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Procedia CIRP 119 (2023) 770–775

www.elsevier.com/locate/procedia

33rd CIRP Design Conference

Towards a Consistent Understanding of Sustainability in Product Engineering – A Systematic Literature Review and Explication Framework

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Abstract

Sustainability in product engineering is becoming increasingly relevant. Expanding stakeholder requirements for sustainable product engineering demand a more detailed and consistent understanding of the field to foster purposeful solutions. In this paper, a total of 174 publications in the field of product engineering were evaluated for their underlying understanding of sustainability based on a hermeneutic analysis. The results are threefold and include guiding questions for the analysis of publications in the field, a description of the current state of sustainability understanding in product engineering, and an explication framework for a proactive and targeted description of a sustainability understanding for use in future research and practice. These results are intended to contribute to establishing a more consistent and explicit understanding of sustainability in product engineering.

Keywords: Sustainability, Product engineering, Product development, R&D, Understanding, Framework

1. Introduction

Sustainability advanced to one of the most topical issues in society, politics, and science [1]. In this context, the understanding of sustainability in product engineering (cf. chapter 2.2.) is quickly developing with an ever-increasing understanding of interdependencies. Therefore, product engineering research proposes various understandings and methods to implement sustainability in product engineering at an increasing pace. [2]

Currently, a consensus on terminology cannot be found [3]. Therefore, this work addresses this gap of consistency in understanding sustainability in product engineering aiming to establish a common ground for further research. For this purpose, chapter 2 summarizes relevant definitions and concepts for understanding the contribution. Chapter 3 covers the research goal broken down into a research question and the methodology followed to answer this question. Chapter 4 contains all relevant results of the analysis and the respective discussion. Chapter 5 draws conclusions and implications for further work.

2. Research background

2.1. Public discourse on sustainability

The Brundtland Commission defined the following definition and basic thoughts on sustainability in its 1987 report "Our Common Future": "Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future." [4]. This definition leads to a multidimensionality of the concept of sustainability, which is initially divided into the dimensions of ecology, economy, and social [5]. To represent these dimensions, the triple bottom line model (TBL) has become established in academia where they are represented as three pillars [6]. In the Paris Climate Agreement of 2015 and the resulting Agenda 2030, the conceptual understanding of

10.1016/j.procir.2023.03.123

sustainability was used as a basis to form a unified framework for sustainable development [7]. It formulates 17 goals known as Sustainable Development Goals (SDGs) [8]. These goals link the different dimensions of sustainability through indicators and targets [9]. Concepts such as corporate responsibility have been developed to translate these 17 goals into actionable concepts for companies, incorporating environmental and social issues into decision-making processes beyond existing (economical) corporate obligations [10]. Moreover, additional concepts such as ESG (environmental, social, governance) are being increasingly used among stakeholders of companies, e.g., financial institutions [11].

2.2. Product engineering understanding

Product engineering can be understood as the basic process from the product or business need up to the successful market launch and comprises three main components: Product planning, product development, and production system development [12]. Both the result and focal object of the process are products, which can consist of any combination of a technical system or component, a service, and a business model, while the latter can be part of the product or the product itself [13]. A commonly used concept to describe products from a sustainability perspective is the product lifecycle [14,15]. This starts from the first idea during product planning and extends over the usage phase up to sunsetting and recycling or reuse of a product. Product engineering, therefore, describes a subset of activities that are conducted within the product lifecycle [16]. This idea is different from the view of the product lifetime, which focuses on the time on the market of the entirety of all manufactured products of the same generation [17].

Product development as part of product engineering is happening within certain boundaries defined by its context. To structure the influencing factors that define a context, different categories can be considered, such as (market) environment, company, or department level [18]. Additionally, product engineering is a highly interdisciplinary process that involves multiple functions within a company [19] (e.g., production, marketing), which may have different perspectives on key aspects. On the contrary, different hierarchical abstraction layers also allow for various granularity levels in the process view [20]. Depending on the application, those views may focus on different interdependencies.

3. Research design

3.1. Research goal and research question

As outlined in chapter 1, existing product engineering research misses a consistent understanding of sustainability. Consequently, this work looks for a consistent understanding of sustainability in product engineering to consolidate a common ground for further research. To achieve this goal, the research question aimed to be answered is:

How is sustainability in product engineering currently understood in literature and what are the implications to support consistent further research and practice?

3.2. Research approach

To answer the research question above, this paper used a systematic literature review as a foundation (see chapter 3.2.1.). The identified publications were reviewed and analyzed for their understanding of sustainability in product engineering in an iterative process (see chapter 3.2.2.).

3.2.1. Literature review

The systematic literature review was conducted using the two literature databases *Scopus* and *Web of science*. Since the focus of this paper lies at the intersection of product engineering and sustainability, these two areas were used as search terms. Related keywords like product development were also included since they are often used synonymously, although, in this paper, we understand product development as a subprocess of product engineering (see chapter 2.2.). Further aspects of the publication focus were introduced to refine results (see table 1). The content-related narrowing was done by searching for strategy, operationalization, and production planning, while German translations of the respective keywords were included. Moreover, the review considered publications from 2020 onwards. The first reason for this limitation was the fast development in this area [2,21] which suggests a rather short time frame to capture the latest understanding. Furthermore, relevant understandings published before 2020 are expected to be reflected in (cited by) current literature.

Table 1. Search terms used for systematic literature review.

Aspect	Search term
Product engineering	Product engineering OR Product development
Sustainability	Sustainab*
Publication aspects	Defin* OR Descri* OR Research need* OR Need* OR Approach OR Method
Content aspects	Strateg* OR Operationali* OR Production planning
Publication year	Since 2020

Overall, a total of 933 publications could be identified during the systematic literature review, where 708 were left after the removal of duplicates and entries not relating to publications. These 708 publications were screened (title and abstract) regarding their relevance. Within this process, two major types of non-relevant publications were identified: Those with deep functional focus (e.g., materials engineering, biomaterials, marketing) or specialized industry character (textile/fashion, tourism, food, construction). The remaining 198 publications were screened in full text for contextual relevance (24 excluded). All remaining publications were

analyzed and discussed regarding the stated research question. This process is shown in fig. 1.

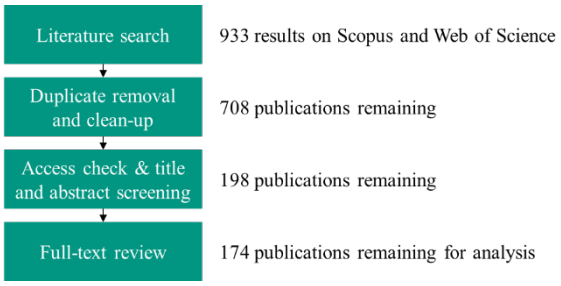

Fig. 1: Process of the systematic literature review

3.2.2. Analysis

Following a hermeneutic approach, a general understanding may be obtained and sharpened iteratively. Since no established, comprehensive understanding of sustainability in product engineering could be found, the research question (chapter 3.1.) was iteratively refined and answered based on the publications analyzed. Three results could be obtained by this process: As a first result, a refined set of guiding questions with evaluation criteria detailing the research question could be identified. The second result is the current understanding of sustainability in product engineering, comprised of the answers to these guiding questions given by the analyzed publications. Building on this, an explication framework to describe and argue a contextualized understanding of sustainability in product engineering could be extracted from the analysis. This process is shown in figure 2, while the results are described and discussed in the following chapter 4.

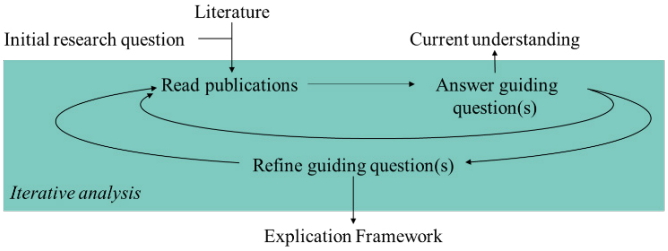

Fig. 2: Process of analysis

4. Results and discussion

The refined guiding questions are outlined in the first place (4.1.), as they are the basis for the following results: The current state of sustainability understanding in product engineering (4.2.) as well as the proposed explication framework (4.3.).

4.1. Refined guiding questions to analyze the current state of sustainability understanding in product engineering

The refined questions as a result of the iterative process cover four guiding questions, which target specific evaluation criteria allowing categorization of publications. Guiding questions, evaluation criteria, and categories were iteratively refined according to the knowledge gained on differences in the underlying understanding of sustainability in product engineering. The final set can be found in table 2.

The contributions analyzed differ in their rationale behind the need for sustainability in product engineering by the either reactive (drivers) or proactive (benefits) character of arguments. The description of sustainability differs in the description models used and focus areas stated, which can be reasoned or assumed as given. Variations in the description of the application area of sustainability considerations were also observed (e.g., company, product, or specific aspect) and can be classified by their respective description models. Another difference between publications can be found in cited approaches that mark the foundation for their respective contributions, as well as the employed description of the respective approach (e.g., as concept, tool).

Table 2. Refined guiding questions and evaluation criteria with example categories.

Guiding question	Evaluation criteria	Example category
How do authors argue the need for sustainability in product engineering?	Drivers	Stakeholder req., responsibility
	Benefits	Specific benefits, …
How do authors describe sustainability and its area of application? How are delimitations done?	Description model (Sust.)	TBL, SDGs, …
	Focus area (Sust.)	Environmental, …
	Reasoning (Sust.)	Yes, no
	Area of application	Product, company, specific aspect, …
	Description model company	Process, function, …
	Description model product	Product life cycle
Which approaches do authors refer to and how do they describe them?	Approach	Circular product design, …
	Description	Concept, tool, …

This set does not have the aim to be exhaustive and can be further refined by taking additional literature into account.

4.2. Current understanding of sustainability in product engineering

4.2.1. How do authors argue the need for sustainability in product engineering?

52% of publications do not reason explicitly why they see a need for sustainability in product engineering and the remaining 48% argue with related drivers and/or benefits. 27% cite drivers pushing product engineering to strive for sustainability (reactive), and 13% outline the beneficial implications of sustainability in product engineering (proactive). A share of 8% uses both benefits and drivers in their reasoning (see fig. 3).

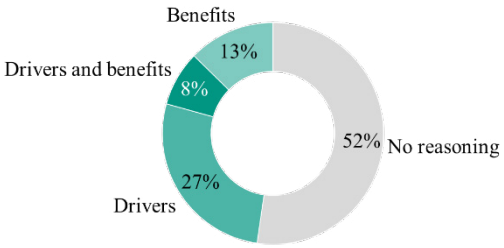

Fig. 3: Reasons cited by authors to argue for sustainability in product engineering

Cited drivers are in over 38% generic stakeholder requirements (stakeholder not explicitly stated or requirements not directly related to product engineering, e.g., societal demand), while 34% give specific stakeholder requirements (e.g., purchase criteria of the customer) and 28% refer to an inherent responsibility (e.g., need for intervention against climate change). Stated benefits of sustainability in product engineering vary in their level of detail: 44% are rather generic (e.g., market potential), while 56% provide specific benefits, such as increased employee motivation.

The range of given drivers and benefits of sustainability considerations in product engineering reflects the general relevance of this topic. However, there is a significant share of publications that do not state their reasoning for the need for sustainability in product engineering. This could be due to various causes, e.g., that reasons are commonly clear for the intended addressees, that this reasoning could be part of literature that has not been reviewed, or that there is a white spot marking an opportunity to foster understanding. The literature predominantly uses drivers (instead of benefits) as motivation for sustainability, which reflects a rather reactive position. The variety and in many cases generic description of drivers also suggest a broad perspective on influencing factors for sustainability in product engineering. To further understand these stakeholders and the implications of their requirements for product engineering, a more detailed analysis should be conducted.

4.2.2. How do authors describe sustainability and its area of application? How are delimitations done?

As shown in fig. 4, 40% of analyzed publications refer to the Triple bottom line as a description model for sustainability. This also includes alternative wordings (e.g., ecologic for environmental) and four instances where another dimension was added to the TBL (e.g., technology). SDGs are also cited regularly (7%), while others are only used on a few occasions. However, 49% of publications do refer to the concept of sustainability but do not explicitly use a description model. Even more interestingly, those publications that refer to a description model tend to use a more comprehensive approach toward sustainability (70% of TBL-based publications cover all three dimensions). Those that do not refer to such a description model narrow their focus to individual dimensions or leave their focus unclear. In only 6% of cases where the focus is narrowed, a reason is provided. Moreover, publications that address single or two dimensions of the TBL most often relate to the environmental dimension (over four times more than the social dimension).

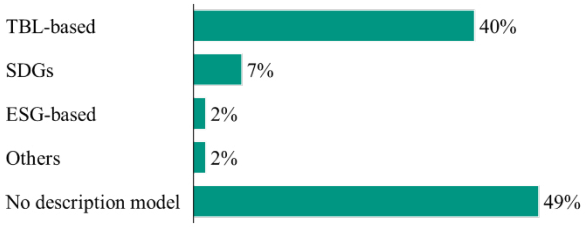

Fig. 4: Description models used for sustainability aspects

Therefore, TBL can be regarded as the predominant basis for description models in a comprehensive view of sustainability in product engineering. In most cases, a narrower focus is neither delimitated using a broader description model for sustainability nor reasoned, which might make the interpretation and application of corresponding findings more difficult. The focus of the literature lies on comprehensive and environmental sustainability, while dedicated social sustainability is comparably underrepresented. Overall, the used models only provide a high-level description of sustainability, why detailing (e.g., by indicators) depending on the area of application can be necessary, and should be analyzed further.

The described sustainability considerations can be applied in different areas of product engineering and its context, with different implications for product engineering. Therefore, the intended area of application of these sustainability considerations is analyzed in the following. 43% of publications identified apply their sustainability considerations completely on products, taking a comprehensive view of the product as the result of product engineering. 16% address the company running the product engineering process in their sustainability considerations. Only 2% of publications address both explicitly. 16% address a specific area of application within a company or product (e.g., supply chain management of a company, material selection for products), while in 22% of cases, a delimitated area of application could not be identified (see fig. 5).

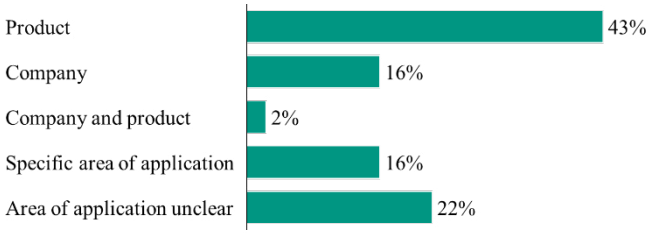

Fig. 5: Area of application of sustainability considerations

The description models used for companies are dominated by process related descriptions with 31%, while only 6% use functional descriptions, 2% hierarchies, and others. However,

61% do not use a description model for the company at all. For product descriptions, in 22% the product lifecycle is used, while 8% use systems as description models. 1% use other descriptions and 61% do not specify the product further.

Summarizing these findings, current product engineering literature strongly focuses on product sustainability, where the product is described by its lifecycle. Addressing the company's sustainability explicitly or even a combination of company and product sustainability is currently less common. Nevertheless, for both areas a significant relevance can be stated, suggesting their relationship should be analyzed in further research. Description models for companies are dominated by process descriptions, while functional views are less common. Since the latter could be particularly interesting for practitioners depending on their respective organizational structures, this aspect should be analyzed in more depth.

4.2.3. Which approaches do authors refer to and how do they describe them?

45 different approaches to sustainability in product engineering with 24 different descriptions (e.g., concept, method, strategy) that served as an immediate basis for the contributions could be identified in the analyzed literature. As shown in table 3, the most common approaches were "Design for ..." (grouped), circular economy, and lifecycle assessment (LCA).

Table 3. Sustainability approaches used as a basis for publications.

Approach	Mentions, #
Design for … (e.g., X, Sustainability, Circularity, …)	11
Circular economy	8
Lifecycle assessment (LCA)	8
Eco-design	6
Corporate Social Responsibility (CSR)	5
…	…

The variety of approaches seen in the literature suggests that a deeper analysis of underlying understandings, their relations, and their area of application would be beneficial. Since linguistic terms for the identified approaches also vary, overlap and misunderstandings cannot be ruled out. Hence, the suggested analysis should be based on a contextualized understanding, with a clear purpose and scope. According to Johansson and Sundin [22], a synergetic reduction of approaches could lead to simplification and support application in practice. This paper uses the description "approach" because it was used the most in the literature.

4.2.4. Implications of current understanding

Conclusively, the analysis in chapters 4.2.1.-4.2.3. shows that current product engineering literature typically covers explicit approaches (e.g., DfX, LCA) and the area of application of sustainability considerations (e.g., product, company), while the purpose (benefits or drivers) and description of sustainability (e.g., TBL-based, SDGs) is explicated more rarely and rather generic.

However, reasoning sustainability considerations could give guidance on narrowing and delimitating a sustainability scope as well as on selecting suitable approaches for the individual application. Without an explicit delimitation based on a description model, the scope can remain unclear. In practice, this can lead to inconsistent sustainability efforts that might fail to support the intended (individual) purpose. Inconsistencies might include mismatches between selected approaches, their area of application, and addressed sustainability aspects, and purpose. The resulting risks seen by the authors are a hindered operationalization of approaches and sustainability efforts as well as unintended "blind spots".

4.3. Explication framework for sustainability understanding in product engineering

The analysis of reasons behind sustainability considerations shows that a comprehensive understanding of sustainability in product engineering needs to allow for individualization for a particular purpose (e.g., company strategy, development project, or research project) and stakeholder requirements. Therefore, the stated findings pose three requirements to describe an explicit understanding of sustainability in product engineering:

- Provision of the intended purpose of sustainability considerations helps to understand the contextualization and its area of application
- Sustainability considerations in product engineering should be based on a comprehensive understanding as starting point, where established description models can be used as a basis (e.g., TBL, SDGs, …)
- Contextualization by a more detailed description and delimitation of addressed sustainability aspects, area of application (e.g., company, product, …), or selection of relevant approaches should be done and explained to allow for a better understanding

In this regard, answering the refined guiding questions of the analysis can help future research and practical work to establish a comprehensive and consistent understanding of sustainability in product engineering as their basis. To support a proactive clarification of the sustainability understanding in product engineering, an explication framework (which is content-wise in accordance with Sinek [23] although phrased differently) is proposed in figure 6.

Overall, these suggestions are made based on only the analysis of explicit statements within the publications, which does not allow drawing any conclusions about the implicit authors' intentions. Nevertheless, the evaluation of the communication of these intentions can help to foster understanding and awareness in the community. Moreover, drawn conclusions and the proposed explication framework are subject to interpretation by the authors of this contribution.

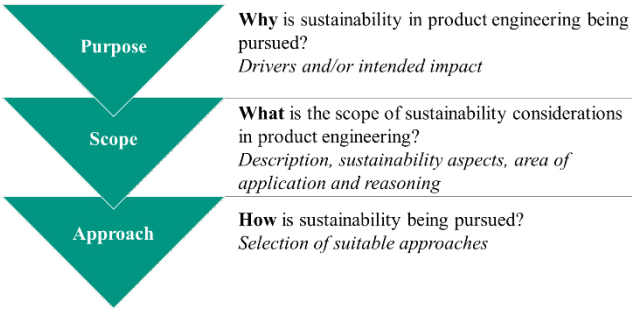

Fig. 6: Explication framework for a contextualized understanding of sustainability in product engineering

5. Conclusions and outlook

In a field of multiple understandings which are used simultaneously, this paper does not offer an additional understanding, but an explication framework based on the assessment of underlying understandings in the existing literature. Moreover, this paper provides an initial basis to define the scope and approaches for sustainability in product engineering for both future research and practice in the intersecting fields of sustainability and product engineering based on an individual purpose. Thereby, purposeful contextualization of sustainability considerations can be supported, while keeping consistency within the research field.

Academia can use the explication framework to delimitate their work and contribute to a consistent and explicit understanding of sustainability in product engineering while being able to focus on individually relevant aspects. Future research should – building on these findings – particularly analyze scope (1) and approaches (2) for sustainability in product engineering in depth:

1. Regarding scope, especially the interconnectedness of different sustainability aspects (e.g., multiple SDGs) and the interconnectedness of the area of application with its environment (e.g., product, company, other processes, and functions within a company) should be analyzed in detail, to align scope setting not only with a purpose but also based on relevant influencing factors within the two fields.
2. Existing approaches should be further analyzed and structured regarding their addressed needs (scope and purpose) to get an overview of remaining research gaps as well as potential overlaps and identify suitable approaches for specific purposes.

For practitioners, this contribution highlights the importance of a thoroughly thought-through and strategic approach to sustainability when working in product engineering to ensure a targeted application of approaches that support the achievement of sustainability goals (purpose). Furthermore, the proposed explication framework and its implications should be further developed and operationalized. Thereby, practitioners would be enabled to consistently select, combine, and tailor sustainability approaches and strategies for their purpose (e.g., given in a corporate strategy or stakeholder requirements) beyond the mere application of existing approaches.

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