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Digital engineering transformation for sustainability: an approach to systematically integrate sustainability data in engineering processes

Fabian Wyrwich [1,✉], Ulf Könemann [1], Denis Tissen [2], Tinus Bohnenkamp [1], Aschot Hovemann [1] and Roman Dumitrescu [2]

[1] Fraunhofer Institute for Mechatronic Systems Design (IEM), Germany, [2] Paderborn University (HNI), Germany

✉ fabian.wyrwich@iem.fraunhofer.de

ABSTRACT: Digital engineering transformation in industrial companies requires addressing diverse needs and their impact on every impacted engineering aspect. This paper analyses Changes initiated by transformation drivers and presents a systematic approach to integrate sustainability into engineering processes and artifacts. As a currently important topic the integration of sustainability data in engineering is used as an example of application. Based on identified use cases, sustainability parameters are derived and linked to engineering data objects to pinpoint their placement within the early product development. The results demonstrate how data-driven approaches enable effective sustainability integration and provide a foundation for future digital engineering transformations due to diverse divers.

KEYWORDS: systems engineering (SE), sustainability, digital engineering transformation, design process

1. Introduction

The digital transformation has been a topic of research for a long time now and the number of scientific publications is steadily rising since 2011 (Dombrowski & Fochler, 2018). It is defined as the application of digital capabilities to processes, products, and assets to improve efficiency, enhance customer value, manage risk, and uncover new monetization opportunities (Schmarzo, 2017). It therefore enables companies to adapt to changing conditions.

Moreover, in many manufacturing companies, the focus is on engineering since it plays an important role in the value creation of the development and manufacturing of technical products. Because the engineering must also constantly adapt to new conditions, the digital engineering transformation is the application of the digital transformation principles to the engineering domain. In this context, the transformation deals with the way complex systems are designed, developed, delivered, operated, and maintained in a vast and changing threat environment (Zimmermann et al., 2019). This call for a change in traditional technical practices in the development and procurement of systems is necessary to counter new threats, maintain superiority and capitalise on technological progress (Baldwin, 2017).

A number of initiatives and plans for digital engineering transformations already exist (Department of Defence Canberra ACT 2024; Hill et al 2024; Palacios & Lerner 2022; Zimmermann et al., 2019). However, these only describe the transformation of engineering at a strategic and overarching level, so that the focus is on objectives and capabilities. There is therefore a lack of concrete recommendations for action or approaches on how and where engineering must specifically adapt in order to counter new threats and integrate new processes, methods and content.

Integrating new processes, methods and content into an existing engineering requires a systematic approach that precisely identifies the problem space and analyses all dependencies to develop the best possible solution. Systems Engineering (SE) offers this approach. SE takes a holistic view of a system to create multidisciplinary solutions. The goal of SE is to communicate a unified and comprehensive understanding of the system to all stakeholders involved (Walden et al., 2015). Thus, Systems Engineering is a central and necessary core competence to analyse and consider the interdependencies within a digital engineering transformation (INCOSE, 2035).
In this case, the system of interest (SoI) is the digital engineering, which must be developed. System development usually starts with a development order. With the transformation of digital engineering as SoI, a transformation driver takes on the role of the trigger or the order. Transformation drivers are characteristics that influence and enable the transformation process to take place (Morakanyane et al., 2017). In the general field of digital transformation, the transformation drivers can be divided in different categories, like experience enhancement, process improvement, technologies, or others, like legal regulations (Levkovskyi et al., 2020). However, most digital engineering transformations deal with the introduction of new technologies, like artificial intelligence, cloud technology or virtual/augmented reality, as they have a major impact on the performance and the efficiency of the engineering.
To integrate the contents of the aforementioned transformation drivers into digital engineering, a systematic approach is needed that identifies the transformation driver dependent necessary and affected data points and information at the application level and takes their dependencies into account. This paper presents such an general approach inspired by SE.
The approach describes how necessary parameters to be integrated are derived on the basis of use cases and assigned to suitable data objects and how the dependencies of these data points can be modelled. The integration of sustainability data into digital engineering serves as an exemplary and current transformation driver, on the basis of which the application and results of the approach are presented. Driven by climate change, resource scarcity, and societal as well as political demands, sustainability is increasingly coming into the focus of engineering (Eigner & Schäfer, 2014). The European green deal, with the aim to be the first climate neutral continent by 2050, shows the relevance of this topic (European Commission, 2019).

2. Research design and objectives

The development of the SE inspired approach for analysing and implementing a digital engineering transformation followed the Design Science Research Methodology (DSRM) according to Peffers et al. (2007). The DSRM process consists of a total of six steps and various research entry points. Since the problem of a missing systematic implementation of a digital engineering transformation on a suitable level of detail and the lack of mapping of dependencies was identified, the problem-centred initiation is the entry point into the DSRM in this case. The problem identified and the motivation for this research have already been given above. This leads to two research questions, which, although they address the integration of sustainability data, can also be applied to other transformation topics:

1) *How can sustainability be integrated digitally in the engineering domain systematically?*
2) *How can the dependencies of the sustainability integration be modelled?*

In the following the approach and the research results answering these questions are presented. In addition, the results are demonstrated and evaluated to show the applicability of the results and to critically scrutinize them.

3. Design and development

The general approach to integrate new content, like sustainability data, into digital engineering is divided into four steps and is shown in Figure 1. The first two steps are used to describe the problem to be solved and the last two steps to describe the solution. In each of the four steps, elements are analysed, described, or derived in different ways and linked to the elements of the previous step. Different methods are used for each process step to generate the content and consolidate it into result artifacts.

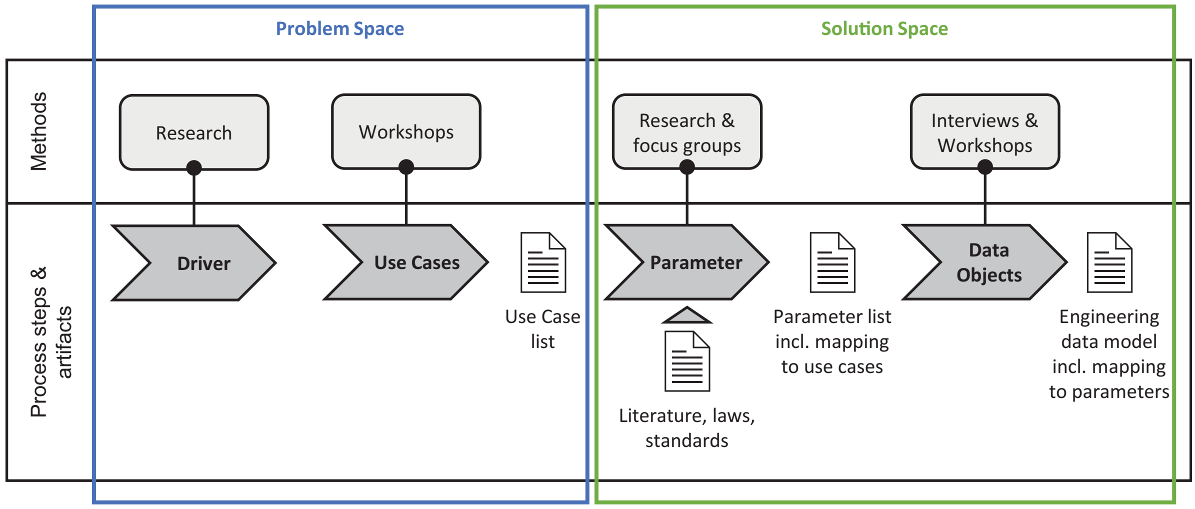

Figure 1. General approach for integrating new content into digital engineering

The first step is to identify the transformation trigger or transformation driver with the help of research. In the selected example in this paper, this has already been determined with the integration of sustainability data, which is why this step is not considered in more detail below. The second step deals with the identification and description of use cases. As a consequence of the selected sustainability example, the use cases include actions that are to be carried out with the sustainability data or for which the sustainability data is to be used. After creating a use case list, the third step is to derive parameters that are necessary to realize or implement the use cases. These parameters serve to make sustainability quantifiable and measurable. In the fourth step, the sustainability parameters are assigned to the data objects that provide the necessary information and data. Among other things, a generic engineering data model is used for this, which provides an overview of the existing data objects and their interdependencies. Finally, this four-step procedure is used to derive which parameters and data objects are required or need to be supplemented to realize the use cases formulated in dependence on the transformation drivers at the beginning. The individual steps and their content-related results in the context of sustainability integration are discussed in more detail in the following subsections.

3.1. Use cases

The second step overall and the first step after the identification of the transformation driver is the identification and description of sustainability use cases. The objective of this use cases is to provide developers with potential sustainability directions and preselection options to support them to identify the necessary parameters and data objects. These use cases are often company-specific since different companies from different industries must fulfil different requirements and have different goals and possibilities regarding sustainability. Since the entire procedure was developed within a research project with six industrial companies and three research institutes, the uses cases were developed in joint workshops. In these workshops the circularity strategies of Potting et.al. (2017) and the circular design strategies by Franconi et. al (2024) have been taken into consideration to identify sustainability use cases. To find a common solution, the use cases were described as specifically as possible and as generically as necessary. This was to ensure that the interests of all participating companies were represented and considered. Furthermore, for each use case, in addition to a description, challenges were identified, possible examples documented, relevant stakeholders defined, and an alignment with the circularity strategies by Potting et al. was carried out. The final collection of use cases consists of 28 sustainability use cases, which are listed in Table 1. These use cases cover almost all life cycle phases of a technical product, so that many stakeholders, parameters, data objects and tools are involved in the further course of implementing these use cases operationally. For example, it should be possible to select sustainable materials or develop products with increased modularity, which is done at a very early stage in the life cycle. Production is also represented by the reduction of emissions and energy consumption. Finally, the end-of-life phase is also considered, including the use cases for reuse and recycling.

Table 1. List of identified sustainability use cases

ID	Name	ID	Name
UC1	Selection of sustainable materials	UC15	Optimization of material usage
UC2	Energy-efficient product design	UC16	Optimization of the material flow
UC3	Development of products for easy recycling	UC17	Optimization of packaging materials
UC4	Development of products for easy reuse	UC18	Reduction of emissions in production
UC5	Increasing modularity	UC19	Reduction of energy consumption in production
UC6	Identification of emission drivers	UC20	Reduction of water consumption in production
UC7	Sustainable use recommendation	UC21	Reduction of waste & scrap in production & in use
UC8	Sustainable maintenance and servicing	UC22	Reduction of toxic, hazardous auxiliary substances/materials
UC9	Sustainability optimization of company locations	UC23	Simulation of energy flows
UC10	Tracking/documentation of the packaging/the packaging concept	UC24	Extending the useful life of products
UC11	Proof of sustainability certificates/audit	UC25	Use of second-life components/materials for another purpose
UC12	Use of the digital twin for the simulation and development of products/systems	UC26	Use of second-life components/materials for the same purpose
UC13	Use of digital twins for monitoring and optimization	UC27	Reuse of production/test equipment
UC14	Optimization of the logistics/supply chain	UC28	Reuse of production waste

Overall, this list provides an overview of many, but not all, sustainability use cases that companies are either already be implementing or will implement in the future. To answer the questions of how and with what the implementation can be carried out, attributes and sources or storage locations must be defined. These are defined below by the parameters and data objects that are derived from these initially collected use cases.

3.2. Parameter

The third step in integrating sustainability into digital engineering involves linking the previously identified use cases with indicators that make sustainability quantifiable and measurable. To achieve this, a systematic literature review after Kitchenham and Charters (2007) was conducted using the following search string at the database Scopus to identify scientific publications that had already developed parameter sets: ("Green" OR "Sustainable" OR "Sustainability" OR "Circular") AND ("Parameter" OR "Factor" OR "Aspect" OR "Criteria" OR "Indicator") AND ("PLM" OR "Product Lifecycle Management" OR "Product Development" OR "Product Lifecycle"). A total of 2,487 publications were initially analysed. In the first step, duplicates and unsuitable documents were removed. Subsequently, papers with thematically irrelevant titles and abstracts were excluded, leaving only the most relevant works for full-text review. In addition, existing standards were analysed to consider already verified and validated sustainability parameter. Ultimately, the process resulted in fourteen papers and three standards being retained. The review of these yielded in a detailed list of sustainability parameter, which were neither structured nor compiled.

Focus groups consisting of employees from industrial companies and research institutes with appropriate technical and sustainability specialization were formed to define suitable indicators for every lifecycle stage of a technical product. The consolidated list of parameters, presented in Table 2, was derived by merging similar ones into unified, descriptive categories and eliminating irrelevant indicators. Some parameters were formulated in a generic way that they can be applied to many use cases and many product life cycle phases and get specific with the combination of their context. For example, "Energy consumption" can be related to the use phase but also to the production phase.

Most of the retained parameters appeared in multiple sources and standards, underscoring a broad consensus in the literature. However, some refinements were made to enhance clarity. For instance, the "Materials used" parameter from literature was subdivided into "Quantity of raw materials", "Quantity of operating materials" and "Quantity of auxiliary materials". A distinction not previously applied, to provide a greater detail level regarding auxiliary and operating materials. Furthermore, the "Reused

water” indicator was introduced to complement existing parameter such as “Water consumption” and “Amount of waste water”. In addition, the “Proportion of rejects” indicator is introduced to differentiate between waste and products that did not pass quality control.
The allocation of the identified use cases to these sustainability parameters was carried out within workshops with all stakeholders involved and with the help of the focus groups mentioned above. All use cases have been made quantitatively measurable by linking them to the parameters.
Whereby, as shown in Table 2, all parameters are used to quantify several use cases. Notably, the indicators “Energy consumption” and “Quantity of raw materials” emerged as being associated with the broadest range of use cases. In contrast, indicators such as “Amount of waste water,” “Reused water,” and “Substances of concern” were applicable to only a limited subset of use cases. The conclusions that can be drawn from this are that the parameters may be more specific than the remaining ones or that the list of use cases is not as detailed for these areas as it is for others.

Table 2. List of the derived sustainability parameters with mapping to sources and use cases

ID	Name	Source ID	Use Case ID
P1	Quantity of waste/scrap	S1, S2, S3, S7, S8, S9	6, 11, 12, 15, 17, 21, 28
P2	Amount of waste water	S7, S8, S12, S15	6, 7, 9
P3	Proportion of rejects		6, 11, 15, 21
P4	Substance of concern	S2, S4, S7, S10, S11, S13, S14, S15	1, 22
P5	CO2 equivalent	S1, S5, S7, S8, S12, S15	6, 11, 12, 14, 17, 18, 27
P6	Disassembly depth	S3, S7, S20, S11, S12, S13, S16	3, 5, 6, 8, 24, 26
P7	Energy consumption	S1, S3, S4, S7, S8, S9, S10, S11, S12, S13, S14, S15	2, 6, 7, 8, 9, 11, 12, 13, 14, 15, 16, 17, 19, 23, 27, 28
P8	Durability	S3, S4, S7, S11, S15	1, 6, 7, 8, 13, 24, 26
P9	Quantity of raw materials	S1, S2, S7, S11	1, 6, 10, 11, 12, 15, 16, 17, 21, 26, 28
P10	Quantity of operating materials		6, 11, 15, 16, 22, 28
P11	Quantity of auxiliary materials		6, 11, 15, 16, 22, 28
P12	Net weight	S5, S7, S11, S12	1, 6, 11, 15, 28
P13	Water consumption	S1, S2, S4, S6, S10, S11, S12, S15	6, 7, 9, 12, 20
P14	Reused water	S15	6, 7, 9
P15	Circularity percentage	S2, S3, S4, S7, S12, S17	2, 3, 6, 17
P16	Circularity potential	S1, S3, S4, S7, S11, S12, S14, S15, S17	2, 3, 4, 5, 6, 12, 25

ID	Source	ID	Source	ID	Source	ID	Source
S1	Upadhyayula et al. 2018	S6	Buchert et al. 2019	S10	Rodrigues et al. 2016	S14	Hassan et al. 2016
S2	Inoue M. et al. 2012	S7	Romli et al. 2015	S11	Ussui 2013	S15	ISO 14031 2021
S3	Mesa et al. 2018	S8	Khan et al. 2004	S12	Helman et al. 2023	S16	DIN EN 45553 2020
S4	Pollard et al. 2022	S9	Wang et al. 2021	S13	De Almeida Souza and De Barros Pereira 2006	S17	DIN EN 45554 2020
S5	Lacasa et al. 2015						

Overall, the derived list of sustainability parameters contains a set of parameters that cover a broad spectrum without covering every special case. Most of these parameters are grounded in established scientific literature or derived from existing standards. Where this was not feasible, the parameters were directly adapted from existing indicators or added due to demands from the industry. The generic formulation of these parameters ensures their applicability across multiple use cases, facilitating broad usability and adaptability. With the help of these parameters, all use cases can be described in a measurable way, thus making the integration of sustainability into digital engineering concrete.

3.3. Data objects

To understand which specific objects can provide the information for the derived and identified sustainability parameters, an overview of existing data objects is necessary. For this purpose, a generic and yet representative interdisciplinary digital engineering data model was created. To develop this data model, individual interviews were conducted with experts from various domains, such as software engineering, product lifecycle management (PLM), systems engineering, etc., to obtain an initial collection of data objects. In addition, joint workshops and work meetings were held to link and describe the interaction between the data objects. The resulting data model is modelled using the SysML notation (OMG 2019). An excerpt of the data model is shown in Figure 2. It provides the overview of data objects in digital engineering, as well as their relationships and links. In total, the data model excerpt contains 25 data objects, categorized with the help of the RFLP concept (Kleiner & Kramer 2012).

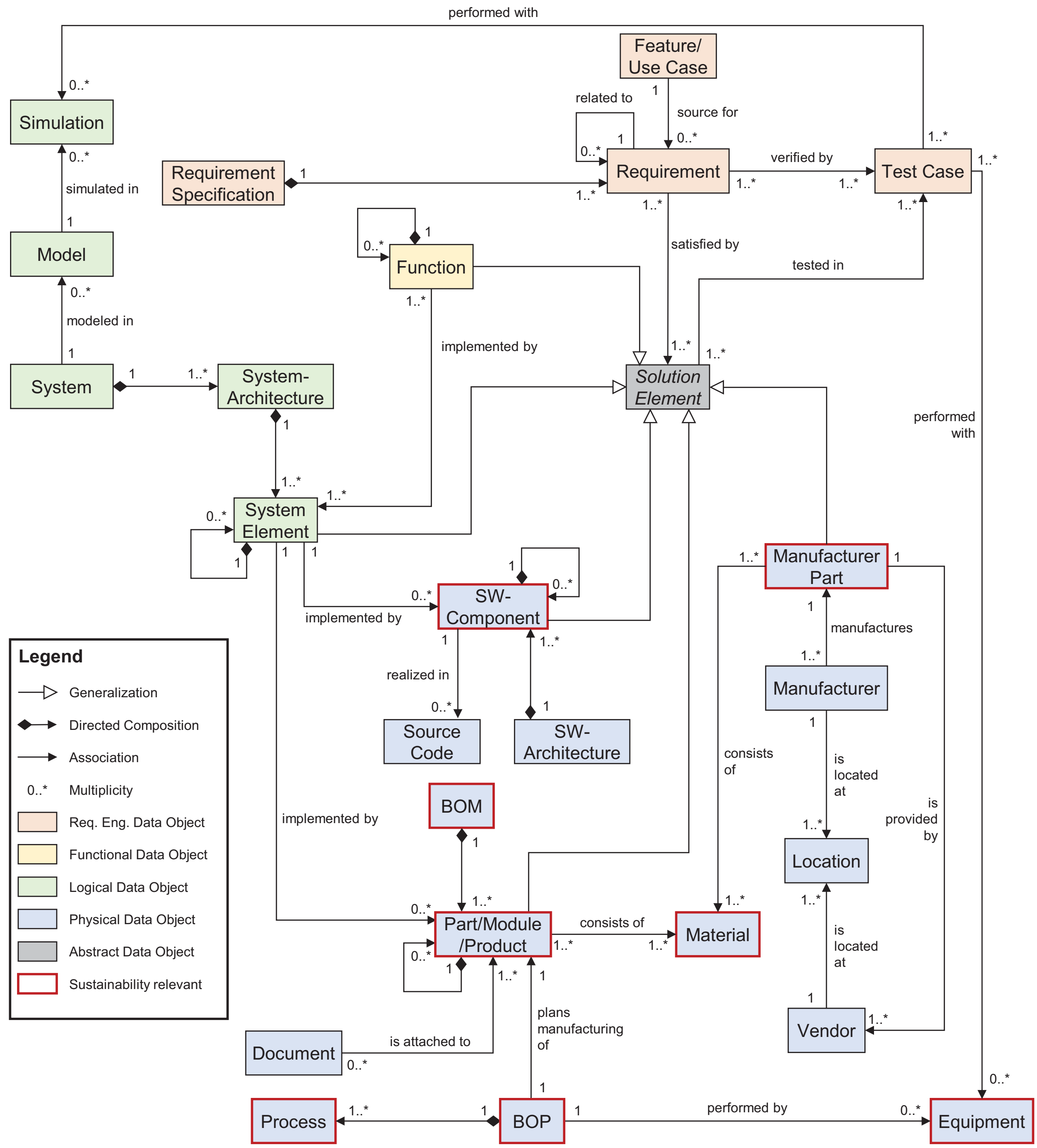

Figure 2. Excerpt of the digital engineering data model

For the mapping of which sustainability parameter is part of which data object, further workshops were held in the research project with a total of 20 experts in sustainability and digital engineering. In this workshop, the 16 sustainability parameters were compared and assigned to the 25 data objects. The result of the mapping workshop is that only eight data objects make a direct contribution to the management of sustainability in digital engineering and are therefore marked in the data model excerpt above. A precise listing of which data objects serve which sustainability parameters is shown in Table 3. It is noticeable, that the sustainability parameters are assigned to data objects handling the product structure, the production and other processes and the materials used. From the point of view of the research project consortium, these three categories of data objects are therefore the centre for report and optimise the sustainability of technical products. It should be emphasized that not only the physical components contribute to sustainability, but also the software components. Particularly regarding modularity, durability, updatability and reuse, software must not be neglected in modern digital engineering or in sustainability considerations.

The other 17 data objects are still necessary and important for successful digital product development but have no direct influence on the sustainability of a technical product over its life cycle. However, some do have an indirect influence. The requirements for a technical system must, of course, provide the basis for complying with, for example, sustainability guidelines and goals.

Overall, the mapping of the sustainability use cases and parameters to the data objects can be used to identify which data objects influence the sustainability of technical products.

Table 3. Mapping of parameters to the sustainability-relevant data objects

Category	Data object	PA1 Quantity of waste/scrap	PA2 Amount of waste water	PA3 Proportion of rejects	PA4 Substance of concern	PA5 CO2 equivalent	PA6 Disassembly depth	PA7 Energy consumption	PA8 Durability	PA9 Quantity of raw materials	PA10 Quantity of operating materials	PA11 Quantity of auxiliary materials	PA12 Net weight	PA13 Water consumption	PA14 Reused water	PA15 Circularity percentage	PA16 Circularity potential
Product structure	Part/Module/Product					×	×	×	×				×	×		×	×
	Manufacturer Part					×	×	×	×				×	×		×	×
	BOM (Bill of Material)					×				×		×	×				
	Software Component						×		×							×	×
Production/Processes	Process	×	×	×		×		×		×	×	×		×	×		
	BOP (Bill of Processes)	×	×	×		×		×		×	×	×		×	×		
	Equipment		×			×		×			×			×			
Material	Material				×	×										×	×

4. Demonstration

An exemplary use case is selected to demonstrate the advantages of the previously presented approach, applied to sustainability integration. This use case and its dependencies on parameters and data objects is shown in Figure 3. The “Selection of sustainable materials” use case (UC1 in Table 1) aims to analyse the environmental impact of different materials (e.g. CO_2 emissions and recyclability) and select the most environmentally friendly option over the entire life cycle. Several parameters need to be considered to assist this analysis or decision. In this case, according to Table 2, these are the parameters P4 - Substance of Concern, P9 - Quantity of raw materials, P12 - Net weight and P8 - Durability. These parameters can be used to assess which materials are toxic or have a negative impact on the environment, how much raw material is required for production and how much material is left in the product at the end or which material is best suited to the planned lifespan of the product. The next step is to examine in which data objects these parameters can be found. According to Table 3, the data objects, that need to be considered for the assignment are Material, Process, Bill of Processes (BOP), Bill of Material (BOM), Manufacturer Part, Part/Module/Product and Software Component.

Overall, this example shows, how it is possible to analyse which parameters and ultimately which data objects are required for a specific need or use case. On the one hand, this information can be used to support the initial introduction of sustainability data in terms of a digital engineering transformation. On the other hand, developers can be supported in their day-to-day work after the initial introduction. In this case, the support consists of information on which data objects are required to select sustainable materials. However, the example also shows that the developer using it must decide in individual cases, which data object is most relevant to him. In the case shown, the exemplary use case refers to both the physical product components and the software components via the durability. While the connection between durability and software components is useful and necessary because software also has durability, software components play a subordinate role in the context of selecting sustainable materials.

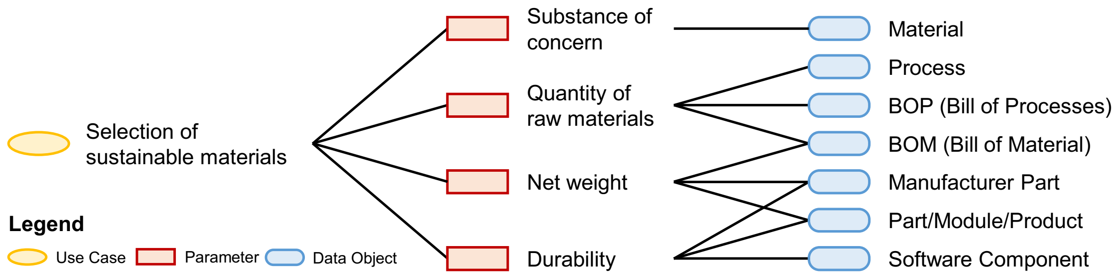

Figure 3. Exemplary dependency chain of the "selection of sustainable materials" use case

5. Evaluation

The evaluation of the presented approach and the results in the context of the sustainability integration in digital engineering were conducted by an expert workshop in form of an adapted Research World Café after Schiele et al. (2022). 14 Experts in the field of digital engineering and sustainability took part in the workshop discussing the meaningfulness of the general approach and of the results of the application for sustainability data in groups of seven experts with one scientist as moderator. The results show that the experts find the approach generally helpful. However, a major point of criticism was the individual assessment of the relevance of the results using the link between use cases, parameters and data objects, mentioned above (e.g. software component relevant for the selection of sustainable materials). It was also stated that the approach must first be applied operationally to assess its practical suitability. Also, for the evaluation of the approach for any kind of digital engineering transformation, the application of other transformation driver is currently missing. Proposed additions and changes to the approach were analysed and added after the evaluation. One example of a desired addition is the inclusion of company-specific conditions, since every company implements and must implement digital transformations differently. This could help to clarify the overarching question of the broader context in which the transformation is taking place and the specifics that need to be considered.

6. Conclusion and outlook

Using the example of sustainability, the SE inspired approach presented shows how new content can be systematically integrated into engineering to support a digital engineering transformation. Starting with a detailed description of the problem with the help of transformation driver and use cases, both the specific requirements and objectives are defined. The derived parameters define quantitative and measurable variables to make the integration as concrete as possible. Finally, the assignment of the parameters to the corresponding data objects shows which elements are responsible for sustainability and where this solution can and must be maintained.

Although this approach was evaluated as helpful, the **clarity and correctness** of the results must be improved and ensured in the general approach. Furthermore, the general approach demonstrated is designed to be applicable to any type of transformation. However, since the approach has currently only been applied to the topic of sustainability, a future research topic is the **application** of the approach to **other digital engineering transformation drivers**. It is also necessary to expand the current approach to include the digital engineering IT tools. Only by mapping the data objects to be integrated to the **IT-**

Tools can the IT perspective be taken and the implementation carried out. The **company-specific framework conditions** mentioned in the evaluation must also be integrated into the approach so that it can be applied to any company. Finally, a **tool-based implementation** of the mapping and use of dependencies would be a helpful addition. Using sustainability as an example, an assistance system would be conceivable that supports users in considering the identified parameters, data objects and their interdependencies to develop more sustainable products.

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