Modeling a sustainability-oriented development process with model-based systems engineering

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Abstract

The shift towards sustainability-oriented product development demands early integration of sustainability criteria, a challenge due to the lack of effective methods and data. Expanding on existing sustainability-oriented development processes, model-based systems engineering is used to model the SDP. The SDP model maps process steps, process objects and information flows. This approach combined with traditional MBSE methods ensures cohesive documentation and integration of sustainability data across various development stages and domains. Illustrated with the example of a battery case for a battery electric vehicle, our approach establishes a solid foundation for future sustainable PD by linking distributed sustainability information and parameters on process and product level.

Keywords

Product Development Process, Sustainability, MBSE

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1. Introduction

Product development (PD) and product development processes (PDP) are currently confronted with the transition from traditionally technically and economically driven development to sustainable and recyclable products with minimal use of resources (e.g. lightweight design) and emissions like the CO2-equivalent (CO2e) [1, 2]. In many industries, this development is accompanied by technological disruptions, like the switch from conventional drive systems to electric drive systems in the automotive industry. To date, sustainability criteria are usually only considered in late phases of development, leading to costly and time-consuming changes. Sustainability assessment during development is particularly challenging in the early stages due to a lack of suitable processes, methods and information.

In order to establish sustainability-oriented PD, sustainability-related methods [3, 4] and parameters such as sustainability criteria (e.g.: green house gas emissions (GHG-emissions), repairability or recyclability) for evaluating designs or life cycle assessment (LCA) results must be integrated into the development process. This leads to the sustainability-oriented development process (SDP) by extending classic development processes [5]. This process includes additional process steps and milestones with the goal to develop products optimized towards sustainability. Accordingly, new information must be integrated into the development process and managed digitally to better understand and support decision making in the development process. One approach for linking the relevant information is to model the SDP and the information generated along the SDP using model-based systems engineering (MBSE). This publication describes results of the project "Digitalization for Sustainability" – DigiTain. The results and examples are part of the development of a prototypical hybrid battery electrical vehicle (BEV) with a high voltage battery system and a fuel cell unit utilizing digitalization- and sustainability-oriented methods.

2. State of the art

2.1. PDP and sustainability - SDP

The VDI 2221 guideline represents a valuable orientation for the methodical development of technical products and systems. It defines a general model for product development, comprising systematic phases, objectives, requirements, activities and results, and provides recommendations for suitable methods. The model abstracts a real development process and serves as a general guideline for interdisciplinary application in industry. Following an initial planning phase, the guideline suggests the division of the development process into work steps, each of which produces intermediate results [6].

In order to structure the development process, individual activities are typically grouped into phases, which allows for the creation of organisational or time schedules. It is important that the requirements of each phase are clearly linked to one another, as this enables the assessment of potential effects of errors and changes to be conducted more efficiently. Consequently, activities that are linked to the aforementioned requirements must be documented continuously or at certain intervals [6, 7]. This is the case with the stage-gate approach (Chapter 3.1), whereby a project review is conducted, documenting obtained results [6].

Due to the coevolution of problems and solutions in systems, it is common practice to process product development activities iteratively. The iteration steps serve to explore, converge, refine, improve and resolve conflicts between various partial solutions, whereby new requirements and definitions can arise [2, 6, 8, 9]. In the V-model according to VDI 2206, which can also be used for product development, the phases are not required to be executed in a strictly chronological or sequential manner. Compared to the less complex stage-gate approach this allows for more room for iterations [10]. As the integration of sustainability and the use of an MBSE approach in the PDP are at the forefront of the project, the more linear stage-gate approach was chosen.

As previously stated, incorporating sustainability aspects, e.g. the ten golden rules or a maximum CO2e, into the early stages of product development is particularly challenging. However, based on the common assumption that around 80 % of a product's environmental performance is determined during these stages, it is evident to utilize the considerable room for manoeuvre in these stages to integrate sustainability [2, 11, 7]. Approaches that consider this circumstance can be grouped under the umbrella term of Design for Environment (DfE), whereby the so-called top-down approach integrates sustainability considerations from the perspective of the development process. Important prerequisites for the application of such an approach include a database of components and materials, a clearly allocated space for environmental aspects in the development process, the definition and testing of the product's environmental compatibility requirements and an overview of applicable eco-design strategies and methods [11]. As Diaz et al. found by interviewing product developers and sustainability experts from different enterprises, although there are a large number of methods that relate to sustainability or implement sustainability, these are only used with restraint in industrial developments [2]. Buchert et al. analyze, categorize and compare a selection of such tools and methods and emphasize the need for holistic approaches using existing methods [12]. Kupfer and Schilling present a sustainability-oriented development process (SDP) with options for integrating sustainability aspects into the PDP and, due to the complexity and systemic nature of the SDP, propose a digitally linked development such as MBSE [5].

2.2. Sustainability in MBSE and process modeling approaches

MBSE is a model centered approach to systems engineering [13]. There are already many approaches for integrating sustainability into classic system models. Bougain and Gerhard describe possibilities for integrating sustainability criteria such as GHG-emissions as parameters of the system elements [14, 15]. Eigner et. al. use MBSE as a backbone for system lifecycle management and use the possibilities of the systems modeling language (SysML) for modeling use cases and parameter diagrams to determine the energy consumption of cybertronic systems [16, 17]. Inkermann assigns suitable MBSE methods to the LCA activities, which can be used to support the LCA [18]. Delabeye et. al. use MBSE to improve the sustainability of manufacturing processes [19]. Schweitzer et. al. propose the Engineering Graph as an extension to MBSE models in order to achieve a better link to sustainability-relevant data in domain-specific systems, product life cycle management/product data management (PLM/PDM) systems or enterprise-resource-planning (ERP) systems [20].

In MBSE, the modeling of processes is typically assigned to the area of system behaviour and is for example implemented in SysML trough activity diagrams. Konrad et. al. link MBSE system models with BPMN [21]. Another alternative to describe processes are event-driven process chains (EPC) [22]. The EPC can be expanded to include swimlanes that include data processing activities in the involved software tools. Processes can also be modeled with flowcharts according to DIN 66001 [23] or integration definition for process modelling (IDEF0) according to ISO/IEC/IEEE 31320 -1. The process modeling approaches mentioned above all focus on the activities or process steps, but the description of the process objects is limited. SysML activity diagrams, for example, provide objects and data storage, but these do not have any properties or options for referencing the respective documents. The link to the system model and its parameters is also not usually provided. Konrad et. al. create the link between BPMN and MBSE via a PDM system [21]. Richter et. al. understand processes as separate systems and describe a MBSE modeling approach that allows the definition of parameters for each activity/process step and each process object and manage the resulting documents in a PLM/PDM system [24].

This article explicitly addresses the possibilities for modeling the process with a MBSE approach using SysML and treats the following research questions:

How can MBSE be used to model the SDP? How can the information generated in the SDP be linked using MBSE and made accessible to the domains involved, particularly for the sustainability assessment?

3. Concept for a SDP and MBSE approach

3.1. Top-Down / Bottom-Up approaches and Stage Gate in SDP

The general approach of the SDP in this paper is grounded in the VDI 2221, the SDP concept proposed by Kupfer et al. [5], and a combination of the Top-Down and Bottom-Up approaches presented by McAloone et al. [11]. This methodology distinguishes three distinct levels: the process level, the product level, and the sustainability level as seen in Figure 1.

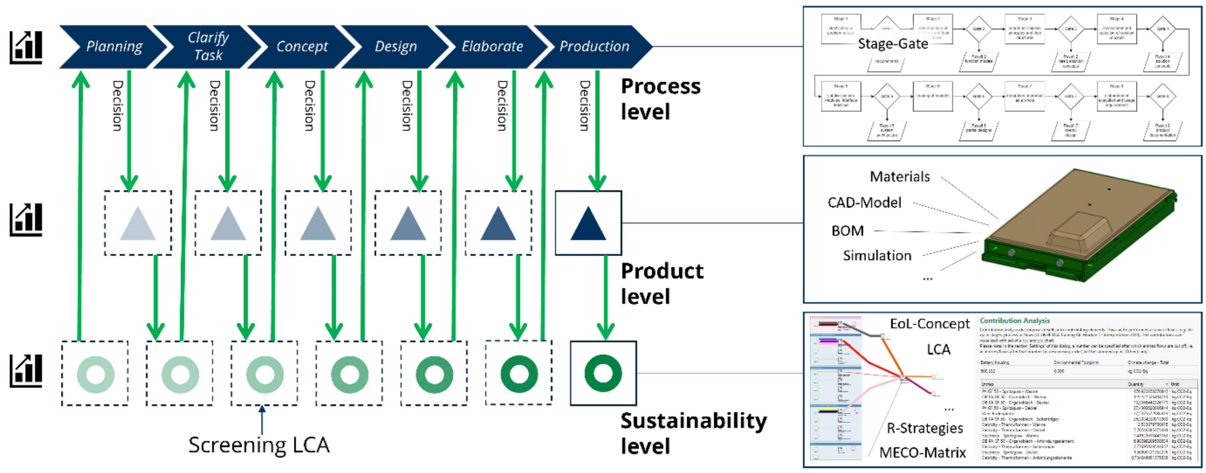

Figure 1: General structure of the SDP used in this paper

At the process level, all activities related to the PDP are carried out, which include the methods of conventional PDP. The product level involves the management of models and data concerning the description of the product system. These models and data serve as inputs and outputs for methods within the process level, as well as for methods and models within the sustainability level.

The sustainability level sets the SDP apart from the traditional PDP. It involves handling methods, models, and data related to describing the sustainability of the product. This includes methods such as LCA and its respective models and data like the environmental footprint or product circularity. For each phase of the SDP, there are corresponding methods, models, and data within both the product and sustainability levels. For instance, in the concept phase, there might be a CAD-model and a bill of materials (BOM) at the product level, alongside a screening LCA with a preliminary GHG-emission value. The quality and quanitity of these methods, models and data increases with each subsequent phase of the SDP.

Each phase of the SDP involves decisions that directly impact both the product and sustainability levels, which, in turn, influence subsequent decisions in the next SDP phase. The objective is to establish a systematic approach to making information-driven decisions based on data from the product and sustainability levels.

Companies use stage-gate procedures as a tool to plan and control the PDP as well as for in-process quality control [25–27]. To apply the stage-gate approach, the activities of the PDP are divided chronologically into different phases, which are finalized at critical points by gates or quality gates [6, 26]. Phases can be, for example, the process phases mentioned in VDI 2221-1 or other summarized activities. Quality gates are control points at which requirements or measurable KPIs agreed by process suppliers and process customers are checked [26, 27]. The objective is to ensure that designs at the respective stage of the PDP are sufficiently developed to commence the subsequent process stage. This approach helps to minimize the potential for costly backtracking and iterations [8, 27]. In comparison, milestones are typically time-bound and indicate the completion of a work package without the necessity of fulfilling specific metrics or requirements [27]. The results of the review of the requirements for the respective phases carried out at the gates are documented in the form of project reviews [6, 27]. In order to facilitate integration, the stage-gate procedures are adapted to the processes and interfaces established in the company [25].

Figure 2 shows the generic structure of the 2nd generation stage-gate model used in the context of sustainably designed components (for the project DigiTain). The project review is conducted using a template form, which is tailored to each phase or gate. The form contains specific details of the variables received that are included in the respective phase, as well as the corresponding outgoing information and its types (e.g. CAD model, simulation results, design solutions, Excel lists, etc.). In addition, the involved development partners, specific requirements of different categories and version numbers for tracking changes to the document are recorded.

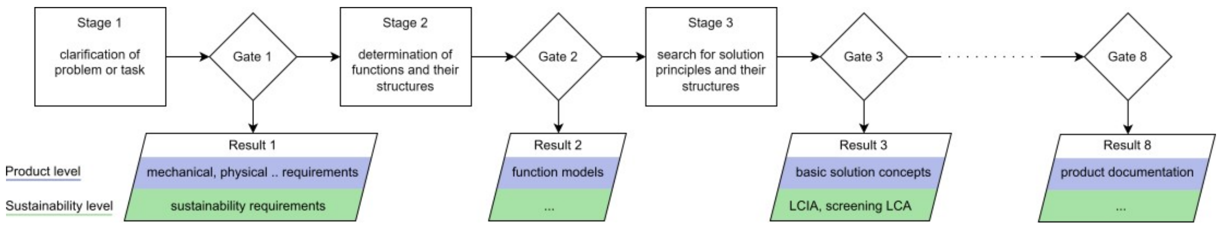

Figure 2: Generic Stage-Gate structure based on VDI 2221

The sustainability-related criteria to be checked in the gates can be drawn from the impact categories for life cycle assessments, such as global warming potential. For instance, specifications such as a limit for the CO2e, the utilisation of non-toxic materials, or the maximum mass of a component and its suitability for recyclability can be defined quantitatively or qualitatively. If a requirement cannot be met, the corresponding solution concept must be adapted accordingly in order to fulfil the requirement and pass the gate.

3.2. MBSE modeling concept for the SDP

The approach to modeling the SDP in MBSE is to understand a process as a system according to our previous publication [24], while following the modeling concepts of established process modeling approaches, see Chapter 2.2. In the general MBSE approach activities/process steps and process objects are interpreted as system elements which have parameters and interactions between each other. The used semantics are based on various standards and guidelines (DIN EN ISO 14067, VDI 2243, DIN EN 45557, DIN EN 45554, DIN 6789, VDI 2221, Catena-X Product Carbon Footprint Rulebook) and existing ontologies (Life Cycle Assessment Ontology, Platform Material Digital Core Ontology). Analogous to Figure 1 the process level - in this case the SDP - is modeled with this approach as the process model. The modeling of the technical system on the product level followes traditional MBSE approaches and results in the technical system model. During the SDP *documents* and *components* are created in domain specific systems (e.g. RQM-, CAD- or FEM-systems) or physically manufactured and typically managed in PLM-/PDM-systems. *Components* describe a constituent part of a product, such as a part, an assembly, a subsystem or a used material. *Documents* contain the information and data that is generated or used in the process [24] and consist of a single file or a group of files as data set. Examples for *documents* are requirements documents, standards, CAD-models, simulations, LCA-reports or manufacturing documents.

In the concrete implementation, SysML blocks (*process blocks*) serve as system elements for modeling the process model. These blocks represent activities/process steps and contain parameters in the form of properties or values, as well as proxy ports that can be used to show realize interactions between the system elements and map the flow of information through the process. The base *process blocks* are the 8 stages according to Chapter 3.1. It is also possible to define sub-processes utilising internal block diagrams and further differentiate the modeled process, if needed. Gates can also be modeled as *gate blocks* with proxy ports and boolean values that represent the results that need to be delivered to pass the gate. In order to manage and document the development process consistently and to enable future analysis and well-founded decision-making, additional blocks are defined that serve as process objects (*input/output block*) for the *process blocks*. These *input/output blocks* represent the mentioned *components* and *documents*. Both types of *input/output blocks* also contain metadata that is modeled as properties/values and proxy ports to model the information flow. *Document* blocks only provide a reference to the actual articles/documents that are managed in the PLM/PDM-systems, while creation and manipulation of data is handled in the domain-specific authoring systems. Finally, it is necessary to link parameters that the documents contain to specific parameters of the technical system model. For this task a *value object* is defined, this block contains the properties ID and Type and can be connected to *documents* and *components*.

Using this approach, process chains can be modeled, see Figure 3. The defined template blocks for an activity/process step (stage), a *component* or a *document* are intended to be used as parents (generalization) for new blocks, to inherit the properties/values. Furthermore, the use of SysML stereotypes should be considered in a corporate development environment, to further differentiate the process model and the system model. The sustainability level is also part of the MBSE approach. While the process model establishes links to sustainability-relevant documents, specific values can be included in the system model by utilising the sustainability-oriented properties/values of the *component* block, e.g. mass, GHG-emissions, secondary material use or repairability, see Figure 3. The sustainability level can also be included in other parts of the technical system model such as requirements, use cases, test cases or parameter diagrams. As the MBSE model is completely machine-readable, it provides a promising basis for assisted analysis (e.g. through graph analysis and machine learning) and process optimization or adaption to new challenges.

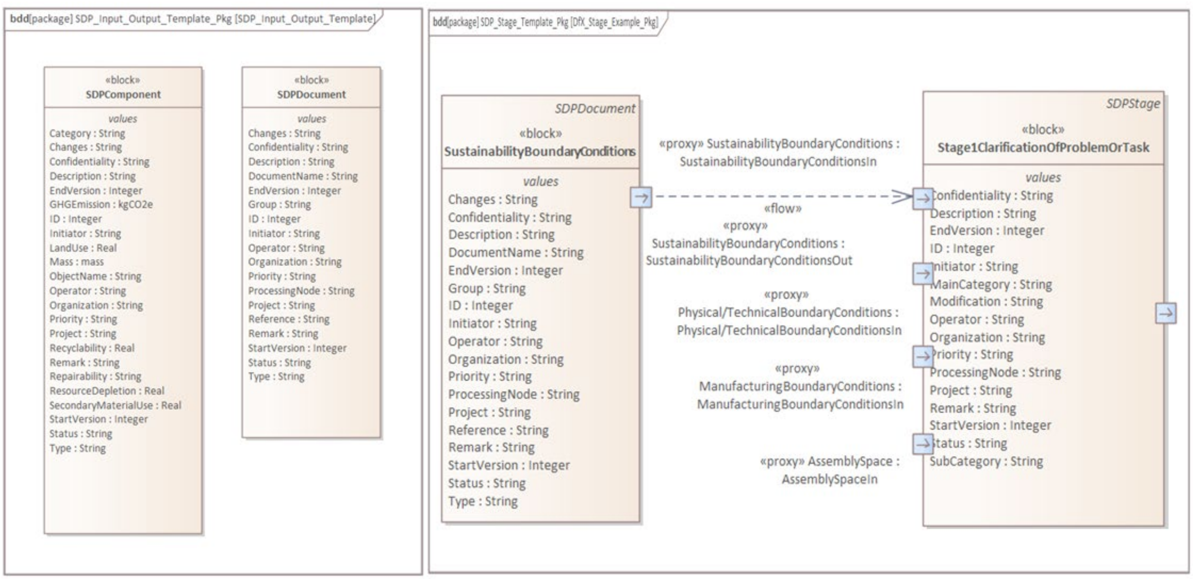

Figure 3: MBSE modeling concept SDP, left: the *input/output blocks - document* and *component*, right: simple process chain example using *document* and *process blocks*

4. Application and results

4.1. Example battery case

For demonstration purposes an example use case for a product is defined. The chosen product is a BEV battery case, shown in Figure 4.

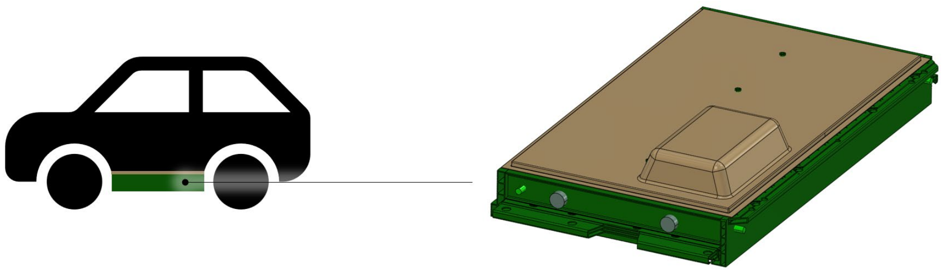

Figure 4: Example use case - BEV battery case

In a BEV, a traction battery serves as the primary energy storage system. This paper focuses on the battery case, whose main purpose is to securely enclose the battery modules along with the electrical and thermal networks. Specifically, the battery case is mounted to the bottom of the vehicle and includes thermal and electrical connectors that integrate with the vehicle's systems. The battery case performs three essential functions:

1. Ensuring safe operation under mechanical loads during vehicle operation.
2. Providing sealing against environmental factors.
3. Preventing the intrusion of objects into the battery modules during collisions.

Requirements for the battery case are derived from a reference system and encompass mechanical, thermal, electrical, packaging, economic, and sustainability considerations. The interfaces for mechanical, electrical, and thermal connections are predefined by the existing vehicle system. The goal is to develop a sustainability-oriented battery case within these defined requirements, utilizing the SDP.

The final design of the battery case has significant potential to influence the overall environmental footprint of the BEV. The choice of materials and manufacturing processes can greatly impact the environmental footprint during the raw materials extraction and manufacturing phases. Enhancing the robustness of the case can extend the battery lifespan, thereby increasing the operational life of the vehicle. Additionally, the mass of the battery case affects the energy required to move the vehicle; thus, lightweighting the case can result in substantial energy savings over the entire vehicle lifecycle. The design also directly influences the repairability and recyclability of the battery case and its components. Design for recycling or repair strategies can therefore greatly reduce the environmental impact during the End-of-Life phase through improved recycling efficiency and reduced energy requirements.

Numerous design variables of the battery case have the potential to significantly impact the environmental footprint of the vehicle throughout all lifecycle phases. Consequently, the battery case serves as an ideal case study for investigating the application of MBSE methods for modeling the SDP.

4.2. Modeling the SDP for the BEV battery case

The development of the BEV battery case uses the SDP and is modeled utilizing the concepts described in chapter 3.1. The process model uses instances of the blocks as the model describes specific process steps and process objects for the specific SDP of the BEV battery case. Additionaly a tradional technical system model is created mainly focusing on the structure and requirements of the BEV battery case. The process model is an abstraction of the real development process and does only include the main stages and development results. Iterations are currently not shown in the model. However, it is possible to integrate subprocesses and iterations in the model, if needed for specific analysis tasks. The granularity of the process modeling must be decided depending on the considered product, the development focus and the purposes that are pursued with the process model. As the process model is too extensive to be described in full, stage 6 is described in detail, see Figure 2.

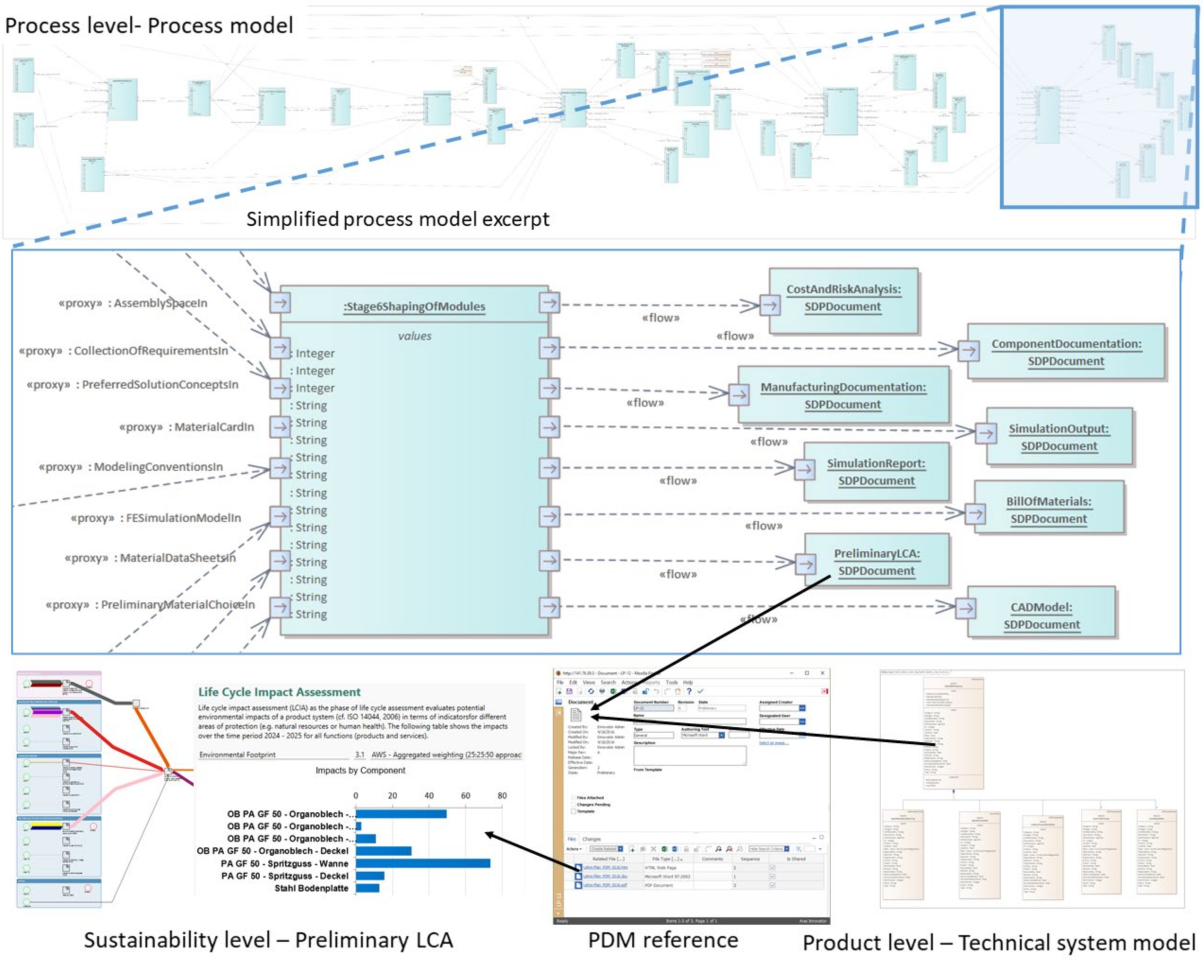

Figure 5: top: MBSE SDP process model for BEV battery case, bottom: representation and relationships of Top-Down and Bottom-Up approach levels

Stage 6 of the SDP is the “Shaping of modules” for the BEV battery case. As a later stage in the SDP it depends on and uses many documents of the previous stages. These are for example the assembly space and preferred solution concepts (other solution concepts are also documented in the SDP), as well as simulation focused inputs like material cards, the FE simulation model itself. Aspects of sustainability are part of the collection of requirements (technical, manufacturing, sustainability) and the preliminary material choice, but are also part of material data sheets e.g.: as GHG-emissions from databases like ecoinvent.

The outputs of the stage are mainly technical oriented and include the component and manufacturing documentation, CAD-models and the BOM and simulation output data as well as a simulation report for the BEV battery case. The main sustainability-oriented result document of this stage is a preliminary LCA for the developed solution.

Sustainability criteria are also integrated troughout the SDP like sustainability boundary conditions as input for Stage 1 the “Clarification of problem or task” which lead to requirements in the collection of requirements (e.g.: requirement list or in MBSE or RQM system). In Stage 4 “Assessment and selection of solution concepts” a preliminary material environmental footprint is calculated for the solution concepts.

The resulting process model serves both as a guideline for the creation of the technical system model in the SDP and as documentation of the activites/process steps, including their process objects. The process model offers the possibility of linking distributed, sustainability-related information and a basis for decision-making for future developments on the foundation of development projects that have already been completed and recorded as a process model. The creation of the process model can be performed alongside the development process when developing with MBSE. Trough the parameters each system element can contain a reference to an article and/or the associated document in a PLM/PDM-system. In this way the process model and technical system model can be linked on a document level, see Figure 5. The mentioned *value object* block can be used to implement the link on a parameter level, which is needed for an efficient use of MBSE in the SDP. The actual implementation of the described connections relies on software connectors between MBSE-system, PDM-system and domain specific software tools and is not described here.

5. Conclusion and outlook

Developing sustainability optimized products in a SDP is a difficult task that requires the implementation of additional activities and information in the development process. The concept for a SDP utilizing combined Top-Down and Bottom-Up approaches, as well as the Stage Gate approach of VDI 2221 explicity implements sustainability-relevant methods and information into the process. This sets the SDP apart from a traditional PDP, as sustainability related activities and results are required at an early stage of the development to pass on to later stages. MBSE is a suitable approach to handle the complexity and interconnectivity associated with the described SDP concept. The modeling of a process model in addition to the technical system model and the incorporation of sustainability ctriteria in the system as well as the process model offers a promising basis for sustainability-oriented product development. The described approach to modeling the process model in MBSE using SysML syntax enables the machine-readable description of a SDP and the results of the SDP. The results can be linked to the system model and its parameters as well as to documents that are produced in the SDP and managed in PLM/PDM-systems. The application of the approach is demonstrated for the example of a BEV battery case.

The process and results of the SDP, combined with a robust system model, are essential for underpinning future development decisions to improve and accelerate sustainability-oriented product development. Understanding why and how decisions were made during development is crucial for this integration. This understanding can be achieved by documenting the development process and the results, creating a comprehensive knowledge base. The described approach offers a way to structure and build this knowledge base, acting as a basis to support decision making with graph databases or machine learning. The described potentials will be investigated in future publications.

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