Design Aspects of Importance in a Sustainability Transition

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Abstract: In this paper, sustainable product design in the aerospace industry is explored. Through a pilot interview study with three aerospace companies, four sustainability aspects, tightly connected to business value, were identified widely prioritized in early phases. Other aspects were currently considered with less importance, but due to external constraints and business opportunities this prioritization can rapidly shift. Prioritized aspects in early phases control a solution's sustainability profile, determine the pace towards sustainability transition, and can provide a competitive advantage.

Keywords: Sustainability, Product Development, Sustainable Design, Design Methodology, Aerospace

1. Introduction

The main argument explored in this study is that engineering design activities, aimed at mitigating sustainability impact and develop more sustainable solutions, are found in nearly all product development stages. However, it is not yet enabling a holistic sustainability approach, which would consider environmental, social and economic sustainability factors together. Moreover, this paper aims to identify which sustainability aspects receive emphasis at different stages of the development process and whether variances exist among aerospace companies.

Sustainability in aerospace

Commercial aviation represented approximately 2% of global greenhouse gas emissions in 2019, but forecasts suggest an escalation due to the 3.6% expected annual average growth rate of passenger market over the next three decades (ICAO, 2022). This industry will represent as much as 20% of manmade greenhouse gas emissions by 2050 if no significant action is taken. However, aerospace has set long-term decarbonization targets, though progress against these goals have been limited (Losada et al., 2020). Moreover, recent developments have made it clear that society's sustainability challenges extend beyond climate impact alone, driving sustainable development in the global business that is aerospace. Just meeting the 2050 net-zero vision, alongside goals for NOx emissions and noise reduction (European Commission, 2022) will demand efforts across the entire value chain of aerospace products.

Society is expecting the aerospace industry to become more sustainable; the flight-shame anti-flying social movement has had a measurable impact in Sweden and Germany, where the number of passengers taking domestic flights decreased to the benefit of the train industry (Pesce, 2019). The movement, however, has had little impact so far in other continents than Europe.

New regulations and policies are already being launched, such as the EU's Green Deal and EU's critical raw materials act, enforcing a transition towards circular economy and more regional value chains (European Commission, 2022, 2023). A circular economy is a model of production and consumption that involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products for as long as possible. These regulations will most likely have an impact on EU's aerospace companies which heavily rely on the other continents to supply special materials or components. The increased number of new regulations and directives require higher attention to sustainability, however with the risk of overemphasizing the reporting itself rather than on actually driving change. In addition to policies and regulations, aerospace organizations (ICAO, 2022, ACARE, 2022), authorities, and industrials (FAA, 2023, EEA, 2022, Van der Sman et al., 2020) are driving the sustainability transition by setting long-term aspirational goals with regards to sustainability. This enables aerospace companies to collaborate internationally in areas such as materials disclosure, greenhouse gases, emerging global regulations, environmental certification and supply chain (IAEG, 2023). Altogether, there are several actors that push and drive the change in the aerospace industry towards more sustainable solutions.

Aerospace faces distinctive obstacles when developing sustainable solutions, which limits the adoption of sustainable design practices developed in other fields.

Time perspective is one such challenge, as the development of aerospace products is often three to seven years in average, constrained by standards, regulations and certifications. The certification of aircraft – determining the overall architecture and definition of an Aircraft is extremely expensive and rarely done from scratch which limits the adoption of radical innovations that could enable a more sustainability, such as electric or hydrogen flight. In addition, the operational lifespan in the civil industry averages around 26.5 years (ICAO, 2019). For instance, the B747 was certified in the late 60s and its derivative aircrafts, building further on the original aircraft certification, has been in production until 2022. In short, aerospace products design today will still be in use in 2050. Given the urgency of a sustainable change, it is crucial to enable this transformation while balancing tactical and strategic goals.

The need to use advanced materials and manufacturing methods is another sustainability challenge that the industry is facing (Hallstedt and Isaksson, 2017). Materials for aerospace products need to be thoroughly certified for safety reasons, and are often expensive. Specific alloys are many times scarce and critical from availability and sustainability perspective, and are not included in a circular loop, as well as frequently hard to substitute. Similarly, promising manufacturing methods for alloy-based components in the aerospace industry, e.g. Additive Manufacturing, can be far more energy-intensive than conventional manufacturing and does not necessarily reduce material use or waste. The operating space to make materials and manufacturing processes more sustainable in aerospace is difficult to comprehend and utilize at its maximum.

Therefore, there is a need to develop knowledge and capabilities in Aerospace industry to deal with the added complexity that sustainability challenges bring. Aerospace companies are invested in research for design to optimize the life cycle of circular solutions by including repair and remanufacturing as design parameters (Handawi et al., 2021). Furthermore, there is a need to enable product development teams to develop resilient solutions and thereby actively contribute to the sustainability transition of aerospace industry.

Sustainable product development

The implementation of UN’s 2030 sustainable development goals (United Nations, 2015) has an impact on the products, systems, solutions, and infrastructure that are needed. Production and decarbonization are areas that need transformation to achieve these goals (Nakicenovic et al., 2019). Through Clean Aviation, aerospace has emphasized the climate change challenge, but also recognized the need to develop new business models to handle energy and materials transformation. Sustainable development brings a range of new constraints and aspects to relate to, which is why the practices of product development continuously need to be adapted. The fact that the well-known insight that 80% of a product’s sustainability impact over its life cycle is set already in the early design phases puts product development and its early phase decision making in focus. The understanding of sustainability challenges and opportunities is consequently critical to include already in the early phases of product development, e.g. in portfolio- and product requirement management (EEA, 2017; Watz and Hallstedt, 2020, 2022; Villamil et al., 2022; Watz and Hallstedt, 2021).

Sustainable product development, can be defined as the integration of sustainability into the early phases of the product innovation process and includes a life-cycle thinking, and is therefore an important measure in the development of a more sustainable product design and production (Watz and Hallstedt, 2022). In a company, integrating sustainability aspects into product development is a complex task. This means: i) developing solutions that benefit from new technologies, i.e., new to the company and the market, with a high sustainability potential; ii) developing business models and solutions that covers the full life-cycle and its value-chain; and, iii) managing and mitigating the risk associated with new technologies and new business models (Schulte and Knuts, 2022).

While various methods and approaches for integrating sustainability in product design exist, efficiently implementing sustainable development remains a challenge for many industries (Faludi et al., 2020). The challenge facing the transportation industry in general, and aerospace in particular, will require a significant transformation in products and technologies. Realizing such challenges requires an equally shift in thinking, acting and confidence and robustness in the new approaches. This needs to be included in the design and development systems, routines and methods, something that is challenged by the systemic and holistic nature of sustainability. The understanding and designing of products to meet increased needs and expectations for sustainable products cannot be seen in isolation, but rather needs to bridge design, technology, business and quality aspects with a complete life-cycle perspective.

In the challenge to provide sustainable solutions, it is expected that product developing companies need to simultaneously address a new type of needs and integrate a new type of technologies into functioning solutions. It is argued that this will require new practices that provide what will be referred to as capabilities, or more specifically, sustainable product development capabilities. Sustainable product development capabilities can be defined as: "Skills and knowledge in the field of sustainable product development, exercised through support methods and tools applied in routines and organizational processes, which enable firms to coordinate activities on strategic, tactical and operational organizational levels to accelerate towards a sustainability transformation and make use of their assets." (Hallstedt et al., 2023b).

At present in the industry, there is a lack of understanding of the sustainability complexity of technology development. There is a need to strengthen i) the ability to direct product development by developing criteria for sustainability that offer both the search for new solutions and evaluation of sustainability performance of emerging and existing products and ii) strengthen the ability to identify and manage risk already in design (Hallstedt et al., 2023b).

Providing sustainable solutions to the market is no longer only of strategic importance for aerospace, but rather business critical. The industrially negotiated strategies in Europe (Clean Aviation, 2021) and the UK (Department of Transport, 2021) outline actions necessary for reaching 2050 greenhouse has emission targets. The Aerospace industry will also need to comply with other targets expressed in the new industrial strategy to meet the European Union's Green Deal (European Commission, 2022). One such area is the use of resources, where circular economy solutions and legislative actions are central. Therefore, in addition to the ambitious targets on emissions, the industry needs to address also material resource targets. Such disruption in the business has not been seen in aerospace since the introduction of jet propulsion more than 60 years ago. Although aerospace is a high technology business, the number one priority for aerospace has been, and still is, flight safety that has practically limited the ability to introduce too radical solutions into business. The safety levels of today are several orders of magnitude higher than the safety levels of early jet age, and a fundamental challenge is how to succeed with radical and disruptive changes while maintaining the high safety standards of today (Hallstedt et al., 2023b).

In the formulation of the conceptual framework underpinning this study, a preliminary investigation was conducted at the three companies. Targeting interview participants with a leading position in sustainability, technology and strategy, this pre-study enabled gaining a better understanding of the sustainability approach across these three companies (Léonard, 2024).

Objective and purpose

This study delves into the argument that engineering design activities, aimed at mitigating sustainability impact and fostering the creation of more sustainable solutions, are not providing a holistic sustainability approach, especially at early design stages. The primary aim of this paper is to conduct a pilot-study that examines the prioritization of sustainability aspects across different phases of the development process and to clarify the underlying reasons. Additionally, it investigates the variability among three aerospace companies in this regard. The scope of the study is within the aerospace industry but can be relevant and applicable to a wider range of industries. From this pilot-study, potential challenges and knowledge gaps can be identified to be further investigated and addressed in future research studies and contribute to the overall research objective.

This pilot-study is part of a larger research topic that aims to propose a comprehensive sustainability transition roadmap for the Aerospace industry, and to outline measures and activities to meet challenges such as:

- how to identify and manage sustainability-related trade-off situation in radical innovation shifts for products with complex life cycles;
- how a sustainability life cycle approach supports a circular economy approach and paves the way towards the sustainability transition of the industry;
- identifying relevant operations to implement sustainable product development in the early engineering design for an acceleration towards a sustainability transition.

2. Methodology

To comprehend the manner in which sustainable product development is approached within the aerospace industry, the involvement of industry professionals emerges as a requisite. Moreover, it is crucial to understand both process knowledge, which involves examining sustainability considerations within established procedures, and context knowledge, which explains the reasons behind and practical manifestations of these processes. The expert interview approach was deemed pertinent, given its capacity to reconstruct both types of knowledge, alongside its suitability for exploration and theory formulation (Flick, 2009). A semi-structured interview study was conducted in which three different companies participated. Due to the limited number of interviewees, this research is considered as a pilot study that can be further expanded. Located in Sweden, the companies provide a comprehensive view of product and technology development in the aerospace industry in Europe through their different sectors (civil, defense) and types of solutions (Original Equipment Manufacturer (OEM), component designer, and system integrator). Therefore, this variety of focus areas increases the understanding of how to accelerate the sustainability transition in a variety of situations. The interrogated companies' development stages were represented by at least two out of the three companies:

1. Early phase and Innovative Product Development, where alternate concepts, materials and design solutions are investigated.
2. Mature and Evolutionary Product Development, where requirements and constraints limit the room for larger changes.
3. Product Development for Derivatives, Upgrades and Remanufacture, where changes and measures need to comply with already certified product solutions.

The participants selected for this pilot-study of interviews – one per company – are key information stakeholders. They are intimately engaged in the formulation and refinement of prescribed standards within sustainability and product development, fostering close ties with practitioners within their organizations. The role of the interview participants and a short description of the case companies is available in Table 1.

Table 1. Types of case companies and roles of interview participants

Company A	Company B	Company C
Component designer/manufacturer to civil and defense sectors Interview participant (s): Sustainability specialist	OEM, systems and component designer/manufacturer to civil and defense sectors Interview participant (s): Sustainability specialist	OEM to civil sector Interview participant (s): Research and Development specialist

From previous research, a comprehensive set of sustainability criteria to consider in the early stages for aerospace components have been identified (Hallstedt, 2017; Kwok et al., 2020; Hallstedt et al. 2023a), which were compared against criteria tested in the automotive industry (Schöggl et al., 2017). The resulting list of criteria is displayed Table 2.

Table 2. Sustainability criteria used for the interview study

Materials	Production	Use	End-of-life
Critical minerals Recycled / bio-based materials Environmental footprint	Material efficiency Substances of concern Health and safety Environmental footprint Scrap recyclability Transport distances	Product weight Energy efficiency Health and safety Noise	Potential for reuse, repair, refurbish Potential for recycling

The semi-structured interviews included an examination of each dimension of Table 2. The interview sessions, each of approximately one hour, were supplemented by e-mail correspondence. Interview participants were presented with the following targeted inquiries:

- Assessment of the current integration of each aspect into product development;
- Rationale underlying the inclusion or exclusion of the respective aspect;
- Description of disparities across distinct product development phases, namely (1) early design, (2) mature design and (3) design for derivatives;
- Anticipation of the incorporation of the examined aspect;
- Evaluation of the availability of support tools and methodological approaches facilitating consideration of the identified aspects

Based on the participant responses, a qualitative measurement approach, adopting the Sustainability Compliance Index (SCI 9 to SCI0) (Hallstedt, 2017) was used. The results were summarized for each case company for each criterion according to the following SCI scale:

- SCI 9: Aspect is systematically considered and prioritized, at any design stage;
- SCI 6: Aspect is systematically considered, but not prioritized, at any design stage;
- SCI 3: Aspect is partially or occasionally considered, at any design stage;
- SCI 1: Aspect is not considered at any design stage;
- SCI 0: Do not know if the aspect is considered during the design process.

3. Results

This pilot study revealed that the three case companies shared similar prioritization views on a set of seven sustainability aspects. However, only three of these aspects held high priority for the companies, (i.e., energy efficiency, weight, and health and safety) and the rest (i.e., transport distances, scrap recyclability, potential for recycling, recycled-bio-based materials) held low priority.

Figure 1 represents a spider web diagram illustrating the sustainability aspects prioritization among the various companies. As each aspect is ranked from SCI 9 to SCI 0 for each case company, each sustainability aspect has 3 data points. In Figure 1, only the highest and lowest SCI levels are represented by a black dot. A black line was drawn between the two points to highlight divergent prioritization among companies, as it is the case for the *Noise* and *Potential for Reuse* criteria. Original Equipment Manufacturers typically bear significant responsibility in these areas but not component designers, which may explain the differences observed. Aspect within the Use phase appears to often have a high SCI level, whereas there are more inconsistencies and low scores in other life phases.

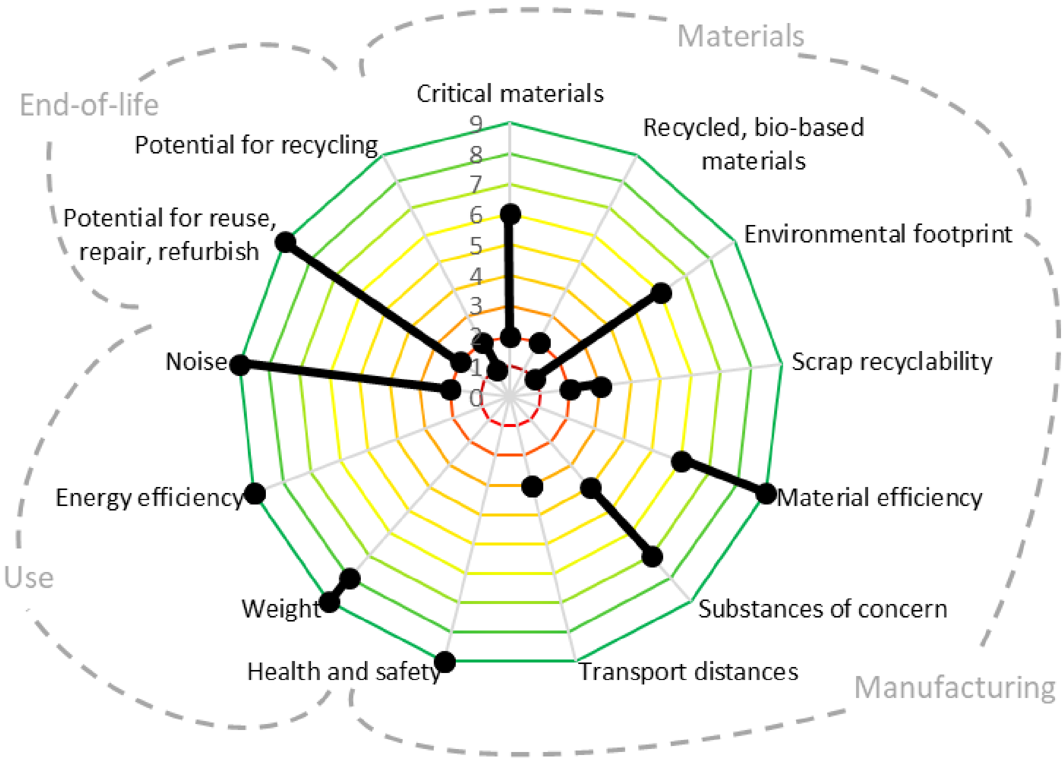

Figure 1. Companies' level of prioritization of sustainability aspects in aerospace product development

The interviews revealed that certain aspects were consistently considered and prioritized while others were not. Additionally, it became evident that the three companies had varying priorities depending on different stages of product development.

Results from the pilot study indicate that *Critical minerals* are an area of sustainability connected to supply risk and economic importance. Many minerals found in aerospace alloys are considered critical. This will be soon targeted by regulations in the EU (European Commission, 2023), and companies will need to secure a portion of their critical mineral purchase within Europe. The interviewed companies see value in considering this aspect early in design to avoid future procurement and regulatory challenges, as they have more freedom to choose materials than in later design stages. One of the interviewed companies considers this aspect systematically as part of their product development process and another was in the process of implementing it for early design phases and mature design phases. However, considering this aspect does not necessarily solve the issue: "Sometimes, we cannot replace critical minerals, so the focus is where we source it instead".

Not yet targeted by regulations but being increasingly part of customer requirements, the pilot study indicates that the *Environmental footprint* is being considered mostly from a climate perspective and using tools such as Life Cycle Assessment. All interview participants conceded that this aspect is foremost considered in early product design (although most frequently qualitatively). “We know how to approach the environmental footprint, but lack the capabilities”. Including more environmental aspects is increasingly important, although not fully implemented: “More and more customers have requirements on climate impact reduction. The industry’s impact on biodiversity is also a growing topic of concern.”

The result of the pilot study also indicated that the *Noise* aspect was considered very differently among the interviewed companies. Two of them are considering it and prioritizing it systematically, using this aspect to benchmark their solutions: “Other than regulatory compliance, it can be real strategic advantage for defense systems to be silent”. Lastly, the only interviewed company that is not an OEM sees this aspect as a strategic area they want to grow and considers it a lot more in new solutions and early design than in mature product design.

Substances of concern is another area being increasingly targeted by regulations and appears to be more considered at late design stages. An interview participant gave an example of their current challenges on this topic: “We have regulatory issues with substances used in repairing our current products. If alternative chemicals are too expensive, it might lead to decommission of certain products that could be repaired otherwise”. It can be unclear at early design stages how to handle this aspect and is seen to be more operation-related than design related.

The *Potential for reuse, repair, refurbish* is not considered equally among companies in this pilot study context. One considers it a topic of growing importance: “We have historically focused our design on durability so the solution can last the life of the aircraft - design for repair is a new way of thinking”. Another interview participant described this aspect as more established in their company “We have internal methods for analysis and review. […] It is a business opportunity for almost all types of products we offer”.

In Table 3, the degree of importance of the sustainability aspects is summarized. Based on the interpretation of the interview participant´s answers in relation to prioritization it is shown that all areas of high importance are closely connected to the economical dimension of sustainability. Some areas of growing importance are connected to an economical value, some not yet, and none of the "low importance" areas are marked as such. Some however have a direct economic impact such as material scrap that can be sold most of the time. Transport distances affect cost of logistics, and high recycled material content can also drive cost down when using valuable raw materials.

From Figure 1, it is possible to classify the aspects further into categories:

- Aspects of high importance: for these aspects, all case companies have an SCI score between 7 and 9;
- Aspects of low importance: for these aspects, all case companies have an SCI score between 1 and 3;
- Aspects of growing importance: for these aspects, the SCI level varies greatly between companies, from 1 to 9.

The aspects are arranged within these three categories of aspects in Table 3, as well as to which sustainably dimension they belong to the most (environmental, social, economic) based on interviews with case companies. Several aspects were not marked as economic, which could be further explored if the business case were further developed to fully understand the economic value.

Indication of lower sustainability requirements on disruptive solutions

The pilot-study of the interview study indicates a difference between the companies regarding the sustainability requirements on suppliers during product development. The OEMs are frequently involved with strategic partners with the capacity to design and manufacture certain key components to their platform, e.g. engine or aircraft. If the supplier provides parts that have a relatively high maturity level, there are typically several suppliers to choose from and the OEM will incorporate more or tougher sustainability requirements. However, the interviews of this pilot study indicated that projects with a lower maturity level and disruptive innovations tend to have lower sustainability requirements, as the potential of successful development may be considered higher with less requirements. On this topic, an interview participant explained: “We are more ‘picky’ when choosing partners providing advanced technology regarding sustainability. Immature technologies, on the other hand, just need rapid development”. The pilot study identified similar approaches at all interviewed companies. Examples mentioned of immature technologies are components that enable sustainable aviation, such as batteries or fuel cells. These examples are disruptive innovations in aerospace, bringing a large potential during use but presenting many challenges in the rest of their lifecycles. Unfortunately, there are many cases where aerospace companies have only one or two suppliers to choose from in the world, in which case sustainability is not considered beyond legal and customer requirements.

Table 3. An interpretation of the companies' prioritization of aspects driving sustainable product development

	Aspect	Environmental	Social	Economical
Areas of high importance	Energy efficiency	▲		●
	Health and safety		◆	●
	Material efficiency	▲		●
	Product weight	▲		●
Areas of growing importance	Critical minerals			●
	Environmental footprint	▲		
	Noise		◆	
	Potential for reuse, repair, refurbish	▲		●
	Substances of concern	▲	◆	
Areas of low importance	Potential for recycling	▲		
	Recycled / bio-based materials	▲		
	Scrap recyclability	▲		●
	Transport distances	▲		

4. Concluding discussion

The purpose of this paper was to explore sustainable product design in the aerospace industry, to identify which sustainability aspects are prioritized, when in the development process, and why. The value of understanding if certain aspects are of higher importance or on the contrary on lower importance in the early design phase is relevant in order to identify potential barriers to a sustainability transition. The scope of this pilot study was within the Swedish aerospace industry and three case companies represented different types of aerospace solutions, both within civil and defense industries. In addition, the companies run development projects that have different degrees of design space freedom.

A set of 13 already defined important sustainability aspects for aerospace-based solutions were mapped in relation to whether they were considered to be systematically considered and prioritized in the design process at the different companies. Using the interview results, the sustainability aspects were divided into three groups:

- Four aspects, i.e., energy efficiency, material efficiency, weight, and health and safety, were considered of high importance in all three companies, and are expected to remain core design drivers in the future. *Energy efficiency* and *product weight* enable fuel savings in flight, hence lower operational costs, which is attractive to both civil and defense customers. The use phase of aerospace products contributes to more than 90% of their total carbon footprint over their lifetime, hence these aspects are very critical to consider from an environmental sustainability perspective. *Material efficiency* enables the manufacture of products at a lower cost. It also contributes to the circular economy through reduction of material usage, however, it is not yet considered from a full life-cycle perspective but from gate-to-gate. Finally, *Health and safety* are paramount in aerospace and contributes to the attractiveness of flying for society.

- Another four aspects had low importance, i.e., *potential for recycling*, *recycled/bio-materials*, *scrap recyclability* and *transport distances*. The main reasonable explanation for this prioritization is that an optimal value of these aspects reduces costs for the company or its stakeholders. This result is context -dependent, meaning that for another industry other aspects may have a higher economic incentive than for the companies within the aerospace industry. This is evident as the four lower prioritized aspects are related to a circular economy, which is highly emphasized in the automotive industry from regulations and customer expectations. These findings correlate with Dias et al., who found that as an enabler to more sustainable practices, the circular economy is gaining significant attention in the manufacturing industry in general, yet not in aerospace (Dias et al., 2022).

- The identified aspects of growing importance are increasingly important to work with due to external constraints (regulations, requirements). This is the case for *critical minerals*, *substances of concern*, *noise*, and *environmental footprint*. It is common, however, that regulations and requirements evolve over time and become tougher to meet. A better implementation in early design stages is desirable to enable more anticipation of future demands. Aspects of growing importance can also be a business opportunity, where substantial financial savings could be made (such as *potential for reuse*), or could support benchmarking of a solution (*environmental footprint*, *noise*). They are seen to be more innovative and the pilot study indicates that they are currently more explored in early product design.

There are several reasons to increase the prioritizations of all the aspects to the same level of high importance. Firstly, in the context of the aerospace industry these aspects together control and limit a solution's sustainability profile during its whole life cycle (Hallstedt et al., 2017). Therefore, these should also be considered in early design, according to previous reasoning. Secondly, they all have an economic value for the company, directly or indirectly, and can provide a competitive advantage to the company in the long run. Thirdly, all these need to be prioritized to reach a sustainability transition. The new policies and regulations, such as the Green Deal, will most likely force the aerospace industry to steer towards a circular economy. A proactive company will most likely be able to gain market positions instead of reacting to regulations and making costly unplanned changes. This may result in high sustainability requirements also on suppliers providing disruptive solutions and thereby support a development directly towards sustainability.

This pilot study has provided some indications of challenges and knowledge gaps regarding what sustainability aspects are prioritized when, and why, in the context of the Swedish Aerospace industry. Further investigations are needed to validate these results, as there are several limitations to this study. A further in-depth study with more companies -including outside of Europe- is planned to expand this study in a global context and validate or rectify the conclusions drawn.

Within the scope of this research, several areas remained unexplored and would be worthy of further investigation:

- what can make the sustainability leading criteria change;
- how the sustainability criteria relate to trade-off situations in radical innovation shifts for products with complex life cycles;
- how sustainability leading criteria can support a circular economy approach and pave the way towards the sustainability transition of the industry.

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