META-ANALYSIS OF SUSTAINABILITY MANAGEMENT IN COMPLEX DEVELOPMENT ENVIRONMENTS: BY INTEGRATING SUSTAINABILITY REQUIREMENTS INTO SYSTEMS ENGINEERING APPROACHES

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Abstract

Purpose – The complexity of developing product service systems continues to increase. At the same time, development cycles are becoming ever shorter and the requirements for safety, conformity and sustainability ever higher. In this article, a meta-analysis is carried out on the possibility of integrating sustainability aspects as requirements in a systems engineering approach and the differences are discussed.

Methodology/approach *- A systematic literature search of articles in* ScienceDirect *between 2016 and 2023 is carried out. The keywords are sustainability and system engineering incl. synonyms. In a further step, the papers are screened for their relevance to* product service systems and the relevance for the purpose*.*

Findings – To address sustainability in complex technical systems, a holistic, model-based approach is required to ensure that sustainability aspects are considered. By using frameworks and methods such as macPro² and SysLM, requirements and indicators for sustainability can be integrated into the development phase, whereas currently only the environmental dimension is usually considered via resource and energy indicators.

Research limitations/implications *– In order to achieve a complete picture, additional databases must be considered and research results from ongoing projects must be awaited.*

Key words: *sustainability**,** Systems engineering*

Introduction

Digitization, sustainability, and customization have already transformed every aspect of product and service development, leading to increasingly complex product service systems (PSS) and significant implications throughout their entire life cycle. Development cycles are getting shorter, and the requirements for safety and regulations are increasing. The product development process is becoming more complex, making a holistic approach and new control methods essential.

Sustainability (Hauff, 2014) and PSS (Kern et al., 2009) should be considered as a system. This leads to the assumption that a system theory-based approach is an appropriate solution for dealing with complexity (Schlüter, 2023).

This leads to the research question for this paper, if sustainability aspects can be integrated as a requirement in a systems engineering approach.

When considering the management of complexities and relationships in economic systems, the "Tableau Economique" is primarily regarded the enabler for input-output analysis (Söllner, 2021: 53). However, a scientific definition of "system" and "engineered systems" can often be

traced back to the concepts of (Bertalanffy and Sutherland, 1974; Bertalanffy, 1950: 23–29) and is ultimately defined by INCOSE (2019) and ISO/IEC/IEEE 15288 (2023): "A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not." A system can be viewed both as a product and in terms of the services it provides. Furthermore, "System of Systems" (SoS), as defined by INCOSE (International Council on Systems Engineering), refers to a complex series of systems that are interconnected and interdependent, each of which can operate independently but work together to achieve a higher purpose.

Sustainability is based on the concept of three pillars: ecology, economy and social (Hauff, 2014) or people, planet and profit (Sanders and Wood, 2020). Many definitions are derived from this. For example, Landrum and Edwards (2009) says that in the business environment, all current and future stakeholders act in a way that ensures the long-term existence of the company and the social, economic and ecological systems associated with it. Brandstotter et al. (2003) even includes the sustainability in his definition of PSS, with the addition of "PSS ties to reach the goals of a sustainable development, which means improved economic, environmental and social aspects". Thus, PSS can serve as an approach to decouple value creation from increased resource consumption (Vezzoli et al., 2014; Kjaer et al., 2019), to combining economic growth and sustainability (Reim, Parida, and Örtqvist, 2015; Tukker, 2004). Goedkoop et al. (1999) have already defined PSS as an aggregation of products and services to deliver value propositions to customers. Used synonyms are "product service bundle", "hybrid service bundle" as well as "hybrid value creation" (Meier, H., Uhlmann, E., Kortmann, D). Meier et al. (2011) even includes PSS in the industrial area as a package of product and service components to provide a solution-oriented and value-added approach across the lifecycle.

The INCOSE Systems Engineering Handbook offers a comprehensive insight into the methodology as well as the available standards and guidelines (Walden, 2023:). However, the aspect of sustainability is only marginally considered. Sustainability engineering is defined in 3.1.10. as an approach that supports the circular economy over its entire life cycle by using the concept of design for sustainability, with environmental and social aspects as key elements: The consideration is not continuous, but rather is highlighted selectively, e.g. only for the application area of "power and energy systems". With regard to the creation of requirements, the manual refers to the technical processes according to ISO/IEC/IEEE 15288:2023: This specifies at 6.4.2.1: "The purpose of the stakeholder needs and requirements definition process is to define the stakeholder needs and requirements for a system that can provide the capabilities needed by users and other stakeholders in a defined environment".

Systemic literature research

A systemic literature research is considered a suitable method for answering the research question, which according to Zawacki-Richter et al. (2020) and Nordhausenet al. (2020), consists of the following steps: ´development of the research question´, ´ design conceptual framework ´, ´ in- and exclusion criteria´, ´define databases´, ´identification of search terms and synonymous´, ´identification of key words´, ´development and verification of search strings´ and ´conduct research´.

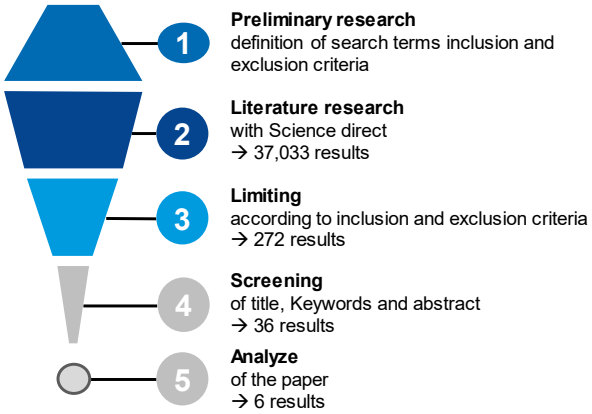

Figure 1: Process of the systematic literature review with results per stage

A preliminary database-unspecific research, showed initiatives such as a special issue “Systems Engineering for Sustainable Development Goals“ of the journal “Sustainability” or the research project “SLE - Sustainable Lifecycle Engineering” started in the end of 2023 to include the dimension of sustainability in MBSE methods (no publications yet), or the publication by Schneider et al. (2023).

To refer to the most recent findings, only publications after the year 2016 are considered, as the "Systems Engineering Handbook V4.0" was published in 2015, and the latest version was released in 2023, along with the most recent version of the "Guide to the Systems Engineering Body of Knowledge" (SEBoK Editorial Board, 2023).

Initial criteria:

- time: 2016 onwards
- language: English
- search string: (sustainable OR impact OR sustainability) AND ("systems engineering" OR "MBSE" OR "model-based systems engineering" OR "advanced systems engineering" OR “requirement engineering”

Limiting criteria:

- peer reviewed and accessible
- subject areas: engineering & environmental science
- Keywords in title: sustainable, impact, sustainability

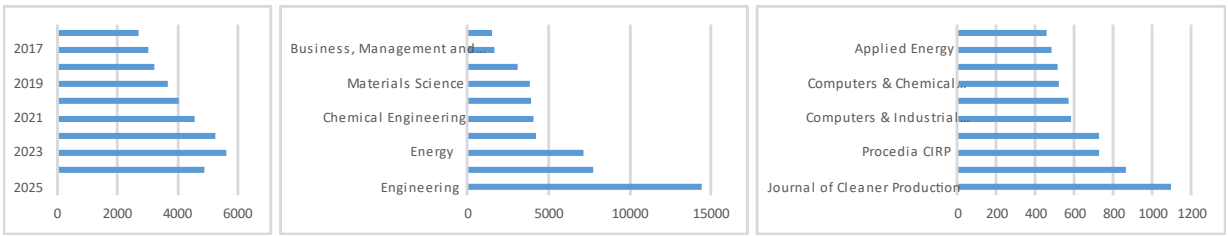

Figure 2: Results of the first literature research (y-axis) by year on the left, by subject area in the middle and by journal on the right (x-axis)

Due to the focus on peer reviewed journal publications ScienceDirect by Elsevier as databases is used. The focus is on journal publications to ensure the quality, but without taking the journal ranking in account. As seen in Figure 2, the initial search produced 37,033 results, which could be limited to 272 by taking the limiting criteria in account. By screening the titles, abstracts and keywords, if the content fits to the problem, they could be limited to 36.

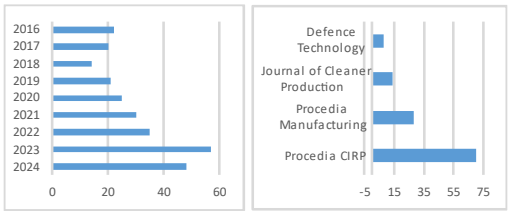

Figure 3: Results of the literature research by *applying limiting criteria* (y-axis) by year on the left and by journal on the right (x-axis)

By reading the papers they could be reduced to 25, which addressed at least two of the following topics and synonyms: systems engineering, sustainable indicators and PSS.
Only six addressed all three topics:

- Bougain and Gerhard (2017)
- Eigner et al. (2017)
- Forte et al. (2022)
- Jaghbeer et al. (2017)
- Mamrot et al. (2016)
- Stürmlinger et al. (2020)

Comparison of the selected papers

The comparison of the papers does not cover fundamental topics such as the Internet of Things and digital twin, but instead focuses on the applied methods. An explanation of the methods cannot be provided here, and reference must be made to the respective publications. However, it can already be deduced from the titles that the lifecycle approach plays a central role and will be compared first before going on to discuss the other methods.

Forte et al. (2022) even writes that the complexity cannot be managed in the in development phase, but that ways must be found to make this possible over the life cycle. Bougain and Gerhard (2017) state that sustainability aspects are not part of MBSE and integrate indicators into four life cycle phases to facilitate eco-design methods. Forte et al. (2022) uses the System of System Lifecycle Concept (Forte, Göbel, and Dickopf, 2021) to enable traceability beyond the actual system boundaries. Eigner et al. (2017) and Mamrot et al. (2016) also rely on data from downstream lifecycle phases to influence product development.

The differences can be found in the applied methodology. macPro² (Eigner, Koch, and Muggeo, 2017), a model based design approach for developing cybertronic systems is mentioned by *Eigner et al. (2017), Stürmlinger et al. (2020) and Bougain and Gerhard (2017)*. *Eigner et al. (2017)* uses SysLM as a basis to support eco-design methods in order to provide data from the subsequent life cycle phases for product development (Eigner, Hauff, and Schäfer, 2011; Eigner, Schäfer, and Apostolov, 2013). *Bougain and Gerhard (2017)* refer to an earlier phase of the lifecycle and develop an abstracted requirements diagram for MBSE to integrate indicators for energy consumption. *Forte et al. (2022)* uses specific SoS KPI management with sustainable requirements for energy and resources to enable reconfiguration. *Mamrot et al. (2016)* employ the "Demand Compliant Design" (Schlund and Winzer, 2009) for the representation of complex socio-technical systems. This approach integrates systems engineering with sensor data and service reports from the usage phase, facilitating the development of these systems.

Stürmlinger et al. (2020) highlights the impact of product changes on the production phase, introducing a new perspective. The underlying methods are MacPro² and Consensus. Despite the focus on simulation-based modelling, the elaboration by *Jaghbeer et al. (2017)* presents valuable approaches for system modelling.

Discussion

The differences in approaches can be attributed to the varying application cases and the associated subjects of investigation. Eigner et al. (2017) use an autonomous excavator as a case study to demonstrate the integration of sustainability aspects, while Forte et al. (2022) examine a scenario of an autonomous construction site to showcase the application of IoT-based reconfiguration approaches. Bougain and Gerhard (2017) use a 3D printer, Stürmlinger et al. (2020) a valve, and Mamrot et al. (2016) a hydraulic pump.

Additionally, the mentioned technological approaches, such as the use of IoT, digital twins, or model-based systems as the basis for implementing the method, influence the results. For example, Forte et al. (2022) IoT-based approach enables real-time monitoring and adjustment of systems, leading to different outcomes than Bougain and Gerhard's (2017) model-based approach, which focuses on the modeling of environmental aspects.

There is a paradox between the focus on the use phase and the associated reactive product changes and the increasing costs of change over the course of the life cycle. This may be due to the fact that the approaches presented are designed bottom-up and take the product or production as a basis to derive sustainability indicators, especially in the energy and resource sector, while there are isolated approaches such as *Jaghbeer et al. (2017),* which pursue a top-down approach, as in (Zhao et al., 2015) und (Lee, Kang, and Noh, 2014), which use higher-level frameworks (e.g. GRI) to derive sustainability indicators. The focus is usually on the environment, sometimes also on the economy, but only rarely on social issues *(Jaghbeer et al., 2017).*

The temporal distribution of the papers is worth mentioning; one is from 2016, three from 2017, two from 2020 and one from 2022. This contradicts the distribution of all papers.

Conclusion and outlook

Sustainability has so far only been dealt with marginally in systems engineering. All authors emphasize the need for holistic, model-based approaches to incorporate sustainability into complex technical systems to ensure that environmental aspects are considered throughout a product's life cycle. By using frameworks and methods such as Macpro² or SysLM, sustainability requirements and indicators can be integrated into the development phase, whereby currently only the environmental dimension is usually considered via resources and energy indicators over the use phase to facilitating the development. In this context, it must be determined whether integration is feasible at an early stage and which indicators can be used in this context. Further research is needed to investigate the extent to which indicators are sector and case dependent and how higher-level indicators can be captured by existing sustainability indicator frameworks and translated into requirements diagrams for MBSE.

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