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Exploring the Potentials of Advanced Systems Engineering and Frugal Innovation for Sustainable Product Development in German industry

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Abstract: Advanced Systems Engineering (ASE) is a new paradigm that approaches engineering practices for future market solutions. Frugal Innovation (FI) represents a promising concept that focuses on sustainable solutions with limited resources. According to the authors, frugal innovation may have a significant impact on sustainable product development but lacks engineering approaches for the systematic development of frugal products. Exploring the links between ASE and FI could help to identify suitable fields of application to ensure sustainable product development. The analysis is based on a comprehensive study on frugal innovation in German mechanical and plant engineering that was recently conducted by the authors. Therefore, this paper explores potential patterns to integrate Advanced Systems Engineering for the development of frugal innovations based on findings from the German mechanical and plant engineering sector.

Keywords: Advanced systems engineering, Frugal innovation, Sustainability, Product development, Frugal engineering

1. INTRODUCTION

Over the past decade, companies from the mechanical and plant engineering sector have faced increasing complexity in their traditional way of product development. With the German research initiative „Advanced Systems Engineering (ASE)", a new paradigm is launched that covers the challenges of rising complexity in companies and provides a holistic framework for the transformation of the engineering strategy (Dumitrescu et al., 2021). In addition to rising complexity the pressure to take responsibility for the sustainability of companies' market solutions is constantly increasing. In this context, Frugal Innovation (FI) has gained importance in the companies' strategies and has established as a promising approach to ensure sustainability in product development (VDMA, 2023).

This paper presents a new research field for the sustainable product development and proposes starting points for accessing potentials in sustainable product development by using Advanced Systems Engineering (ASE) methods for Frugal Innovation (FI). The findings provide directions for future research of ASE and FI by synthetizing the similarities and differences between both areas from the perspective of the overarching term of sustainability. Due to the exploratory nature of this contribution a state-of-the-art analysis is conducted to emphasize the theoretical novelty and relevance for both research areas. A comprehensive study was employed for the main findings which is based on 29 qualitative semi-structured interviews and was enhanced by a quantitative online survey in which 127 companies from the German mechanical and plant engineering sector participated. The mixed-method approach allows conclusions to be drawn about various research patterns for the potentials of ASE and FI for sustainable product development in German mechanical and plant engineering.

2. BACKGROUND OF THE STUDY

The following section provides an overview of the theoretical background of FI and ASE. Further, a state-of-the-art analysis for both research fields in relation to sustainability is presented.

2.1 Theoretical background

A main driver for rising complexity in companies is the shift from mechanical products towards intelligent cyber-physical systems that interact in an autonomous network of systems. This had a tremendous impact on the current engineering methods and organizational structures, which must be adapted to the outlined development (Dumitrescu et al., 2021). The paradigm ASE which challenges the outlined development consists of three pillars: Advanced Systems (AS), Systems Engineering (SE), and Advanced Engineering (AE) (Dumitrescu et al., 2021).

Advanced Systems (AS) considers technical systems, organizational processes, and humans for the future value

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creation. To handle these systems, companies must be able to cope with new requirements with respect to autonomy and connectivity, as well as a higher amount of software and electrics/electronics in products (Dumitrescu et al., 2021).

Systems Engineering (SE) is an interdisciplinary approach for managing the increasing complexity through technical systems described in AS. According to the understanding of INCOSE, SE describes a "transdisciplinary and integrative approach to enable the realization, use and decommissioning of technical systems successfully. It uses system-oriented principles and concepts as well as scientific, technological, and management methods" (INCOSE, 2024). Model-based systems engineering (MBSE) is considered to have great potential as a formalized description of complex systems based on models (Dumitrescu et al., 2021). MBSE is a holistic approach to support the modeling and linkage of digital partial artefacts across the interdisciplinary product development (Eigner, 2021).

Advanced Engineering (AE) includes methods and tools for rethinking established engineering approaches and technologies. These methods include innovative approaches towards agility and creativity, such as Design Thinking (Dumitrescu et al., 2021).

Besides the increasing complexity, European regulations, such as the Corporate Sustainability Reporting Directive (CSRD), require companies to trace and report relevant product and lifecycle data concerning their social and environmental impact (European Commission, 2024). Therefore, companies carry additional costs and liabilities to comply with emerging regulatory demands related to sustainability. Furthermore, the limited availability of raw materials has pushed several industries to rethink previous engineering concepts to achieve the named objectives.

FI offers non-complex solutions with high customer value under resource constraints and follows the principles of simplicity, affordability, and sustainability (Dabić et al., 2022; De Marchi et al., 2022). FI can reduce complexity in products, processes, and business models in both advanced and emerging markets (Dabić et al., 2022; Melnikova & Gilsanz, 2024; Wohlfart et al., 2016). Frugal innovation as a term was first published in 2010, based on the term "frugal engineering" that was coined by Carlos Ghosn, the former CEO of Renault-Nissan, in 2006 (The Economist, 2010). Frugal engineering emphasized the use of less resources while ensuring high product quality and the linkage towards an engineering discipline. Despite the theoretical origin of FI as an engineering concept, less research was conducted in this area. Especially research in systematic approaches for FI are still rare (Beise-Zee et al., 2021). Therefore, the authors declare frugal engineering as methodological engineering discipline for the development of FI.

Despite the theoretical similarities between FI and sustainable product development, an in-depth investigation is still lacking (Dima et al., 2022; Stöber et al., 2022). ASE could represent an emerging field of research, where synergies between both areas are linked to ensure a systematic approach for the development of sustainable frugal products. This will encourage the development of the established understanding of FI from a stand-alone concept to an interdisciplinary concept on a system level, considering complex interdependencies within the environment (Dabić et al., 2022).

2.2 State-of-the-art

The state-of-the-art review is based on the results from Elsevier's Scopus database and IEEE Xplore and summarized below.

2.2.1 Frugal Innovation and Advanced Systems Engineering

Conducting a literature review using Elsevier's Scopus database and IEEE Xplore, searching for "frugal innovation" OR "frugal engineering" AND "systems engineering" in title or keywords two results were found (Achtelik et al., 2023; Molfino et al., 2024). A search request for the ASE pillars "Advanced Systems" and "Advanced Engineering" would not lead to any results due to their high generalizability and are not discussed below. Molfino et al. define FI as a reductionist trend in future robotics, which hardly matches the concept from an engineering perspective (Molfino et al., 2024). Therefore, only the remaining paper by (Achtelik et al., 2023) will be analyzed in the next section.

Achtelik et al. propose a system-oriented approach for the implementation of sustainable polymer materials. They refer to the premise that today's prevailing mindset of over-engineering, which is reflected in numerous products, in turn leads to complex technical requirements that make it difficult to ensure efficient integration of sustainability aspects (Achtelik et al., 2023). By focusing on the core functionalities and establishing an optimized quality level, frugal engineering makes the obstacles in complex requirements management feasible and is able to accelerate the introduction of sustainable materials. However, the reference to SE is limited to the V-model in systems engineering for reducing complexity by decomposing systems into sub-systems to identify core requirements and core functionalities. However, the suggested approach neglects the aspect of a formal modeling language and technical integration into the higher-level product development process and the underlying IT infrastructure. Nevertheless, the paper successfully shows that methods from the (A)SE context have the potential to be transferred to FI. Over-engineering may be identified in systems as soon as the system requirements no longer meet the overall requirements of the market and stakeholders (Achtelik et al., 2023).

2.2.2 Frugal Innovation and Sustainability

FI as a concept for ensuring sustainable solutions is an emerging field of research (Albert, 2022; D'Angelo & Magnusson, 2021; De Marchi et al., 2022; Dima et al., 2022; Stöber et al., 2022). FI fosters sustainable economic growth and takes the environment as well human beings into consideration (VDMA, 2023). Regarding the latest conducted systematic literature review on FI encouraging sustainable development, the highlights below can be derived. The findings are structured into the three sustainability pillars, namely economical, ecological, and social. They each depict the most common classification in the referred literature.

Economical

- FI in advanced markets emphasizes economic sustainability (Dima et al., 2022),
- FI has an impact on sustainable development both in emerging and advanced markets (De Marchi et al., 2022; Stöber et al., 2022; Wohlfart et al., 2016),
- FI relies on technological advancements in the information and communications technology (ICT) sector, including digital design software to meet economic sustainability (Niroumand et al., 2021).

Ecological

- FI is a unique kind of environmental innovation approach matching sustainable development goals (Dima et al., 2022; Rosca et al., 2018),
- FI emphasizes the sustainability of economies by their minimalistic design using less raw materials, physical resources, and components (Dima et al., 2022),
- Sustainable innovation is a specific notion for FI (Dima et al., 2022),
- FI is liable to resource constraints and naturally aligns with the principles of circular economy (Albert, 2022; Dabić et al., 2022).

Social

- FI emphasizes its impact in mastering global challenges due to their initial roots in emerging markets (Brem, 2017),
- Interdisciplinary and cross-partner collaboration is crucial through the product life cycle of FI (De Marchi et al., 2022),
- A shift towards systemic frugal economy is the key to address the global economy challenges (D'Angelo & Magnusson, 2021),
- FI requires less resources and a minor effort for maintenance due to its robustness and makes products affordable to a wide range of consumers (Stöber et al., 2022).

The findings from the literature review indicate a positive link between FI and sustainability. However, an in-depth investigation on operationalizing sustainability indicators for FIs within their environment are still missing and should be examined in the future (Albert, 2022; Dabić et al., 2022; De Marchi et al., 2022). Further digital tools are needed to foster this objective (Albert, 2022; Levänen et al., 2016).

2.2.3 Advanced Systems Engineering and Sustainability

As a new paradigm for future value creation, ASE must consider megatrends such as digitalization and sustainability (Dumitrescu et al., 2021). Sustainability has the impact to be integrated in any future approach of product development (Schneider et al., 2022). Companies are confronted with regulations such as CSRD, which are intended to promote the responsible use of available resources in addition to mandatory documentation (European Commission, 2024). As part of ASE, sustainability not only refers to the economic and ecological pillar, described by concepts such as circular economy and second life strategies, but also increasingly includes social sustainability aspects in the sense of sharing economies and intercultural cooperation (Dumitrescu et al., 2021). There is a huge potential to foster sustainable concepts with methods of ASE.

3. METHODOLOGY

This paper employs a mixed-method approach, where 29 qualitative semi-structured interviews with experts on FI from the German mechanical and plant engineering sector were taken into consideration. Additionally, the database used for the findings was enhanced by a quantitative online survey in which 127 companies from the German mechanical and plant engineering sector participated.

3.1 Qualitative research design

For the semi-structured interviews, a set of 27 guiding questions were predefined, which allowed conclusions to be drawn about various criteria for the sustainable introduction of FI in companies, e.g. motivation, target markets, business model, requirements elicitation, mindset, development methods, product structure, contribution of digitalization technologies and effects through FI on sustainable, ecological, and social environment.

The expert interviews were conducted with different companies, which all originate from Germany. They are classified into original equipment manufacturers (OEMs), system developers and component suppliers, thus covering the relevant stakeholders in the value chain. The reliability of the results can be assumed, as the entire sector was covered by 16 small and medium-sized enterprises and 13 large multinational companies. The experts are senior employees, of whom the majority come from product/innovation management (11 participants) and executive management (9 participants). Companies from the trade association for process engineering machinery and equipment (6 participants) were the most represented. To evaluate the qualitative data, the interviews with a length of 90 minutes were transcribed and summarized for each criterion using qualitative content analysis.

3.2 Quantitative research design

The standardized online survey with predefined answer options provided an empirical analysis concerning opportunities, challenges, and recommendations of FI in the German mechanical and plant engineering sector. Identical to the qualitative research design, the 127 companies surveyed can be divided into original equipment manufacturers (OEMs), system developers and component suppliers for a better comparison of the results. With 68 participants, the highest rate of participation was among companies with fewer than 250 employees, followed by 44 participants (250-2999 employees) and 15 participants (greater than or equal to 3000). Companies from the construction machinery and building material plants

and drive technology sectors were the most represented with 12 companies.

The mix of qualitative and quantitative research designs allows a verification or falsification of the statements made in the interviews through the data obtained from the comprehensive online survey. Initially, the data collection was conducted as a study contribution for the German engineering federation VDMA (VDMA, 2023). Within this context, a comprehensive benchmarking study on FI in German industry was realized. The focus of this study was to identify strategic and operational key factors for the sustainable introduction of FI in German mechanical and plant engineering. Relevant findings for this paper were derived from the study. Conclusions were obtained for ASE-related topics like product design, development process, digital tools, requirements elicitation, and sustainability. The findings will provide valuable insights into the opportunities and future research paths between ASE and FI for sustainable product development.

4. FINDINGS

Eight patterns were derived from the qualitative content analysis exploring potentials between ASE and FI for sustainable product development.

Simplicity vs. Complexity

Apart from the increasing amount of electronic and software components in products, the cultural awareness in the German mechanical and plant engineering industry, in terms of "over-engineering", contributes significantly to the growth in complexity. The pursuit of highly technological solutions that could cover all eventualities takes precedence over the FI's mindset to develop tailor-made solutions according to the FI principles of simplicity, affordability, and sustainability.

According to the 29 interviewed experts, the emphasis in the simplification of products is based on six criteria, listed below according to their frequency (multiple mentions were allowed): High quality (20 mentions), affordable for the target customer (18 mentions), simple product structure (13 mentions), match performance exactly to the use case (10 mentions), focus on core functionalities and fulfillment of purpose (9 mentions) and ease of use (6 mentions) (VDMA, 2023). Frugal engineering may help to select technologies and methods that are both efficient and cost-effective to meet the requirements of the target users. Operationalizing „over-engineering“ by matching system functionalities with stakeholder needs for each system could uncover potential inefficiencies.

Systems Thinking as new mindset for FI

One of the key issues mentioned for the failure of FIs was the lack of alignment with the corporate strategy and internal mechanisms and resources (VDMA, 2023). A systematic alignment was not evident and hindered the implementation of frugal products. By adopting systems thinking, frugal innovators can better understand the interactions between different components of their product, which enables optimization of the overall performance. In context of the SE literature a high relevance is assigned to the two main objectives of system thinking “system integrity” and “life cycle compatibility” and should be integrated into the overall strategy (Gräßler & Oleff, 2022).

The systems engineering V-model could be considered as an approach for systems thinking to ensure acceptance and dissemination in FI. First research was conducted and discussed in the previous chapter with the example of sustainable polymer materials and should be extended on other product components.

Sustainability

The German mechanical and plant engineering industry anticipates that frugal innovations could provide a competitive advantage in terms of economic sustainability. The main benefits that were mentioned were the development of new customer or market segments and competing against low-cost competitors (VDMA, 2023). Regarding the sustainable use of resources, the focus was on reducing the number of integrated components and variants and increasing robustness by considering longer service life or designs for reuse (VDMA, 2023). Ecological and social sustainability are listed as significant mentions. FI should also be considered as an entry-level solution in new markets to attract potential unknown target groups to the higher-value product portfolio (VDMA, 2023).

FI focuses on developing cost-effective solutions. By integrating ASE, advanced technologies and materials can be applied and combined in a way that minimizes costs without affecting sustainability objectives. FIs are closely aligned with the needs of local markets and consumer groups. ASE enables products to be adapted to local requirements while ensuring the use of local resources and sustainability. ASE may support this adaptation process by enabling the integration of these requirements into the system design.

Model-based systems engineering as enabler for FI

ASE applies model-based approaches to design and optimize systems. MBSE provides a holistic approach to system development by modeling the interactions between different requirements and components. This helps frugal innovators consider all aspects of their system and create a more comprehensive design. Frugal engineering may employ such models to design cost-effective variants while ensuring that systems fulfill their core functions efficiently. Further, models can be updated and revised frequently to reflect changes in market requirements or constraints. The reusability of models saves time and resources for the development of new FIs.

By utilizing models, complex systems can be represented in a visually appealing form. This facilitates communication within the development team and with other stakeholders. This collaboration can lead to the exchange of ideas and support co-creation of FI in different cultures.

MBSE uses basic modeling and simulation to predict the behavior of systems (Eigner, 2021). This makes it possible to evaluate different design options. By analyzing models, frugal innovators can identify which components or processes are "over-engineered" and develop enhanced solutions. By

integrating FI principles, the focus can be shifted not just to maximizing technological performance but also to improving the efficiency, material use, and environmental compatibility of the entire system.

Requirements engineering for local market demands

Requirement elicitation is considered an essential aspect of FI (80 of 127 mentions from the online survey). Considering the local variety of frugal solutions offered for specific target markets and groups, the requirements change considerably for each further development. This is made more difficult by the fact that often requirements are not recorded systematically, and data is collected using various instruments. The use of digital tools for requirement management does not play an important role and shows that standardized documentation is necessary (VDMA, 2023). Requirements engineering as method may support frugal innovators in understanding the users' needs and ensuring that the FI meets these requirements (Koelsch, 2016).

Frugal product design and development process

The design of frugal innovations is most frequently implemented in product variants (18 of 29 mentions from the expert interviews). Often as an offset of a previous variant that has been adapted to local market requirements. Comparisons and derivations from existing variants are particularly useful from a product architecture perspective and help FI develop more efficiently.

The development approach mainly involves adapting existing products, with a proportion of individual components being newly developed (47 of 105 mentions from the online survey). Exclusively, de-functionalizing existing products without linking and considering local requirements does not lead to the intended outcome, as no conclusions can be drawn about the effects across individual system boundaries (VDMA, 2023).

Advanced (digital) engineering tools for FI

Digitalization offers several opportunities for FI in product development. The use of digital tools for FI is limited and does not play a significant role in German mechanical and plant engineering (VDMA, 2023). The most frequently mentioned tool associated with FI were product configurators (6 of 24 mentions from the expert interviews). Advanced engineering may support the integration of new technologies into cost-efficient solutions. It is important to prioritize sustainable technologies that are environmentally conscious.

For instance, usage data collected through cloud technology and optimized by Artificial intelligence can be used to determine specific user behavior and identify unnecessary functions faster to avoid over-engineering (7 of 24 mentions from the expert interviews). The integration of the technologies used should also be evaluated based on the existing IT infrastructure to exploit synergies and avoid the emergence of new silos.

Advanced engineering methods for FI

The integration of agile methods enables the flexible and iterative development of frugal solutions. Design thinking is occasionally used in German mechanical and plant engineering for requirements elicitation, in which the benefits for specific target groups are promoted through the creation of personas (5 of 29 mentions from the expert interviews). Personas are suitable for narrowing down and differentiating specific customer groups based on criteria. Advanced engineering may support the integration of methods in agile product development into FI.

5. DISCUSSION AND CONCLUSION

This paper presents starting points for accessing potentials in sustainable product development by using Advanced Systems Engineering (ASE) methods for Frugal Innovations (FI). The findings of this paper show that frugal innovation could have a significant impact on sustainable product development by addressing the identified patterns. ASE has the potential to streamline the design of frugal products by introducing engineering methods. The identified patterns between ASE and FI will encourage the stand-alone concept of frugal engineering to become an interdisciplinary, awareness-enhancing engineering approach for sustainability.

Various research implications are addressed in this paper by the eight categories within the findings. MBSE seems to be a promising research field in the FI context because there is no integrated approach between MBSE and FI. Mapping frugal innovations in system models is intended both to simplify the product structure and to accelerate the transfer of data from the early product creation phase to the subsequent phases of the product lifecycle. Here, future research must be applied to real industry cases.

The mix of qualitative and quantitative research designs was preferred as research design because it allows a verification or falsification of the statements made in the interviews through the data obtained from the comprehensive online survey. Due to the limited scope of this paper, a comprehensive systematic literature review and full consideration of positive and negative factors identified between sustainability and FI could not be covered and cannot substitute additional review approaches, such as meta-analysis and qualitative literature review. Deeper research could lead to further promising avenues between ASE and FI for sustainable product development.

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