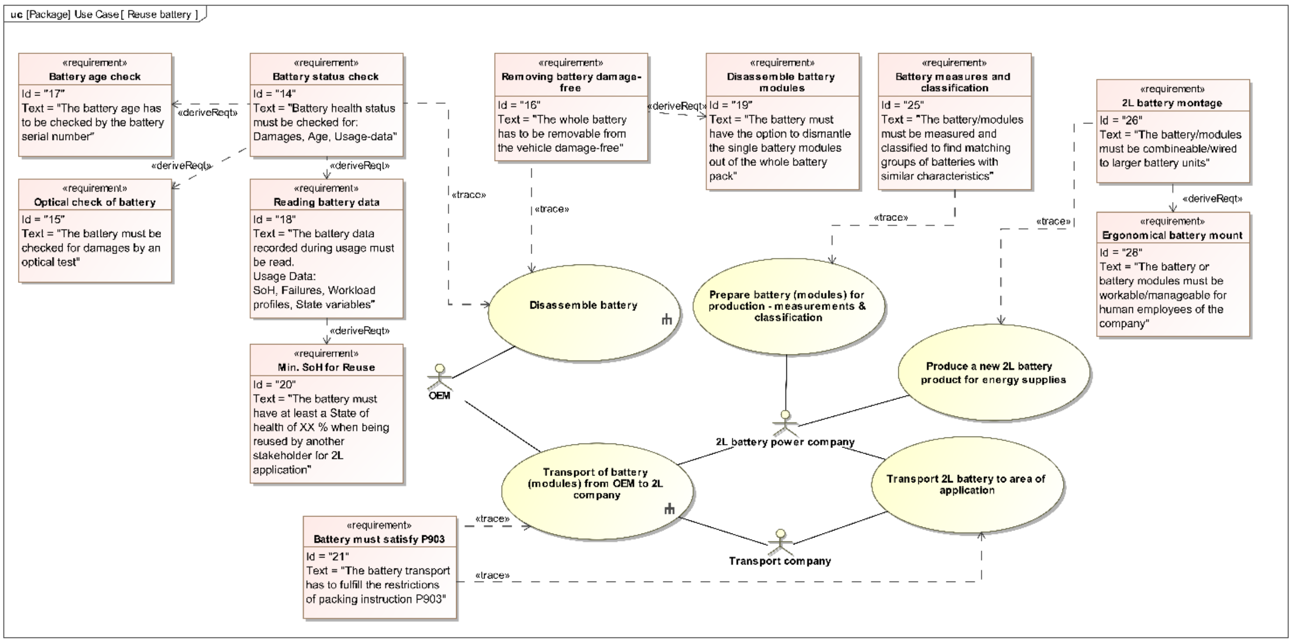

Figure 2. Use cases and derived requirements of the Circular Economy (CE) model

Finally, the gained requirements from the battery example can be linked to the general vehicle model. The main objective is to transform and link the requirements gained with the CE model into the vehicle model for a better understanding and a potential “Design for Second-life” of the vehicle battery in this case. The new design of a battery in a vehicle system could be part of an upcoming engineering challenge, for which the CE model usage provided the relevant information in form of stakeholder needs. Figure 3 shows the two models next to each other on the highest model level view with Sys ML. The main vehicle model consists of the three pillars described at the beginning of the chapter and the System of Interest is the vehicle. The CE model inherits the Comet Circle, stakeholders, use cases, activities, and requirements modelled with the Sys ML diagrams available for that. Some of the determined requirements can be directly inserted into the base model of the vehicle, as they fit into as system requirements, e.g., for the battery component. Other requirements could be more process-related ones that must be discussed in a responsible development team first and then could be transformed into the vehicle model as system requirements on the next detailed level. This steps needs to be done as it is a typical procedure in early development phases when stakeholder needs are gathered and transformed in requirements to be fulfilled.

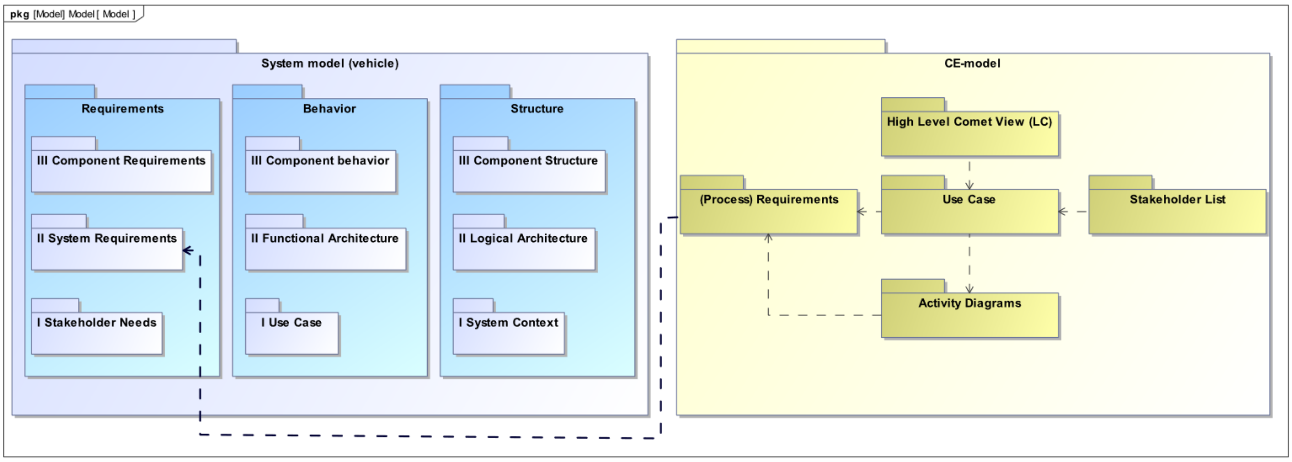

Figure 3. Vehicle system model and Circular Economy (CE) model

5 Conclusion, Discussion & Outlook

This paper presented an approach for extending a development model, which was created according to the principles of Model-Based Systems Engineering, with methods and strategies of the circular economy to map a more circular product life cycle and capture information as possible new inputs in the development process. By this, possibilities and benefits for expanding the lifetime of a product for secondary use cases after the main usage phase can be found early in the development process. By that, the planning for a next life cycle phase whilst handling additional stakeholders and needs after the primary usage is supported.

Due to the increasing complexity of vehicle development projects, a model-based development approach (MBSE) is particularly suitable, as more circular products also mean an increase for stakeholders, associated processes and correspondingly further requirements to consider.

A primary vehicle model is extended with the invented CE model in this paper. The CE model reflects Ricoh's Comet Circle approach at the highest level of consideration and thus as a starting point for analysis on a high level view, early in a development. Based on this, different components/subsystems of a product/system can then be examined and modelled next to the processes of the Comet Circle. In this paper, a battery electric vehicle (BEV) is selected as the application example, and the traction battery is focused as a component to increase the circularity through reuse in a potential second-life usage.

The extended view using the CE model is a cross-domain approach for product development. In this case, however, an initial criterion for the search of a circular life cycle base model was the suitability for use in the automotive development domain. In addition, the chosen circularity model should describe those aspects that can be adapted with the MBSE approach, such as the stakeholders and the corresponding processes in the Comet Circle do.

The modelling for the battery example showed that the principles of the top-level view with the CE model help to consider and connect possible stakeholders along a circular life cycle. The second-life (SL) battery reuse was an example of handling one specific vehicle system component. The stakeholders for the SL application follow the circular path of reusing the parts with additional product manufacturing. Looking further into the details of this process, several requirements can be noted, either direct system requirements or more indirect process-related requirements. Modelling the processes with SysML behavioral diagrams and elements like use cases and activities allows to connect the stakeholder stages and the corresponding actions to specific requirements for the second-life battery reuse to a closed loop with traceability along the chain. When comparing these results from the CE model to the base vehicle model, the requirements show the necessity of possible adjustments of the system of interest regarding a more circular product development in a next phase. Nevertheless, there is a need to check and transform new requirements before implementing them into an already existing model. Otherwise, a development team could face dangers like contradictions, or misunderstandings.

When applying such a MBSE approach in practice to model a real complex system another challenge arise while respecting sustainable aspects. Using the CE model can set the objective of developing a new and more sustainable design of the product. However, an existing older product version may only differ in a few aspects to a new one. So parts of the old MBSE model could potentially be reused in some ways for the new design. Shinozaki et al. showed the potential of reusing an existing SysML model for a new product design. Their approach starts with updating an existing requirements set for the new design purpose by adding new, modifying existing, or discarding existing requirements. Due to the linkage and traceability of elements in a MBSE model, associated model elements can be adjusted accordingly. Such an approach will work best in terms of time savings when following a systemically MBSE design approach, e.g. with black box and white box modelling, where the system on black box level should have the most reusing potential. [Shinozaki et al., 2017]

Further, Eckert et al. discussed the topic of handling design margins in the development and stated that especially when designing complex systems, that the process is often iterative and the involved development domains or departments work with margins so they are able to react to later demanded change requests and reduce further iterations needed. In addition, a potential overdesign, as a special form of margin, is discussed and the fact that overdesign is used in practice, where it is less critical for products characteristics. Overdesign can play a significant role to improve a product design, e.g. when following sustainable objectives lead to new or adjusted requirements set, as some of the components could be able to fulfill those new or adjusted requirements. [Eckert et al., 2019]

The CE model approach can be compared to the step of gathering new stakeholders, processes and related requirements, and then finding new design solutions and perhaps adjust an existing model afterwards. Here, the benefit is created by finding and tracing secondary usage possibilities in a first stage and linking them to existing or potentially new build models.As mentioned, the CE model approach was first developed concerning an implementation in the automotive development domain. Currently, there are no findings yet from a real life application of the CE model approach, this contribution is based on theoretical work. In the future, there should be a practical phase with a validity and usability assessment. The implementation should happen in the concept development team that uses MBSE in practice, and especially the requirements engineering team must be conducted, as they are responsible for collecting requirements. In addition, handling the emerging challenges and options, like the reuse of existing models when they must respect more sustainable aspects in an updated version, should be checked. Regarding further research, it is also recommended to link the CE model with other domains base product models to validate general utilization potential for overall product development.

The battery reuse is one example being modelled to potentially show the options for extending the life cycle of parts in a product. That approach could encourage the shift from a traditional linear "take-make-dispose" model to a more circular and sustainable approach. Investigating and modelling further stakeholders and corresponding processes out of the different paths with different Circular Economy strategies should raise further options for a project team to increase the circularity of system components. By following that, there could occur the challenge for the development team that some parts of a product that are developed initially without a plan for a second-life application can be used for a second-life use case with a suitable adaption according to the found possibilities with the CE model. Whereas on the other hand, some parts may be not usable for a second-life usage and would be discarded on a less sustainable way after the primary usage. Therefore, parts that are not capable of fulfilling such second-life phase requirements within the margins cannot create further value. The benefit of doing so could then pay off in a later application phase.

The CE model in its presented form should raise the awareness of involved parties for possibilities when extending the lifespan of products and show what possible benefit can be found in current or maybe future relevant secondary application phases. By analyzing with the model, a project team is able to find secondary product usages with different kinds of stakeholders being interesting for that. Accordingly, an existing product can be prepared for the next generation, for planned second-life applications and a development team should handle less uncertainty while finding solutions for that. The discussed challenges of reusing already existing MBSE-models or the dangers of extensive design margins and overdesign, have to be considered when following the proposed approach in real life.

In the future, there will probably be an ongoing demand from society for more sustainable products and a tightening of environmental laws by government legislation. Manufacturers of first-life products should look at supporting options to find opportunities for a longer lifespan and utilization period. Thus, the implementation of more circular and new product after-sales options could be forced. MBSE usage and extensions like the presented CE model approach in the presented contribution can help to consider potential stakeholders in the future and handle different needs for optimized product development, handling the complexity, and creating added value for the involved entities.

References

Bundesregierung, 2023. EU-Umweltrat: Nur noch CO2-frei fahren. https://www.bundesregierung.de/breg-de/schwerpunkte/europa/verbrennermotoren-2058450. Accessed: 06.02.24

Bocken, N., Baldassarre, B., Keskin, D., Diehl, J. C., 2023. Design thinking tools to catalyse sustainable circular innovation. In: The Routledge Handbook of Catalysts for a Sustainable Circular Economy by Lehtimäki, H., Aarikka-Stenroos, L., Jokinen, A., Jokinen, P., Kotilainen, J., 1st ed., Routledge as an imprint of Taylor & Francis Group. DOI: 10.4324/9781003267492

Cudok, A., Huth, T., Inkermann, D., Vietor, T., 2017. Life cycle development - A closer look at strategies and challenges for integrated life cycle planning and upgrading of complex systems. Maier, Anja and Škec, Stanko and Kim, Harrison and Kokkolaras, Michael and Oehmen, Josef and Fadel, Georges and Salustri, Filippo and Van der Loss, Mike, DS 87-5 Proceedings of the 21st International Conference on Engineering Design (ICED 17), 209–218, Glasgow, The Design Society. https://www.designsociety.org/publication/39743/Life+cycle+development+-+A+clos…

David, I., Bork, D., Kappel, G., 2024. Circular systems engineering. Software and Systems Modeling, Springer. https://doi.org/10.1007/s10270-024-01154-4

den Hollander, M.C., Bakker, C.A. and Hultink, E.J. 2017. Product Design in a Circular Economy: Development of a Typology of Key Concepts and Terms. Journal of Industrial Ecology, 21: 517-525. https://doi.org/10.1111/jiec.12610

Dori, D., 2016. Model-Based Systems Engineering with OPM and SysML. Springer New York, New York. https://doi.org/10.1007/978-1-4939-3295-5

Eckert, C., Isaksson, O., Earl, C., 2019. Design margins: a hidden issue in industry, Design Science, Volume 5, e9, Cambridge University Press. DOI: 10.1017/dsj.2019.7

EllenMacArthur Foundation, 2024. Case studies and examples of circular economy in action; Examples of the circular economy in design. https://www.ellenmacarthurfoundation.org/topics/circular-design/examples. Accessed: 08.02.24

European Union, 2024. 2050 long-term strategy. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en. Accessed: 06.02.24

Fischhaber, S., Regett, A., Schuster, S., Hesse, H., 2016. Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen Analyse von Nachnutzungsanwendungen, ökonomischen und ökologischen Potenzialen. Begleit- und Wirkungsforschung Schaufenster Elektromobilität (BuW), Ergebnispapier Nr. 18, Deutsches Dialog Institut GmbH.

Friedenthal, S., Moore, A., Steiner, R., 2015. A practical guide to SysML. The systems modeling language. Morgan Kaufmann is an imprint of Elsevier, Massachusetts. https://doi.org/10.1016/C2013-0-14457-1

GETEC, 2016. Weltweit größter 2nd-Use-Batteriespeicher geht ans Netz. https://www.getec.de/de/weltweit-groster-2nd-use-batteriespeicher-geht-ans-netz/. Accessed: 08.02.24

Haberfellner, R., de Weck, O., Fricke, E., Vössner, S., 2019. Systems Engineering. Fundamentals and Applications. Birkhäuser Cham, Switzerland. https://doi.org/10.1007/978-3-030-13431-0

INCOSE, 2022. Systems Engineering Vision 2035. INCOSE – International Council on Systems Engineering. https://violin-strawberry-9kms.squarespace.com/Accessed: 29.04.24

ISO/IEC/IEEE 15288:2023(E). Systems and software engineering— System life cycle processes. Second Edition 2023-05

Konietzko, J., Baldassarre, B., Bocken, N., Ritala, P. (2024). Initiating a Minimum Viable Ecosystem for Circularity. In: Ometto, A.R., Sarkis, J., Evans, S. (eds) A Systemic Transition to Circular Economy. Greening of Industry Networks Studies, vol 12. Springer, Cham. https://doi.org/10.1007/978-3-031-55036-2_4

Kuhnert, F., Stürmer, C., Koster, A., 2017. eascy – Die fünf Dimensionen der Transformation der Automobilindustrie. PricewaterhouseCoopers GmbH Wirtschaftsprüfungsgesellschaft.

Krog, J., ¸ Şahin, T., Vietor T., 2022. Towards a Systems Engineering Methodology for Architecture Development of Vehicle Concepts. Editors: Mortensen, N.H., Hansen, C.T., Deininger, M. DS 118: Proceedings of NordDesign 2022, Copenhagen, Denmark, 16th - 18th August 2022. https://doi.org/10.35199/NORDDESIGN2022.35

Morkevicius, A., Aleksandraviciene, A., Mazeika, D., Bisikirskiene, L., Strolia, Z., 2017. MBSE Grid: A Simplified SysML-Based Approach for Modeling Complex Systems. In: INCOSE International Symposium 27, Volume 27, Issue 1, 136–150. https://doi.org/10.1002/j.2334-5837.2017.00350.x

Opazo-Basáez, M., Vendrell-Herrero, F., Bustinza, O.F., 2018. Uncovering Productivity Gains of Digital and Green Servitization: Implications from the Automotive Industry. MDPI, Sustainability 10, 5: 1524. https://doi.org/10.3390/su10051524

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular economy: Measuring innovation in the product chain. PBL Netherlands Environmental Assessment Agency, The Hague. PBL publication number: 2544. https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pd. Accessed: 06.02.24

Raulf, C.; Proff, M.; Huth, T.; Vietor, T., 2021. An Approach to Complement Model-Based Vehicle Development by Implementing Future Scenarios. MDPI, World Electr. Veh. J., 12, 97. https://doi.org/10.3390/wevj12030097

Ricoh Group, 2024. Comet Circle. https://www.ricoh.com/sustainability/environment/management/policy/comet. Accessed: 06.02.24

Şahin, T., Köster, L., Huth, T., Vietor, T., 2021a. How to Upgrade Vehicles? Release Planning in the Automotive Industry. In: Bargende, M., Reuss, HC., Wagner, A. (eds) 21. Internationales Stuttgarter Symposium. Proceedings, 155-173. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-33521-2_12

Şahin, T., Raulf, C., Kızgın, V., Huth, T., Vietor, T., 2021b. A Cross-domain System Architecture Model of Dynamically Configurable Autonomous Vehicles. In: Bargende, M., Reuss, HC., Wagner, A. (eds) 21. Internationales Stuttgarter Symposium. Proceedings, 13-31. Springer Vieweg, Wiesbaden. https://doi.org/10.1007/978-3-658-33521-2_2

Shinozaki, M., Mhenni, F., Choley, J. -Y., Ming, A., 2017. Reuse of SysML model to support innovation in mechatronic systems design, Annual IEEE International Systems Conference (SysCon), Montreal, QC, Canada, DOI: 10.1109/SYSCON.2017.7934709.

Seidel, M., 2022. Circular Economy in der Automobilindustrie – Die Perspektive eines OEMs. In: Mayer, R. (eds) XXXIX. Internationales μ-Symposium 2022 Bremsen-Fachtagung. IμSBC 2022. Proceedings, 84-86. Springer Vieweg, Berlin, Heidelberg. https://doi.org/10.1007/978-3-662-66328-8_6

Shahjalal, M., Roy, P. K., Shams, T., Fly, A., Chowdhury, J. I., Ahmed, MD. R., Liu, K., 2022. A review on second-life of Li-ion batteries: prospects, challenges, and issues. Energy, Volume 241, 122881, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2021.122881.

Stoewer, H., 2023. Perspectives on SE, MBSE, and Digital Engineering: Road to a Digital Enterprise. In: Handbook of Model-Based Systems Engineering. Madni A. M., Augustine, N., Sievers, M., 1-37. Springer, Cham. https://doi.org/10.1007/978-3-030-27486-3_83-1

Toyota Motor Corporation, 2023. Toyota Revs Up Efforts for Battery 3R to Achieve Circular Economy. https://global.toyota/en/newsroom/corporate/40102076.html Accessed: 06.02.24

Volvo, 2024. Environment and Resources. https://www.volvogroup.com/en/sustainable-transportation/responsible-business/resources.html. Accessed: 06.02.24

Walden, D. D., Shortell, T. M., Roedler, G. J., Delicado, B.A., Mornas, O., Yew-Seng, Y., Endler, D., 2023. Systems engineering handbook. A guide for system life cycle processes and activities. INCOSE-TP-2003–002-05, 2023, International Council on Systems Engineering (INCOSE), fifth edition. John Wiley & Sons Ltd.

Weilkiens, T., Soley, R.M., 2014. Systems Engineering mit SysML/UML. Anforderungen, Analyse, Architektur. Third ed. Dpunkt.verlag, Heidelberg.

Contact: Lars Everding, Technische Universität Braunschweig, l.everding@tu-braunschweig.de