Proceedings of the Design Society, Volume 5: ICED25
https://doi.org/10.1017/pds.2025.10104

Challenges in addressing sustainability within product development

Katharina Zumach ✉, **Sven Wehrend** and **Dieter Krause**

Hamburg University of Technology, Germany

✉ katharina.zumach@tuhh.de

ABSTRACT: Due to climate change, sustainability has become a crucial topic in product development, while addressing it is associated with many challenges. Based on a literature review, those challenges are collected and clustered into nine categories and sub-categories defined for this purpose. Additionally, a research project is analysed. The exhibited challenges such as data availability versus influenceability, a lack of unified sustainability criteria, and decision-making trade-offs underscore the need for refined methodologies and collaboration in sustainability-oriented design. The differently sourced challenges are compared and the new challenges arising from the research project are sorted into the categories. Finally, possible reasons are discussed for why within the project only challenges from four out of nine categories are encountered.

KEYWORDS: sustainability, product development, challenges, design practice, design process

1. Introduction

Due to the urgency of climate change and the associated increase in regulatory requirements, such as the European Green Deal (EGD) and the resulting policies like the Ecodesign for Sustainable Products Regulation (ESPR), sustainability in product development has become an imperative for companies. Furthermore the integration of sustainability aspects is seen as crucial to ensure long-term competitiveness (Schulte & Hallstedt, 2017a). However, this integration is associated with challenges since there are several approaches to measure sustainability as well as various approaches to address sustainability in product development focussing on different aspects and product life phases. The development of modular product families offers additional potential with regard to sustainability, for example in relation to the realization of the R imperatives (Sonego et al., 2018), and a way of mastering variety-induced complexity (Krause & Gebhardt, 2023). With regard to product development, new methods are needed to integrate sustainability in design as a new target variable (Schuh et al., 2023). Yet, it is important to clearly identify challenges in addressing sustainability. Therefore, this paper first presents a literature review to identify challenges that arise in addressing sustainability in product development. This paper also presents challenges faced by the authors in the context of a research project for the development of sustainable aircraft cabin components and systems using a holistic understanding of sustainability. The challenges encountered in the project are then compared with the challenges found in the literature.

2. Research background

Sustainability is becoming an increasingly important issue in society, politics and business. Policy initiatives such as the EGD (European Commission, 2019) are increasing the pressure on companies to assess and improve the sustainability of their own operations and products. In the EGD, the European Commission has set itself the goal of achieving net-zero emissions by 2050 and decoupling economic growth from resource consumption. To this end, the EGD is being concretised in other initiatives such as

the Circular Economy Action Plan (European Commission 2020), enforcing the call for businesses to become more sustainable.
However, assessing the sustainability of a product throughout its lifecycle can be a complex, labour-intensive process, and there are many different indicators to evaluate. Regulatory requirements do also not address a uniform indicator or sustainability aspect. For example, the ESPR mentioned above explicitly addresses R-imperatives such as product durability or reusability, while the Corporate Sustainability Reporting Directive requires the measurement and disclosure of sustainability in the form of greenhouse gas emissions.
In addition to the well-known economic target values of time, cost and quality, sustainability indicators therefore need to be added as a further operational target variables, thus increasing complexity of the development process. Modularisation in general is an established approach of dealing with increasing internal complexity. It describes the targeted development of the modularity of a product, i.e. the combination of components into modules and the definition of interfaces (Krause & Gebhardt, 2023). Modularisation can also have a positive impact on the sustainability of a product, for example by making it easier to disassemble products into modules at the end of their life cycle, so that they can be reused or recycled in a targeted way (Sonego et al., 2018). However, in order to adequately address these positive effects of modularisation, especially towards the end of the life cycle, a holistic view taking into account the entire life cycle is required. Such a holistic approach, which on the one hand takes into account the entire product life cycle and on the other also includes all three pillars of sustainability, brings with it various challenges.
The challenges that can go hand in hand with a holistic approach to sustainability were also identified within a research project. The aim of this project is to design sustainable, resource-efficient components and systems for aircraft cabins, focussing on the modular product architecture in particular. Together with project partners from the aviation industry and science, a holistic view of all three pillars of sustainability is being pursued across the entire product lifecycle. The project team encountered various challenges that prompted to carry out in-depth research on this topic and to see which challenges are already found in the literature and which are not.

3. Research approach

To systematically collect challenges in addressing sustainability, a brief literature review was conducted. As the topic of sustainability is continuously gaining relevance and thus numerous contributions discuss various aspects of sustainability, the initial search string already tried to narrow down the results to contributions within the field of product development. Based on the assumption that challenges in addressing sustainability arise not only in the development of modular product families, but also in the wider field of product development, we did not limit the search to modularity. Therefore, the three search fields “challenges”, “sustainability” and “product development” were defined, whereby each search field contains multiple search terms (Table 1).

Table 1. Search fields and respective search terms for the literature review

Search field“challenges”	Search field“sustainability”“	Search field“product development”
Challenge*	Sustainab*	“product development”
Problem*	Ecodesign	“product design”
Difficult*	Ecological*	
Obstacle*	Green*	
Barrier*	Environment*	
	“Life cycle assessment”	
	Circular*	

Using the online database Scopus, a query (TITLE-ABS-KEY) for the defined search fields with the respective search terms led to 12,432 results as of November 2024. The results were reduced to 5,564 entries by enforcing the explicit reference of the keywords for the search terms in the fields “sustainability” and “product development”. Deeming the number of publications still too high for

detailed analysis, the keywords for the search terms were changed to be the used author keywords. This follows the assumption that author keywords are chosen consciously by the author whereas keywords also include index terms. This resulted in 582 documents found. To further ensure that the results focus on challenges connected to addressing sustainability, the search field "challenges" was narrowed to a search within title or keyword, excluding contributions mentioning the search terms only in the abstract. As the scope of this contribution lies within the field of engineering, filtering for this subarea results in a further reduction from 115 results to now 69 entries. An exclusion of duplicates leads to 67 entries that need to be analysed derived from the scopus search. Snowballing was additionally used in order to be observant of further publications relevant to the topic. The selection process started by reading the title, followed by the abstract, and then, if considered relevant, the entire contribution.
The literature review resulted in a catalogue of challenges, in which many challenges mentioned by different authors overlapped. Thus, duplicate challenges were identified and merged. With respect to their content, the challenges were then clustered into categories. The clustering of challenges found in the literature enabled their comparison with challenges encountered in the research project.
The challenges encountered in the research project are the result of subjective observations and reflections by the project team. With the project focus on researching and designing sustainable, resource-efficient components and systems, challenges mainly occurred concerning sustainable product design itself and not as much the implementation into operational processes. The challenges were discussed repeatedly but informally during project meetings, both in joint workshops between the project partners and in status meetings. They were listed and systematized for the comparison with the challenges found in the literature.

4. Categorisation and comparison of challenges

The following section provides an overview of the results from the literature review, clustered into nine categories building on the challenges and five categories introduced by Dekoninck (2016). This is followed by a comparison of challenges derived from the literature and the challenges encountered in the research project.

4.1. Challenges derived from the literature and categorisation

The literature review resulted in the collection of 72 challenges that can be grouped into the nine categories which is visualised in Figure 1. Each category is further divided into two to five sub-categories, which are briefly described below with the help of exemplarily picked challenges.

Figure 1. Overview of categories and number of challenges therein

Challenges that are connected to a company's ***strategy*** can be grouped into three sub-categories. In terms of *management decision and support*, a lack of management commitment and support hinders the transition to sustainable product development as measures to implement sustainability are not prioritized and support is not consistent (Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Schulte & Hallstedt, 2017a; Wang et al., 2022). For a successful implementation., a clear division of responsibilities

is needed additional to management support, as otherwise it can be difficult to know which department should house the implementation activities (Dekoninck et al., 2016). In order to *develop a long-term strategy*, environmental topics need to be integrated into management and corporate strategy (Dekoninck et al., 2016). Furthermore, to integrate sustainability aspects into product development, new *business models* and solutions that take into account the entire product life cycle are needed (Hallstedt et al., 2023).

On the level of ***operations***, the *integration into the product development process* is considered difficult in terms of the implementation of activities into the process (Dekoninck et al., 2016). On one hand, this might be due to problems fitting with timescales of the process, on the other hand, it could be connected to the lack of systematic approach for the implementation throughout the entire company (Dekoninck et al., 2016). Especially early on in the development process, the *involvement of different stakeholders* is difficult, as is the management of their expectations (Dekoninck et al., 2016). Sustainability aspects should already be included in the planning phase of the product development process (Paulson & Sundin, 2019). Nonetheless, the *management of* customer *requirements* concerning sustainability can be challenging (Dekoninck et al., 2016).

Challenges related to ***society and culture*** as well as ***organizational culture*** can be categorized into *societal challenges*, *company-internal inhibitions*, *policies and regulations*, *infrastructure* and *customer acceptance*. On a *societal* level, environmental impacts have yet to be seen as a global target, so that sustainability becomes a goal to be met (Dekoninck et al., 2016). On the *company* level, there exist *inhibitions* that result in inertia and a lack of motivation for change (Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023). *Policies and regulations* set the framework for industrial practices. Both a lack of governmental action and support hinder the transition towards sustainable product development (Wang et al., 2022). In addition to governmental support, a suitable *infrastructure* needs to be created, e.g. to support circular resource flows (Wang et al., 2022). Additionally, *customer acceptance* ensures the companies' economic continuity. Especially in regard to circular products and services', concerns regarding the performance, quality or safety remain on the customers' side (Wang et al., 2022).

In the category ***collaboration***, *awareness-raising and communication* are important for the implementation of sustainability activities into the development process and the value chain (Dekoninck et al., 2016; Paulson & Sundin, 2019). Thereby, communication among stakeholders with different expertise, be it company-internal or -external stakeholders, is difficult (Dekoninck et al., 2016). For the *internal collaboration* within a company, multidisciplinary as well as multi-department collaboration is needed, even though it can be difficult to collaborate between different departments (Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023). For the *collaboration within the value chain*, the identification of stakeholders from the value chain to be included in the sustainability efforts is challenging (Dekoninck et al., 2016). Companies experience a lack of control over sustainability aspects throughout the whole value chain and need to ensure the fulfilment of sustainability requirements within the value chain (Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a).

The category ***data availability*** can be divided into four sub-categories. In the sub-category of *sustainability assessment and quantification*, one challenge is the definition of criteria used to assess sustainability. On the one hand, there is a variety of criteria that could be applied, on the other hand, sustainability remains hard to quantify and measure which results in a lack of applicable criteria for deciding on the most sustainable solution difficult (Schulte & Hallstedt, 2017a). The missing transparency of decisions and their impact on sustainability hinders the communication to designers and engineers (Hallstedt et al., 2023). In terms of *data collection and depth of analysis*, especially the early stage of product development, the fuzzy front end, poses challenges (Chang et al., 2014). Finding the environmental impact data required is difficult and there is not enough specified information, e.g. to support the definition of goals and scopes (Chang et al., 2014; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023). The *data quality* influences the results of the assessment, which makes the assessment itself sensitive to uncertainties (Chang et al., 2014). In terms of *inherent risk properties*, the challenge of quantification refers to the difficulty of expressing the sustainability risks in numbers and to connecting them with other attributes such as profitability, which ultimately leads to a vague connection between short-term and long-term effects (Schulte & Hallstedt, 2017b).

Different challenges arise connected to ***resource allocation***, more specifically to the allocation of data (cf. data availability), *money*, *time*, and *expertise*. *Money* is needed for example for investment in larger innovation projects, as there are start-up costs to be dealt with (Held et al., 2018; Skjøndal Bar, 2015; Wang et al., 2022). If no extra *time* is allocated for new process steps and initiatives, steps such as the

assessment of sustainability, the redesign of components and the search for suppliers that provide sustainable solutions are not implemented (Paulson & Sundin, 2019). The lack of *expertise* is two-fold. Employees often do not have the necessary level of sustainability knowledge (Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019; Skjøndal Bar, 2015; Wang et al., 2022). Additionally, there is a lack of common definition or shared understanding of the term sustainability within companies (Gröbe-Boxdorfer & Engeln, 2023; Schulte & Hallstedt, 2017a, 2017b).

Challenges concerning ***method or tool support*** either refer to the *selection* or the *implementation and application* of tools or methods. For the *method or tool selection*, criteria are needed to identify the most appropriate tool or method (Dekoninck et al., 2016; Held et al., 2018). The *implementation and application* pose challenges, which can be seen from the fact that many tools are not used in industrial practice (Hallstedt et al., 2023; Held et al., 2018; Skjøndal Bar, 2015). Furthermore, the implementation of new tools into the development process is difficult and there is also a need for new tools, e.g. for tools that are able to give an overview of the impact of different design alternatives and how conflicting goals can be dealt with (Dekoninck et al., 2016; Schulte & Hallstedt, 2017a).

Results from the application of methods, e.g. results of sustainability assessment methods such as life cycle assessment (LCA), are not immediately applicable for ***decision making*** (Dekoninck et al., 2016). The assessment results are therefore mainly used for reporting instead of for product improvements (Held et al., 2018). Using sustainability knowledge to support decision making across different functions poses a challenge concerning *decision making in the product development process* (Dekoninck et al., 2016). Furthermore, *trade-offs* exist within different sustainability criteria themself as well as between sustainability goals and economic goals. There is a perceived inherent conflict between sustainability and financial goals and the connection to cost and value is vague (Schulte & Hallstedt, 2017a, 2017b). As the relation between sustainability and profitability is not obvious and the customers' willingness to pay is unclear (Held et al., 2018; Schulte & Hallstedt, 2017a), sustainability still is seen rather as a add-on than a necessity (Gröbe-Boxdorfer & Engeln, 2023). On top of that, there is no formalized approach to handle trade-offs and the quantification and measurement of sustainability is, as discussed above, challenging (Schulte & Hallstedt, 2017a).

In terms of *methodological* ***complexity***, sustainability in itself is generally seen as complex, as it is interwoven with societal and economic processes (Gröbe-Boxdorfer & Engeln, 2023). As described above, the implementation and assessment of sustainability is difficult, especially in early phases. With the limitation of time and of data available in the early design stages, the integration of sustainability needs to be done without compromising the completeness of sustainability assessment and improvements (Hallstedt et al., 2023). The *technology-induced complexity* is connected to the need to address new types of needs and simultaneously integrate new types of technologies with high potential for increasing sustainability in process or product (Hallstedt et al., 2023). *Product-induced complexity* is related to understanding the product's effect on the environment (Balkenende & Bakker, 2015). Especially technologically advanced products such as electronics entail an intrinsic complexity, that can pose challenges for example for end-of-life treatment (Balkenende & Bakker, 2015). Lastly, the lifespan of a product influences the pace of change. Especially products with long life spans, such as machinery, constitute long-lasting investments, that can cause a lock-in preventing investment in new environmentally better solutions (Skjøndal Bar, 2015).

Table 2 summarizes the categories and sub-categories as well as the references in which challenges, that are grouped into the respective category, are mentioned. Below the table, the challenges encountered in the research project are described and compared to the challenges from the literature.

Table 2. Categories and sub-categories of challenges in addressing sustainability

Category	Sub-category	Reference(s)
Strategy	Management decision & support	(Abu et al., 2018; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a; Wang et al., 2022)
	Development of long-term strategy	(Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Schulte & Hallstedt, 2017a, 2017b; Skjøndal Bar, 2015)
	Business model	(Dekoninck et al., 2016; Hallstedt et al., 2023)

(*Continued*)

Table 2. Continued.

Category	Sub-category	Reference(s)
Operations	Integration into the product development process	(Dekoninck et al., 2016; Hallstedt et al., 2023; Paulson & Sundin, 2019)
	Stakeholder involvement	(Dekoninck et al., 2016)
	Management of requirements	(Dekoninck et al., 2016; Paulson & Sundin, 2019; Skjøndal Bar, 2015)
Society or (organizational) culture	Societal challenges	(Dekoninck et al., 2016)
	Company-internal inhibitions	(Abu et al., 2018; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Wang et al., 2022)
	Policies & regulations	(Abu et al., 2018; Gröbe-Boxdorfer & Engeln, 2023; Wang et al., 2022)
	Infrastructure	(Gröbe-Boxdorfer & Engeln, 2023; Wang et al., 2022)
	Customer acceptance	(Wang et al., 2022)
Collaboration	Awareness & communication	(Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019)
	Internal collaboration	(Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Schulte & Hallstedt, 2017a, 2017b)
	Value chain collaboration	(Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a)
Data availability	Sustainability assessment & quantification	(Gröbe-Boxdorfer & Engeln, 2023; Hallstedt et al., 2023; Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a, 2017b)
	Data collection & depth of analysis	(Chang et al., 2014; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019)
	Data quality	(Chang et al., 2014)
	Inherent risk properties	(Schulte & Hallstedt, 2017b)
Resource allocation	Money	(Abu et al., 2018; Held et al., 2018; Paulson & Sundin, 2019; Skjøndal Bar, 2015; Wang et al., 2022)
	Time	(Dekoninck et al., 2016; Paulson & Sundin, 2019)
	Expertise	(Abu et al., 2018; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a, 2017b; Skjøndal Bar, 2015; Wang et al., 2022)
Method or tool support	Method or tool selection	(Dekoninck et al., 2016; Held et al., 2018)
	Method or tool implementation & application	(Dekoninck et al., 2016; Hallstedt et al., 2023; Held et al., 2018; Schulte & Hallstedt, 2017a; Skjøndal Bar, 2015)
Decision making	Results of method application	(Dekoninck et al., 2016; Held et al., 2018)
	Decision making in the product development process	(Dekoninck et al., 2016; Wang et al., 2022)
	Trade-offs	(Chang et al., 2014; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Hallstedt et al., 2023; Held et al., 2018; Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a, 2017b)
Complexity	Methodological complexity	(Chang et al., 2014; Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Hallstedt et al., 2023)
	Technology-induced complexity	(Dekoninck et al., 2016; Gröbe-Boxdorfer & Engeln, 2023; Hallstedt et al., 2023; Wang et al., 2022)
	Product-induced complexity	(Balkenende & Bakker, 2015; Skjøndal Bar, 2015)

4.2. Challenges encountered in the project compared with the literature

The first challenge encountered in the project is the contradiction between influenceability and data availability. Especially at the beginning of a development project in the conceptual design phase, when many decisions have not yet been made, sustainability can be strongly influenced (Han et al., 2021). In contrast, assessing sustainability at this stage is afflicted with inaccuracies as the product is still vague and therefore assumptions have to be made. The assessment is furthermore dependent on the individual

company processes. This gives rise to the following question: At which point in the development process is the influenceability of the different sustainability aspects constrained by decisions. For example, material selection can be decided early on in order to narrow the sustainable design space (Hallstedt, 2017) and the materials themselves can be assessed, but the final sourcing decision is often not in the responsibility of product development. Decisions about the sourcing of raw materials, semi-finished products and components, which are relevant to social sustainability, are finalised later in the process, when the product is sufficiently concrete. The suppliers can also change after start of production which impacts the product's sustainability assessment. Decisions on different functional principles, which can strongly influence the efficiency of a product in its use phase, are made at an early stage and therefore have to be decided on the basis of vague data. This is confirmed by the challenges relating to data availability that are mentioned in the literature, especially concerning the limitation of data in the early stage of product development (Chang et al., 2014; Hallstedt et al., 2023) and the challenge of finding a balance between simplification and potential loss of accuracy, reliability, or quality (Dekoninck et al., 2016). However, the challenge of unclear influenceability of aspects could be added to highlight the contradiction between influenceability and data availability.

The consortium within the research project consists of four project partners. Both on company/university level as well as on an individual level, everyone had a unique understanding of sustainability. This goes in hand with the lack of a common definition of sustainability, as described by Gröbe-Boxdorfer and Engeln (2023) as well as Schulte and Hallstedt (2017a, 2017b). To overcome this challenge, various definitions of sustainability as well as sustainability criteria were researched by the different research partners. They were compiled and compared in several joint workshops. This aimed towards sharing a joint understanding of sustainability within the project and in the context of the aviation industry.

When researching sustainability criteria within the project, a variety of different criteria and indicators, from quantitative to qualitative, were found. However, there was no consistency in the information provided to explain the different criteria, nor was there a catalogue of criteria and indicators with support or guidelines on when to use which indicator in terms of solution space within the product development process. This confirms the challenges within the sub-category of *sustainability assessment and quantification*. That is, that sustainability is hard to quantify and the transformation of sustainability goals into measurable requirements remains subject of research (Paulson & Sundin, 2019; Schulte & Hallstedt, 2017a, 2017b).

The challenge of the lack of sustainability criteria that was perceived by the companies in the questionnaire study of Schulte and Hallstedt (2017a), which aimed at identifying preconditions and capabilities for the integration of sustainability in product development, first seems to be in contrast to the variety of criteria found within the research project. However, as explained by Schulte and Hallstedt (2017a), the lack of sustainability criteria refers to the lack of approach or applicable criteria for identifying and deciding the most sustainable solution. This strengthens the other challenges mentioned in terms of the quantification of sustainability and its translation into specific requirements. No single criteria of sustainability can be found, as sustainability entails different dimensions and therefore many different aspects. The phrasing could therefore be changed to lack of (directly applicable) criteria or lack of criteria to find sustainable solution, which would then entail the variety of criteria within the literature and the difficulty for companies to choose a criterion. Additionally, the challenge of the lack of support for choosing sustainability criteria could be added, analogously to the lack of criteria for selecting the most suitable tools or methods mentioned in Dekoninck et al. (2016) and Held et al. (2018). In connection with the above-mentioned contradiction between influenceability and data availability, the selection of criteria should be focused on aspects that can be influenced by the decision maker. In early design stages, for example, it can be helpful to relate the sustainability criteria to the different levels of the product architecture as described by Wehrend et al. (2024).

Within the realm of decision making, sustainability goals add further requirements that have to be taken into account. Therefore, as mentioned in the literature, trade-offs arise (Dekoninck et al., 2016; Schulte & Hallstedt, 2017a). This was also encountered within the project as different criteria are evaluated and therefore target-conflicts emerge. In the context of aviation, the product life cycles or, more precisely, the time in use of the product is long, as aircrafts are usually operated for roughly 30 years. Due to the long time in use and the fuel consumption during operation, the use phase is currently the phase in which most emissions are emitted. As mentioned by Skjøndal Bar (2015) the product influences the possible pace of change. In the context of sustainability and criteria to be applied, the type of product also influences the levers that should be applied to improve the product's sustainability. Currently, weight is the determining

factor to evaluate sustainability in the aviation industry. No alternative concept would be implemented, if it was heavier than another. In the aviation industry, the following question therefore arises: When will the shift in perspective happen when weight is not enough? The information about product types and a respective categorisation of methods, as proposed by O'Hare and McAloone (2014), would hereby support the selection of suitable methods. Therefore, the challenge of a lack of support in choosing tools or methods (Held et al., 2018) is encountered in the research project.
To summarize the challenges encountered in the research project, they are visualised in Figure 2.

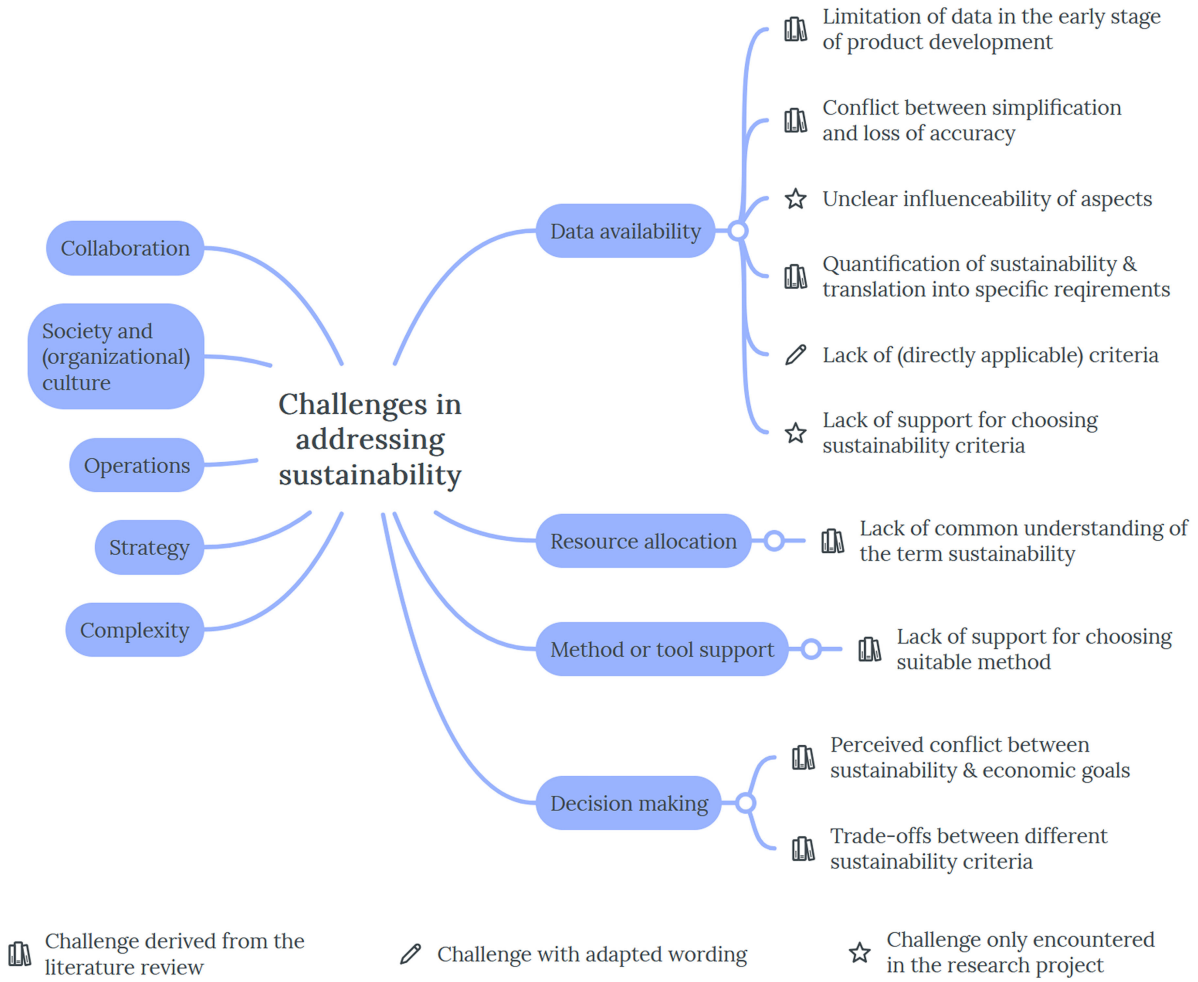

Figure 2. Challenges encountered in the research project and sorted into the categories

Figure 2 shows that the main challenges in the project can be sorted into the four categories *data availability*, *resource allocation*, *method or tool support*, and *decision making*. The other five categories remain unchanged and are briefly discussed below. The icon on the left of the challenge indicates its origin. The books represent a challenge derived from the literature review. The pencil marks a challenge that was found in the literature but was slightly adapted in wording. The star represents a challenge that was encountered in the research project but not found in the literature review.
Challenges in the category *strategy* focus on the strategic considerations and decisions on the corporate level of a company. In contrast, work on a research project is associated with methodological aspects. Therefore, the strategic challenges were not encountered in the project, even though they may exist for the companies of the industrial partners. The fact that no challenges arose in the project with regard to *operations* can be attributed to the fact that it is a research project, meaning that the activities are not subordinate to the general product development process of the industrial partners, but are detached from it. The same applies to the category *Society or (organizational) culture*, as the research activities take place to a certain extent away from the daily business. Potential contact with internal resistance tends to take place later, when results are to be transferred into the development process. Within the scope of the

project, no challenges in *collaboration* arose which might be attributed to the nature of researching somewhat apart from operational business. Having a methodical research background, the challenges associated with *complexity* are recognized, but not directly perceived as hurdles by the researchers.

5. Conclusion and outlook

This contribution presents the results from a literature review concerning challenges in addressing sustainability in product development. The challenges found in the literature were clustered into nine categories, namely the categories *strategy*, *operations*, *society or (organizational) culture*, *collaboration*, *data availability*, *resource allocation*, *method or tool support*, *decision making*, and *complexity*. The challenges from the literature were furthermore complemented by and compared to experiences from a research project. Out of ten challenges identified in the research project, seven were identical to challenges mentioned in the literature. For one existing challenge a slight change in wording was proposed. The two additional challenges that were identified were furthermore assigned to the categories. Lastly, it was discussed why in the project there were only found challenges from some of the categories and not from all of them.

Concerning the limitation of this contribution, the conducted literature review concentrated on contributions that explicitly focused on identifying and discussing challenges. However, foundational publications about sustainability in product development could also be analysed in regard to challenges met. The literature review conducted in this study therefore needs to be extended to a systematic literature review including fundamental publications about sustainability. Furthermore, the collection of challenges encountered in the research project is the subjective perception of the project members and could therefore be limited to the project context. Hence, an interview study in the companies of the project partners would be beneficial to further explore the challenges in addressing sustainability and verify whether the challenges encountered in the project generally apply.

The challenges identified in relation to addressing sustainability in product development highlight the multifaceted nature of sustainability. This is also reflected in the different categories to which the identified challenges have been assigned. Addressing sustainability in product development brings new objectives and thus additional complexity to the development process. This leads to different areas for future research. Especially the category *data availability*, which encompasses challenges associated with the assessment of sustainability, poses room for further investigations as with twelve challenges it contains the highest number of challenges therein. On one hand, there is a need for support in selecting suitable sustainability indicators and mapping existing approaches to improving sustainability to these indicators. On the other hand, supporting decision making in the context of sustainability should be further researched. This involves dealing with uncertain data in the early stages of product development on the one hand, and with trade-offs between sustainability and economic efficiency as well as between sustainability criteria on the other. The challenges in the category *strategy* should furthermore be analysed and targeted more in depth, as they lay the foundations for the successful implementation of sustainability measures in the company.

Acknowledgement

The presented research is based on the results of the project “RECab - Resource Efficient Cabin (FKZ: 20K2103E)” and is funded by the Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the sixth Civil Aeronautics Research Program (LUFO VI-2).

References

Abu, N. H., Kean Huat, K., & Mansor, M. F. (Eds.) (2018). *Implementation of Green New Product Development among SMEs: Barriers and Critical Success Factors*. Vol. 150. https://doi.org/10.1051/matecconf/201815005038

Balkenende, A. R., & Bakker, C. A. (2015). Developments and challenges in design for sustainability of electronics. In *Advances in Transdisciplinary Engineering*. https://doi.org/10.3233/978-1-61499-544-9-3

Chang, D., Lee, C., & Chen, C.–H. (2014). Review of life cycle assessment towards sustainable product development. *Journal of Cleaner Production*, 83, 48–60. https://doi.org/10.1016/j.jclepro.2014.07.050

Dekoninck, E. A., Domingo, L., O'Hare, J. A [Jamie A.], Pigosso, D. C., Reyes, T., & Troussier, N. (2016). Defining the challenges for ecodesign implementation in companies: Development and consolidation of a framework. *Journal of Cleaner Production*, 135, 410–425. https://doi.org/10.1016/j.jclepro.2016.06.045

European Commission. (2019). *Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions- The European Green Deal*. Publications Office of the European Union. https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-https://doi.org/10.2777/33415

European Commission: Directorate-General for Research and Innovation. (2020). *Circular economy action plan: For a cleaner and more competitive Europe*. Publications Office of the European Union.

European Parliament, Council of the European Union. (2024). *Regulation (EU) 2024/1781 of the European Parliament and of the Council of 13 June 2024 establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC*. http://data.europa.eu/eli/reg/2024/1781/oj

Gröbe-Boxdorfer, B., & Engeln, W. (2023). Challenges in integration of sustainability requirements into product development of companies. In *Stuttgarter Symposium für Produktentwicklung*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85171805278&partnerID=40&md5

Hallstedt, S. I. (2017). Sustainability criteria and sustainability compliance index for decision support in product development. *Journal of Cleaner Production*, 140, 251–266. https://doi.org/10.1016/j.jclepro.2015.06.068

Hallstedt, S. I., Isaksson, O., Nylander, J. W., Andersson, P., & Knuts, S. (2023). Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from GKN Aerospace Engine System. *Design Science*, 9. https://doi.org/10.1017/dsj.2023.22

Han, J., Jiang, P., & Childs, P. (2021). Metrics for Measuring Sustainable Product Design Concepts. *Energies*, 14(12), 3469. https://doi.org/10.3390/en14123469

Held, M., Weidmann, D., Kammerl, D., Hollauer, C., Mörtl, M., Omer, M., & Lindemann, U. (2018). Current challenges for sustainable product development in the German automotive sector: A survey based status assessment. *Journal of Cleaner Production*, 195, 869–889. https://doi.org/10.1016/j.jclepro.2018.05.118

Krause, D., & Gebhardt, N. (2023). *Methodical Development of Modular Product Families*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-65680-8

O'Hare, J. A [J. A.], & McAloone, T. C. (2014). Eco-Innovation: The Opportunities For Engineering Design Research. In D. Marjanović, M. Štorga, N. Pavković, & N. Bojčetić (Chairs), DS 77: Proceedings of the DESIGN 2014 13th International Design Conference.

Paulson, F., & Sundin, E. (2019). Challenges When Including Sustainability Aspects in Product Development at Two Large Manufacturing Companies in Sweden. In *Technologies and Eco-innovation towards Sustainability I: Eco Design of Products and Services* (pp. 229–243). https://doi.org/10.1007/978-981-13-1181-9_18

Schuh, G., Kuhn, M., Keuper, A., Patzwald, M., Schenk, L., Feucht, M., Kantelberg, J., Rossmair, G., Schroth, H., Viethen, U., Zeller, P., & Guo, D. (2023). *Neue Modularität und Technologie-Roadmapping*. https://doi.org/10.24406/publica-960

Schulte, J., & Hallstedt, S. I. (2017a). Challenges and preconditions to build capabilities for sustainable product design. In *Proceedings of the International Conference on Engineering Design, ICED*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029747884&partnerID=40&md5

Schulte, J., & Hallstedt, S. I. (2017b). Challenges for integrating sustainability in risk management-current state of research. In *Proceedings of the International Conference on Engineering Design, ICED*. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85029742256&partnerID=40&md5

Skjøndal Bar, E. (2015). A case study of obstacles and enablers for green innovation within the fish processing equipment industry. *Journal of Cleaner Production*, 90, 234–243. https://doi.org/10.1016/j.jclepro.2014.11.055

Sonego, M., Echeveste, M. E. S., & Galvan Debarba, H. (2018). The role of modularity in sustainable design: A systematic review. *Journal of Cleaner Production*, 176, 196–209. https://doi.org/10.1016/j.jclepro.2017.12.106

Wang, J. X., Burke, H., & Zhang, A. (2022). Overcoming barriers to circular product design. *International Journal of Production Economics*, 243. https://doi.org/10.1016/j.ijpe.2021.108346

Wehrend, S., Schwan, L., Zumach, K., & Krause, D. (2024). Towards a holistic approach to increase sustainability in aircraft cabin design. In *4th Congress of the International Council of the Aeronautical Sciences, ICAS 2024*, Florence. https://doi.org/10.15480/882.13645