



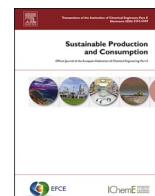
## **Capability needs for sustainable product development in aerospace: A systematic literature review**

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## Review article

# Capability needs for sustainable product development in aerospace: A systematic literature review

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## ABSTRACT

Carbon emissions of the aviation sector are expected to double by 2050, and there is an urgent need to change the approach to product and system design to enable a sustainability transition. Through a systematic literature review, this paper analyses 51 studies and provides a comprehensive overview of the current state of sustainable product development in the design of aircraft systems and sub-systems. A taxonomy of challenges across six categories is proposed, ranging from socio-ecological issues, regulations, economic context, design process, cognitive barriers, and technological limitations. This taxonomy supports clarifying the nature of problems practitioners may encounter when implementing sustainable product development. While aerospace companies face systemic challenges, this study argues that they can overcome structural, human, and technical barriers. But to overcome this, sustainable product development capabilities need to be developed, which this study maps across product development phases and organisational levels. Fourteen aerospace-tailored support methods are reviewed through the lens of these capabilities, showing gaps in enabling cross-functional communication, managing trade-offs systematically, and mitigating sustainability risks. This study advances the field of Sustainable Product Development by offering a sector-specific synthesis of challenges, capabilities, and support methods in aerospace. The findings align with broader sustainability literature and provide a foundation for future cross-sectoral research and methodological development. Together, these contributions support aerospace practitioners in navigating sustainable product development challenges, developing critical capabilities, and calls for further research to accelerate sustainability integration in product development.

## 1. Introduction

Over the past three decades, the role of product design for sustainable development has gained significant attention (Bhamra and Hernandez, 2021). However, product sustainability has not been successfully “taking off” in the aerospace industry. While the flight-shame anti-flying social movement has had a measurable impact in Sweden and Germany (Pesce, 2019), the civil aviation sector is projected to grow significantly, with carbon emissions estimated to double by 2050 in business-as-usual scenarios (ICAO, 2025). Therefore, a radical shift in aircraft systems design is essential to enable a sustainability transition in the aerospace sector.

Achieving a successful transition to a sustainable society requires a strategic and systematic approach that considers ecological, social, and economic dimensions together. In the Framework for Strategic Sustainable Development, sustainable development requires that both

society and nature must be sustained and not systematically and increasingly degraded (Broman and Robert, 2017). The framework includes adopting backcasting thinking from a vision framed by eight first-order principles for environmental and social sustainability. This framework has been applied in product development (e.g., Hallstedt, 2017) and provides a structured, science-based approach for guiding sustainability transitions in complex systems.

Product development plays a pivotal role in accelerating the sustainability transition (Gaziulusoy et al., 2013), and companies can develop sustainable products within a sustainability design space constrained by those sustainability principles (Hallstedt, 2017). Sustainable Product Development (SPD) is a research field that supports the integration of a strategic sustainability perspective with a focus on the early phases of the product innovation process, including lifecycle thinking (Hallstedt and Isaksson, 2017). While various forms of SPD support exist, their efficient implementation in the industry remains a challenge

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(Faludi et al., 2020; Vilochni et al., 2024a). Practitioners can be reluctant to use SPD methods, as they might not see their value before they are adopted (Mallalieu et al., 2024). Moreover, the implementation of support methods does not inherently guarantee that products are designed with improved sustainability performance (Watz and Hallstedt, 2022).

Given these challenges, research emphasises the need to focus on the development of SPD capabilities: skills and knowledge in the field of SPD, exercised through support methods applied in routines and organisational processes. Companies must transform across organisational levels: i) *strategic*, including long-term planning and target setting, ii) *tactical*, involving the management of the product development process and supporting design teams, and iii) *operational*, covering the development, evaluation, and selection of concepts (Hallstedt et al., 2023).

Compared to sectors such as automotive, consumer goods, and electronics, aerospace has received relatively limited attention in SPD literature, leaving a gap in understanding sector-specific barriers and capability needs. The aerospace sector is shaped by many stakeholders forming a complex, multi-level decision-making hierarchy, where decisions on sustainability topics are often delayed (Singh et al., 2022). Sustainability is systemic and holistic, and an aircraft cannot be defined as sustainable unless the system it operates within and all its enabling systems are also sustainable (Paletti et al., 2024). Therefore, to design a sustainable aircraft would require the entire value chain to adopt SPD practices, from aircraft manufacturers to material suppliers and process developers.

To situate this research, we summarise recent background on the integration of sustainability in aerospace product development. Hallstedt et al.'s (2023) longitudinal study with an aerospace company revealed that it is still a challenge to define and represent sustainability criteria that are both compliant with a strategic sustainability perspective and sufficiently precise to guide designers. Additionally, in aviation, sustainability often describes efforts towards energy efficiency and climate change mitigation, which has received a lot of attention in the lifecycle assessment sphere (Keiser et al., 2023). Few initiatives aim to integrate all sustainability dimensions as a driving force in the initial stages of design (Filippatos et al., 2024). Holistic approaches are not well implemented in industry, and certain sustainability aspects are currently missing in design practice (Léonard et al., 2024a).

Recent studies have systematically mapped over a hundred innovations in the aviation sector, revealing how value is being created through improvements in efficiency, customer experience, and environmental sustainability (Pereira et al., 2021). Despite these innovation efforts, aerospace systems remain costly and complex to design, develop, and produce, resulting in long development cycles (10 years) and extended operational lifespans (20–30 years) (Elsayed et al., 2019). These characteristics make early design decisions disproportionately impactful for sustainability and difficult to reverse once a product is in service. Consequently, achieving sustainability in this sector remains uncertain, as it requires navigating complex trade-offs between economic, environmental, and social impacts at early design stages where decisions might impact the entire value chain.

Given the strategic role of SPD and the specific barriers in aerospace, understanding capability needs in product development is essential to enable sustainability transitions in this sector. Therefore, this research aims to systematically identify the challenges hindering SPD in aerospace and to clarify the capabilities needed to overcome them. This paper provides a comprehensive state-of-the-art overview of SPD research in the aerospace sector, focusing on aircraft systems and subsystems. Through a systematic literature review, this study aims to answer the following research questions:

RQ1. *What are the main challenges hindering Sustainable Product Development in the aerospace industry?*

RQ2. *What are the capabilities needed to advance Sustainable Product Development in aerospace?*

This study proposes a taxonomy for classifying SPD challenges, outlines the capabilities needed to address them, and maps existing supports tailored for the aerospace industry in relation to the capability needs. This article is structured into five sections. Section 2 describes the research methodology, Section 3 presents the review results, Section 4 discusses the findings, and conclusions are drawn in Section 5.

## 2. Methods

### 2.1. Review planning and selection process

A Systematic Literature Review was conducted to analyse state-of-the-art knowledge (Booth et al., 2022) in Sustainable Product Development (SPD) within the aerospace sector, following the three-phase methodology proposed by Biolchini et al. (2005): planning, execution, and results analysis. After defining objectives, expected outcomes, and research questions, a source selection strategy was developed using two search engines to identify a broad range of sources. The search string was designed to focus on papers with a strategic sustainability perspective, instead of one single dimension of sustainability. The search string was iteratively refined using a control group of 10 papers and consisted of four clusters: (1) *aerospace*, (2) *sustainability*, (3) *product development*, and (4) *challenges and capability needs*. The inclusion and exclusion criteria (including indexed keywords) were determined in an iterative process to ensure finding papers from the control group and on the topic of design and sustainability, while narrowing the scope.

- **Scopus:** search string used in title, abstract and keywords: (“aerospace” OR “aviation” OR “aeron\*”) AND (“sustainab\*”) AND (“product development” OR “design” OR “technology development”) AND (“challeng\*” OR “opportunit\*” OR “solution\*” OR “barrier\*” OR “capabilit\*”).
- **Google Scholar:** searching in title only, excluding citations: (“aerospace” OR “aviation” OR “aeron\*”) AND (“sustainab\*”) AND (“product development” OR “design” OR “technology development”)

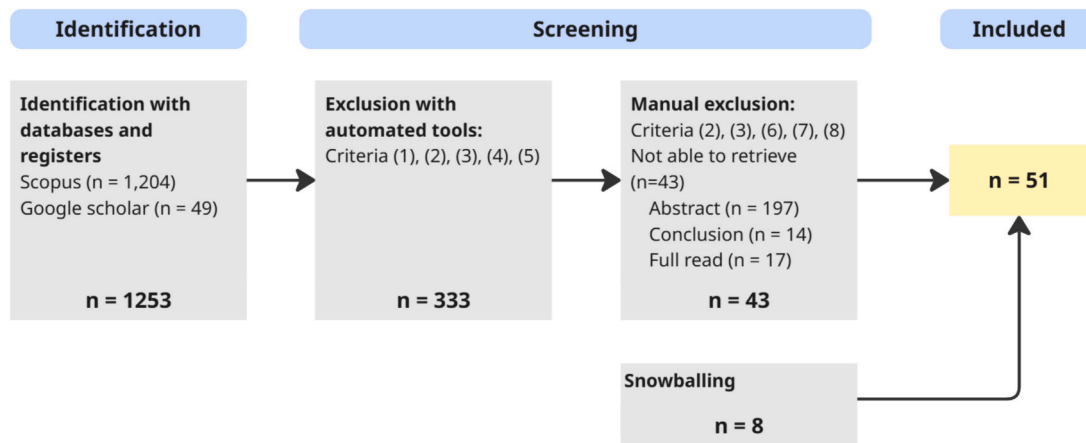
#### Inclusion criteria:

- (1) **Publication date:** after 2010;
- (2) **Language:** English;
- (3) **Document type:** Journal articles, Conference articles, Reviews, Doctoral theses
- (4) **Subject area:** within Business, management and Accounting, Decision Sciences, Earth and Planetary Sciences, Engineering, Environmental Science, Social Sciences or Multidisciplinary;
- (5) **Indexed keywords:** Conceptual Design, Decision Making, Design, Ecodesign, Environmental Impact, Environmental sustainability, Life Cycle, Product Design, Product Development, Sustainable development, Sustainability
- (6) **Aerospace focus:** Paper is primarily focused on product and technology development related to aircraft systems;
- (7) **Sustainability focus:** Paper contains a form of assessment, method, framework or discussion related to environmental, social or economic sustainability.

#### Exclusion criteria:

- (5) **Indexed keywords:** Space Research;
- (6) **Duplicates:** duplicates or precursor of other papers in the review.

This review focuses on literature published from 2010 onwards to capture the most relevant and contemporary developments in SPD within the aerospace sector. The source selection process was executed on the 3rd of June 2025 and is summarised in Fig. 1. A detailed selection protocol following the PRISMA framework is available in Appendix A



**Fig. 1.** Source selection phases. The source selection took place in four phases: Identification, Exclusion with automated tools, Manual exclusion and Snowballing. Full protocol using PRISMA framework is in Appendix A.

(Page et al., 2021). Additionally, eight papers were identified through snowballing to find later and similar works using ResearchRabbit, a citation-based literature mapping tool. The final selection of 51 papers is listed in Appendix B.

### 2.2. Information extraction and analysis

To define context of application, this study uses product development process stage definitions proposed by Vilochani et al. (2024b), which includes both supporting processes and core processes. The review execution and results analysis consisted of three main steps:

- i) **General analysis** of paper content, scope and focus
- ii) **Identification of SPD challenges:** citations discussing issues, problems, barriers, or challenges related to enabling sustainable innovation, technologies, products, or projects were collected and coded. Special focus was placed on collecting challenges for all stages of Product Development (PD) and affecting a variety of stakeholders and organisational levels (strategic, tactical, operational). The challenges were progressively and inductively collected in groups presenting a similar focus. This led to the inductive development of a taxonomy, covering both internal and external factors.
- iii) **Identification of SPD capability needs:** citations discussing skills and knowledge needs related to SPD were collected and coded. Capabilities were mapped within challenges categories defined in step ii) answering the question “which challenge does this capability support addressing?”. They were also mapped with an existing framework of 61 SPD management practices (Vilochani et al., 2024b). This process of mapping helps formulate the capability needs in generic terms that are not specific to the aerospace sector. The 11 most frequent capability needs were identified based on their recurrence in the reviewed papers. Finally, existing methods and methodologies for SPD were identified among reviewed papers using Gericke et al.'s (2017) definitions. They were conceptually analysed to determine whether they address the 11 most recurring capability needs identified.

Following principles for qualitative data analysis (Miles et al., 2018), data collection and analysis were rigorously conducted at steps ii) and iii) through in-vivo coding of citations. Terms from the analysed paper were used for synthesis to reduce researcher bias. The analysis was conducted in an iterative manner, which included comparison and moving back and forth between the papers several times. Emerging results were continuously discussed and validated among co-authors.

## 3. Results

Initial search in databases identified 1200 studies, of which 43 met the inclusion criteria. An additional 8 papers were identified through snowballing, resulting in a final selection of 51 publications. This section presents the results from the analysis, including a scope and focus analysis, a classification of SPD challenges in aerospace, and an overview of capabilities needed to advance SPD.

### 3.1. Background and focus

The field of Sustainable Product Development (SPD) in aerospace is rapidly expanding. Of the 51 reviewed studies, 32 were published between 2021 and 2025. Europe is the most active continent in this topic, contributing to 38 papers, notably Sweden (8), Germany (6), and Portugal (3). Among the reviewed works, 34 are journal articles (6 in the Journal of Cleaner Production), 14 are conference articles, and 3 are doctoral theses. The papers employ a range of research approaches: 21 quantitative, 13 qualitative, 8 mixed, and 9 literature reviews, reflecting the methodological breadth of SPD in aerospace.

Table 1 presents the categorisation of the reviewed papers in relation to the product development phases using Vilochani et al. (2024b) (see Section 2.1). The majority focus on early design phases, which is essential to address in the context of SPD and technology development.

The studies were classified by level of analysis, ranging from sector-level to materials and manufacturing (see Table 2). Studies that included multiple levels of analysis were classified to the highest applicable level. Most papers focus on “sector and company level”, and “aircraft level”, indicating a high-level focus in aerospace SPD research.

The lifecycle phases addressed in the papers include raw material production, manufacturing, transportation, use and maintenance, and end-of-life. Of the 51 publications, 21 focused exclusively on the use phase and 13 adopted a full lifecycle perspective. The sustainability scope of the reviewed studies varies; several papers focused on energy usage or fuel consumption, which can be considered either economic or

**Table 1**

Distribution of reviewed papers across product development phases. Number in parentheses indicates studies attributed to two phases.

Product development phase	Publications reviewed
(support) Technology development	20 (3)
(core) Conceptual design	19 (2)
(core) Planning	7 (3)
(support) Strategic planning	6 (2)
(support) Program management	3
(core) Production, Product review	1

**Table 2**  
Level of analysis of the reviewed studies.

Level of analysis	Publications reviewed	Examples
1 - Sector and company	15	Identifies and evaluates circular practices at three aerospace companies (Rodrigues Dias et al., 2022) Discusses the need to address transport taboos to achieve significant emission reduction in passenger transport (Gössling and Cohen, 2014)
2 - Aircraft	18	Establishes a list of requirements for the development of future sustainable aircraft (Paletti et al., 2024) Shows the potential of hybrid-electric aircraft concept to reduce environmental impact over lifecycle (Ribeiro et al., 2020)
3 - Propulsion system	3	Reviews development and future trends for aviation electrification (Zhang et al., 2022)
4 - Component and sub-system	9	Develops a design methodology for composite components that integrates sustainability (Filippatos et al., 2024)
5 - Materials and manufacturing	6	Method development for green textile development in aerospace (Moreira et al., 2015)

environmental aspects. While 14 papers adopt a holistic sustainability approach, the social dimension (focusing on human or societal problems) is found to be the least addressed.

A temporal comparison reveals a shift between early publications (2010 to 2020) and recent publications (2021–2025). The share of papers with a full lifecycle perspective has decreased from 42 to 16%, while more studies focused on the use phase only, resulting in an increase from 26 to 50%. However, no clear evolution is observed in terms of sustainability scope, with 25% of the papers adopting a holistic sustainability approach.

The level of analysis and its relation to the lifecycle approach and

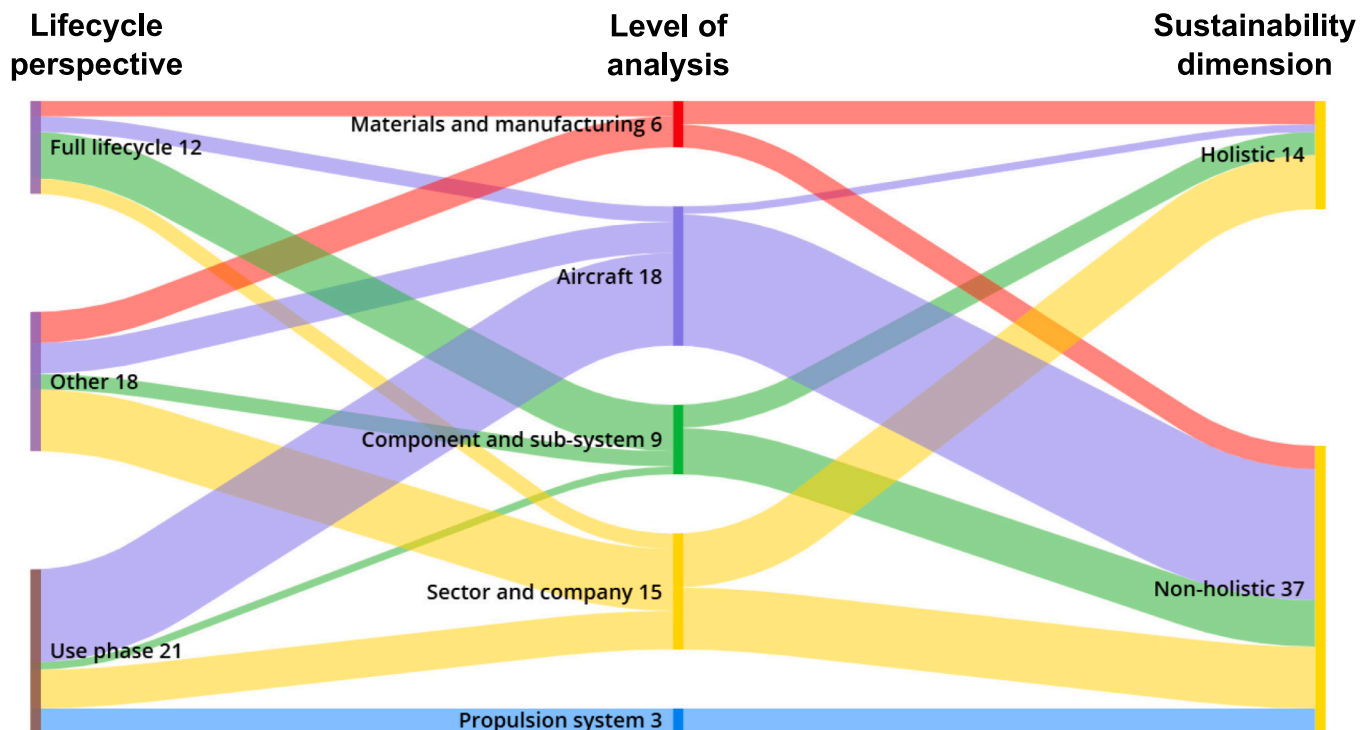
sustainability scope are shown in Fig. 2. The figure is organized around the level of analysis shown in the centre and should be read starting from this point. It illustrates how the reviewed studies approach product sustainability across different levels of analysis and how these levels relate to the life cycle perspective (left) and the sustainability dimensions (right). Studies focusing on the component and sub-system level most frequently adopt a full-lifecycle perspective, while studies focusing on the aircraft, propulsion, and company levels mostly focus on the use phase. In terms of the sustainability dimension covered, most levels of analysis focus on one or two dimensions, but the sector and company level stands out with a large portion of holistic studies.

### 3.2. Challenges

The analysis of the reviewed literature led to the identification of 191 unique challenges to Sustainable Product Development (SPD) in aerospace. These challenges were inductively clustered into six overarching categories, classified by systemic level (see Fig. 3). The systemic scale ranges from broad and global to detailed and product-level.

#### 3.2.1. Socio-ecological impact

34 (18%) of the 191 identified challenges relate to the environmental and social impact of aerospace. A recurring concern is that the pace of technology development is not sufficient to reduce the climate impact of the rapidly growing aviation industry (Haan, 2010; McDonald et al., 2021). The literature predominantly focuses on the use phase of aircraft systems, addressing issues such as emissions (CO<sub>2</sub>, NO<sub>x</sub>, hydrocarbons), fossil resource depletion, global warming from non-CO<sub>2</sub> climate effects, noise, and local air pollution (e.g., Tuccillo and Della Vecchia, 2024). Estimating non-CO<sub>2</sub> from flight is described as particularly complex, as it depends on many parameters, many of which are independent of the aircraft itself (Delbecq et al., 2023; Sliwinski et al., 2017). Operational practices also contribute to sustainability challenges. For example, Kabashkin et al. (2024) describe that components are often replaced instead of repaired to simplify maintenance procedures and ensure reliability, leading to material waste. Authors note that the aerospace



**Fig. 2.** The level of analysis (in the middle) and its relation to lifecycle perspective (left) and sustainability dimension (right). The figure reads from the centre outward and shows how the reviewed papers approach product sustainability based on the level of analysis.



Fig. 3. Taxonomy of challenges to Sustainable Product Development in aerospace. The scale ranges from broad and global to detailed, product-level. Each category is further divided in two to three sub-categories.

industry employs materials with high environmental footprint, such as titanium and composites (Bachmann et al., 2017; Nyamekye et al., 2023), and uses critical minerals with availability and ethical risks in the production (Hallstedt and Isaksson, 2017). While few authors discuss social consequences, Gössling and Cohen's (2014) research shows that climate mitigation strategies, such as market-based measures, may mostly affect low-income populations, highlighting the existing trade-off between ecological and social sustainability.

### 3.2.2. Regulatory frameworks and industry norms

31 (16%) challenges identified are linked to governance, international policies, and regulatory frameworks. Keiser et al. (2023) outline that the rising demand of air travel conflicts with the civil aviation sector's objectives to reduce noise, emissions, resource depletion. As flights are often cross borders, it is not directly addressed by the Paris Agreement (Delbecq et al., 2023). Instead, sustainability targets are set by organisations like ACARE in Europe and ICAO globally, though some authors mention they lack a holistic approach (e.g., Paletti et al., 2024). Gössling and Cohen (2014) point that there is strong lobbyism which waters down ambitious goals, linking mobility to human rights, and often excludes aerospace from policy frameworks. Authors describe public acceptance as an obstacle to the adoption of radical technologies (Afonso et al., 2021) alongside stringent safety standards. Another factor slowing down innovation is business risks and costs according to Dhara and Lal Jeyan (2021), who explain that the introduction of new materials, technologies or configurations are a risk for manufacturers, particularly in meeting airworthiness requirements and managing cost of the certification processes.

### 3.2.3. Business drivers and economic context

27 (14%) of the identified challenges are of an economic nature. Many studies highlight the expected growth of the aviation industry, but acquiring new aircraft is a large capital investment for airlines, which is why many old aircraft are refurbished instead of being replaced (Singh

et al., 2018). Aircraft design is a costly process in itself (Falcão e Cunha, 2022), and sustainable solutions tend to be perceived as expensive, such as the acquisition cost of circular materials or sustainable aviation fuels (Eoukich et al., 2024; Rodrigues Dias et al., 2022). Some sustainable technologies have operational constraints that would increase the aircraft's operational costs. For example, using batteries and fuel cells as energy sources would require replacement over an aircraft life and have long charging time compared to today's drop-in fuels (Melo et al., 2022; Melo et al., 2023; Vieira and Bravo, 2016) and some routes would become unprofitable (Dhara and Lal Jeyan, 2021; Ribeiro et al., 2020). To be successful, new aircraft systems need to minimise direct operating costs (e.g., fuel, crew, maintenance) and improve full lifecycle economics (Bravo-Mosquera et al., 2022). While civil aviation customers show limited interest in sustainability, "green" products could have advantage for marketing in the executive business (Santos et al., 2016).

### 3.2.4. Design process and organisation

25 (13%) of the identified challenges are structural, primarily linked to the aerospace design process. Although described as lengthy, the process also faces time constraints and often lacks a lifecycle perspective (Andriankaja et al., 2015; Hallstedt and Isaksson, 2017; Quiben Figueroa et al., 2024). Sustainability is most frequently considered at later stages of design, which can be due to a lack of data availability in early stages or resources to perform sustainability assessments (Hallstedt et al., 2015; Paletti et al., 2024). Social sustainability receives minimal attention in the literature, and there is no consensus on assessment methods, which depend widely on the stakeholders considered (Léonard and Nylander, 2020). It is generally difficult to see the impact of methods for product development, such as customer satisfaction, revenue generation, or sustainability impact, due to long lead times (Bertoni et al., 2020). The identified organisational barriers include the spread of knowledge and data among different functions at companies and the lack of link between design actors, tools, and processes (Andriankaja et al., 2015; Bertoni et al., 2020).

### 3.2.5. Behavioural and cognitive influences

30 (16%) of the identified challenges are classified as cognitive and affective, relating to human judgment, uncertainty, and resistance to change in the context of design. The aerospace business has not known a major disruption since the introduction of jet propulsion 60 years ago (Léonard et al., 2024b), and incremental technologies remain the norm, constraining environmental progress (Bravo et al., 2022). While there is a belief that technology can solve many problems in aerospace (Haan, 2010), there is uncertainty about which technologies will best support the route to net zero (Adu-Gyamfi and Good, 2022; Bravo-Mosquera et al., 2022; Gössling and Cohen, 2014). According to Frota (2016), the term “sustainable aviation” lacks a unified definition, which could mean improved passenger experience, reduced noise pollution, or environmental friendliness. Hallstedt and Thompson (2011) found a belief among practitioners that sub-systems have little influence on overall sustainability. Hallstedt et al. (2023) further elaborate on the issues related to this bias: while new technologies are often introduced on the component level, they impact the system level, which implies they can have a large impact on aircraft system sustainability. Working with sustainability also includes challenges in terms of decision-making, as it often includes new trade-offs, increased complexity (Bravo-Mosquera et al., 2022; Wehrend et al., 2024), and potentially shifting problems from one life phase to another (Melo et al., 2023). It is not evident which criteria should be used to evaluate sustainability, and communicating the value of sustainable solutions is difficult (Bertoni et al., 2020).

### 3.2.6. Technology, infrastructure and products

44 (23%) of the challenges identified are rooted in the physical, technical, and systemic limitations of aerospace design and production. Current aircraft systems are reaching a performance plateau and can only be incrementally improved (Polepeddi, 2022; Zhang et al., 2022). Radically innovative configurations need to be investigated, but would take a decade to be implemented due to technology immaturity (Bravo-Mosquera et al., 2022; Iemma et al., 2017). A wide range of papers discuss technical limitations of potential solutions for sustainable aviation, such as battery-electric aircraft, fuel-cell propulsion, and alternative fuels. Sustainable innovations often involve engineering trade-offs, e.g., weight reduction vs. safety, climb fuel vs. cruise fuel optimisation, efficiency vs. development cost, etc. Additional systems and features on an aircraft might come with weight penalties, requiring higher thrust and fuel consumption, thereby increasing the climate impact over the system lifecycle; this snowballing effect is crucial to manage for design engineers (De Paula and Rozenfeld, 2015). Several authors describe data

availability as a recurring issue, affecting the accuracy and reliability of sustainability assessments (e.g., Kabashkin et al., 2024; Stefana et al., 2024). Compatibility issues with existing airport infrastructure were also mentioned in the literature, whereas production capabilities were not discussed.

### 3.3. Capability needs

68 different capability needs were identified through the literature review. They were analysed in terms of product development phase, target group, and relation to SPD challenges, although this was typically not explicit in the papers. Most skills and knowledge needs were directed at design teams (59), product managers (15), and other tactical and operational roles at companies (10).

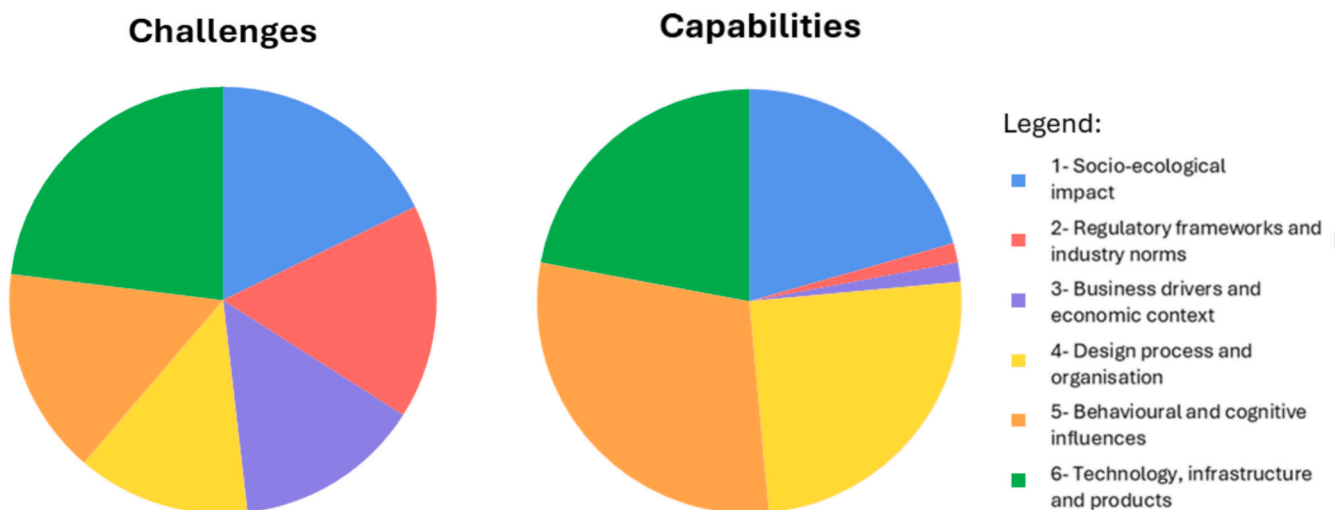
#### 3.3.1. Capabilities and sustainable product development challenges

Each capability need was matched to a category of SPD challenges (see Section 3.2) based on the nature of the problem it aims to address. As shown in Fig. 4, the categories “2- Regulatory frameworks and industry norms” and “3- Business drivers and economic context” are less addressed than the others in terms of capability needs.

This paper identified three main types of support needed to overcome cognitive barriers to approach sustainability in design: risk assessments, sustainability impact assessments, and sustainability improvements (see Table 3). Several papers advocate that decision-making support should be usable without specific sustainability

**Table 3**  
Support needs to overcome cognitive barriers for approaching sustainability in design.

Nb. of references	Support needs	Description	Reference example
11	Risk assessment	Evaluating and managing sustainability and business risks and opportunities	(Hallstedt et al., 2015)
7	Sustainability assessment	Evaluating a product's potential sustainability impacts throughout its lifecycle	(Wehrend et al., 2024)
5	Sustainability improvement	Identifying and implementing actions or guidelines to reduce the product's sustainability footprint	(Andriankaja et al., 2015)



**Fig. 4.** Categorising of challenges and capabilities identified in the review. The pie charts represent the percentage of challenges and capabilities identified in the literature belonging to each category.

training and should support the integration of socio-ecological factors in decision-making (e.g., [Andriankaja et al., 2015](#); [Jemma et al., 2017](#)).

[De Paula and Rozenfeld \(2015\)](#) and [Filippatos et al. \(2024\)](#) highlight the need to obtain fact-based evidence and advocate for adopting a quantitative sustainability approach. They argue that this approach can support navigating trade-offs as it facilitates the integration of sustainability at a level comparable with other design parameters. [Hallstedt et al. \(2023\)](#) call for the development and use of sustainability criteria, but there are still issues with connecting those to business value. To overcome communication hurdles, designers should make explicit assumptions: it not only supports the making of a decision, but also the explanation to other stakeholders afterwards ([Haan, 2010](#)). It is necessary to define the degree to which a product is regarded as “more sustainable” and have a common view to work strategically towards sustainability ([Hallstedt and Isaksson, 2017](#)).

On capabilities related to solving socio-technical challenges, literature focuses mostly on recommending how sustainability should be approached and assessed in design. [Table 4](#) shows a summary of the main characteristics found in the literature review with a reference example. While most of these recommendations apply to designing new products, [Wehrend et al. \(2024\)](#) also highlighted the need to focus on improving the sustainability impact of the existing fleet and conventional configurations. A small number of papers discussed the need to adopt an absolute sustainability approach, i.e., aim to operate within environmental limits instead of relative improvements. Few papers account for rebound effects, which occur when the environmental benefits

of innovation are undermined by increased consumption. Overall, the concept of absolute sustainability and rebound effects appear to be rather immature in the aerospace industry.

On capability needs to solve structural challenges, most papers focus on the design process and how it can be improved or transformed. Adopting a systems engineering approach could improve the efficiency and effectiveness of product development. To facilitate the integration of sustainability in today's practice, [Andriankaja et al. \(2015\)](#) propose to balance generic guidelines and industry- or product-specific guidelines, as some sustainability aspects are not relevant in all contexts and would add unnecessary complexity. Moreover, sustainability should be considered systematically and not ad hoc. [De Paula and Rozenfeld \(2015\)](#) suggest that integrating sustainability in product lifecycle management systems can be a solution. Literature highlights the need to consider challenges that will come later in the design, such as manufacturing or certification of radical designs. Unconventional configurations might even require a new design process that would also need to be certified beforehand ([Afonso et al., 2021](#)). To address organisational challenges, designers need to interact with non-engineering disciplines. To address this issue, [McDonald et al. \(2021\)](#) propose to create multidisciplinary project structures.

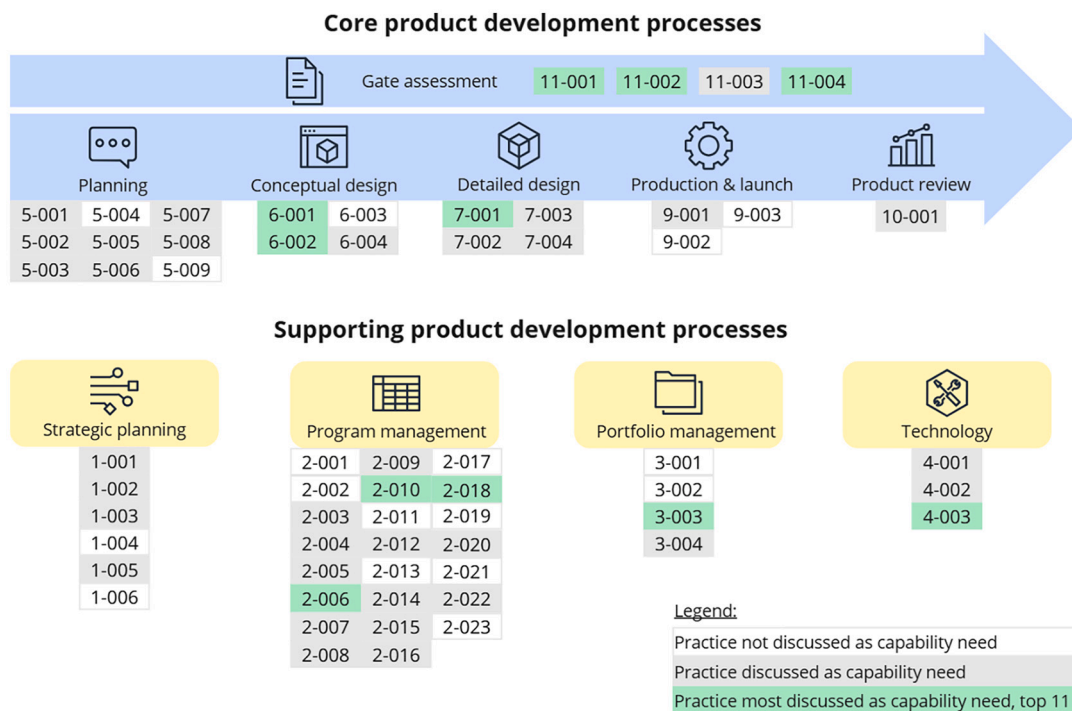
On to technical challenges, the literature describes the need to get a better understanding of the sustainability impact of upcoming technologies, but also of technology readiness and performance (e.g., [Tuccillo and Della Vecchia, 2024](#)). Designers also need to understand which design variables can affect sustainability indicators ([Bertoni et al., 2020](#)). When designing aircraft systems, [Melo et al. \(2023\)](#) and [McDonald et al. \(2021\)](#) advocate inclusion of geographical and temporal aspects to adopt a global optimisation perspective and include usage, infrastructure, and monitoring phases. Furthermore, [Andriankaja et al. \(2015\)](#) and [Moreira et al. \(2015\)](#) highlight the need to have better data management practices, allowing to share and trace data between engineering tasks and product lifecycle.

3.3.2. Capabilities and sustainable product development practices

The capability needs identified in this study were matched with Vilochani's list of SPD management practices. For example, the citation

**Table 4**  
Characteristics required to approach sustainability in design effectively.

Nb. of references	Characteristics needed	Reference example
14	Lifecycle perspective	( <a href="#">Vieira and Bravo, 2016</a> )
7	Holistic	( <a href="#">Hallstedt and Isaksson, 2017</a> )
7	System perspective	( <a href="#">Andriankaja et al., 2015</a> )
5	Applicable in early design	( <a href="#">Jemma et al., 2017</a> )
4	Data transparency	( <a href="#">Haan, 2010</a> )
3	Quantitative	( <a href="#">Filippatos et al., 2024</a> )



**Fig. 5.** Coverage of SPD practices identified as capability needs in the systematic literature review. Each code x-xxx corresponds to an SPD practice defined by [Vilochani et al. \(2024b\)](#).

**Table 5**

Top 11 practices most cited as capability needs in the reviewed papers. Codes and practice description from [Vilochani et al. \(2024b\)](#).

Code	Practice description	Organis. level
2-006	Implement Life Cycle Thinking into the product development and related processes	Tactical
2-010	Select and/or customise methods and tools to support sustainability integration into product development	Tactical
2-018	Ensure appropriate communication across departments and hierarchical levels concerning SPD	Tactical
3-003	Manage trade-offs within and across the sustainability requirements (e.g., social vs. environment; or quality vs. cost)	Operational
4-003	Evaluate the sustainability performance of technologies	Operational
6-001	Design product concepts to deliver functions with better sustainability performance	Operational
6-002	Consider the sustainability performance of alternative design concepts for concept selection	Operational
7-001	Select the most relevant design guidelines to address the sustainability hotspots	Operational
11-001	Make sustainability considerations a part of the decision-making criteria during product development	Tactical/ Operat.
11-002	Define indicators and measure the sustainability performance of products during development	Tactical/ Operat.
11-004	Systematically identify and mitigate potential sustainability risks across the products' lifecycle	Operational

“In order to analyse a product family's sustainability potential, criteria and indicators for sustainability need to be defined” ([Wehrend et al., 2024](#)) was coded as “Need to define sustainability criteria and indicators to analyse sustainability potential” and correspond to practice 11–002: “Define indicators and measure the sustainability performance of products during development”.

An overview of the SPD practice coverage is shown in [Fig. 5](#). Among the 61 practices, 17 were not explicitly discussed as needed by the reviewed papers. While the majority of papers are focused on technology development and conceptual design (see [Section 3.1](#)), the capability needs have a much broader scope: practices at the stages of Planning, Detailed design, Product review, and Gate assessment are well covered in this literature review. Strategic management, Program management, Portfolio management, and Production have the lowest percentage of capabilities covered, although this could be explained by the search string used in this review.

The 11 most discussed practices identified in this study are shown in [Table 5](#). Each practice has also been matched to an organisational level, either strategic, tactical, or operational. According to the literature, these items are the most important capability needs to be addressed to enable sustainable product development. They represent five product development stages and focus on tactical and operational levels within an organisation. At the operational level, the practices typically relate directly to the design teams and their ways of working. At the tactical level, practices often relate to the management of product development, design projects, or SPD deployment: while they influence the way design is conducted, they are not typically employed by design engineers. This overview of the most important practices shows the need to develop capabilities both at the tactical and operational levels.

### 3.3.3. SPD support methods for aerospace

Through the systematic review, 14 papers presenting a SPD support method were identified, which are further described in this section. A brief support description is shown in [Table 6](#), and further information on the conceptual analysis is available in [Appendix C](#). All methods and methodologies have a clear goal to support sustainability integration into product development and support the design of products with better sustainability performance. More than half of the supports are adopting a life cycle approach or aim to bring light to life cycle stages usually disregarded.

**Table 6**

List of identified SPD support methods in the systematic literature review.

Reference	Role of support
( <a href="#">Filippatos et al., 2024</a> )	Proposes a design process where holistic sustainability performance is integrated with technical performance
( <a href="#">Fusaro et al., 2024</a> )	Assess the environmental impact of supersonic aircraft from high-level requirements
( <a href="#">Kabashkin et al., 2024</a> )	Assess the potential of health monitoring systems technology on operational cost and aircraft durability
( <a href="#">Paletti et al., 2024</a> )	Provides high-level requirements for future sustainable aircraft systems
( <a href="#">Wehrend et al., 2024</a> )	Proposes a design process where lifecycle assessment is integrated to support concept selection
( <a href="#">Franchino, 2023</a> )	Assess holistic sustainability impact of aerospace manufacturing processes
( <a href="#">Rohacs, 2022</a> )	Models potential sustainability impact of technologies on aviation CO <sub>2</sub> emissions
( <a href="#">Bertoni et al., 2020</a> )	Assess the sustainability performance and business value of a product
( <a href="#">Hallstedt and Isaksson, 2017</a> )	Assess criticality of materials to support selection and procurement
( <a href="#">Santos et al., 2016</a> )	Guides in the selection of materials for aircraft interior
( <a href="#">Andriankaja et al., 2015</a> )	Assess environmental impact of a product and proposes improvement strategies
( <a href="#">Hallstedt et al., 2015</a> )	Assess the sustainability performance and risks of a product
( <a href="#">Moreira et al., 2015</a> )	Proposes a design process including value chain collaboration to reach environmental sustainability in the aircraft completion field
( <a href="#">Haan, 2010</a> )	Models potential sustainability impact of technologies a variety of aviation sustainability indicators

[Paletti et al. \(2024\)](#) and [Fusaro et al. \(2024\)](#) focus on high-level requirements for aircraft system design and adopt a systems engineering approach. This approach can support the building of capabilities identified in [Table 5](#). Requirements include measurable sustainability criteria (practice code 11-002). As requirements are widely used in aircraft design, this approach facilitates the integration of sustainability in decision-making (11-001). Supports developed by [Bertoni et al. \(2020\)](#), [Franchino \(2023\)](#), [Filippatos et al. \(2024\)](#), and [Wehrend et al. \(2024\)](#) integrate environmental, social, and economic sustainability with engineering performance indicators, hence facilitating the consideration of sustainability for design engineers and communication to decision-makers. These papers contribute to developing practices 11-001 and 11-002 as in previous papers, but also consider sustainability performance for concept selection (6-002) and provide visibility to existing trade-offs (3-003). [Andriankaja et al. \(2015\)](#) and [Santos et al.'s \(2016\)](#) papers have a strong focus on supporting decisions by providing guidelines and strategies, contributing to practice 7-001. Papers by [Haan \(2010\)](#), [Rohacs \(2022\)](#), and [Kabashkin et al. \(2024\)](#) focus on evaluating the sustainability performance of upcoming technologies, supporting practice 4-003. [Wehrend et al.'s \(2024\)](#) method focuses on integrating lifecycle assessment into concept selection. While the identified SPD support covers most critical practices identified in [Section 3.3](#), three main gaps remain:

- Most papers do not focus on supporting communication between departments and hierarchical levels (practice 2-018).
- While some papers give visibility to trade-offs, their support appears limited when it comes to managing them, and prioritising among them (practice 3-003).
- Most papers do not address the need to systematically identify and mitigate sustainability risks (practice 11-004).

## 4. Discussion

This paper examined the state-of-the-art in Sustainable Product Development (SPD) in the aerospace industry, a sector that has received relatively limited attention in SPD literature, yet with an urgent need for

a sustainability transition. In this study, typical challenges hindering sustainable product development in the aerospace industry were identified, and a taxonomy was developed to support practitioners and researchers in clarifying their nature. Furthermore, the capabilities needed to advance sustainable product development in aerospace were discussed, highlighting priorities for capability building at companies. Finally, existing SPD support methods were reviewed, supporting practitioners in selecting a relevant approach for their context. The following discussion aims to answer the research questions and reflect on the implications of the findings.

*RQ1. What are the main challenges hindering Sustainable Product Development in the aerospace industry?*

The taxonomy proposed in this study groups SPD challenges into six categories which supports in clarifying the nature of problems practitioners may encounter while implementing SPD. Although developed inductively from aerospace literature, this taxonomy presents similarities to other frameworks within economics, design, and circularity (see Table 7). The first three categories gather challenges with a high systemic level, which we argue should be addressed through international policies. While continental policies are essential to drive innovation, the increasing carbon emissions from aerospace will only be significantly reduced through global initiatives. However, it is essential for SPD practitioners to gain an understanding of these categories of challenges as they set the context and would facilitate managing the design space and stakeholder expectations when planning an intervention:

- 1- **Socio-ecological impact:** Companies directly affect the environment and society, and today's products are far from the definition of being “truly sustainable” (Dyllick and Rost, 2017). These sustainability impacts span the whole aircraft lifecycle, though current research focuses significantly on the use-phase climate impact.
- 2- **Regulatory frameworks and industry norms:** Lobbying and established industry norms can weaken sustainability targets (Gössling and Cohen, 2014), and regulations do not sufficiently push companies to develop sustainable products. Companies that are part of industrial associations could be more proactive and steer decisions towards sustainability, but significant change would most likely require a unified movement from the largest companies.
- 3- **Business drivers and economic context:** Market dynamics and operational constraints are difficult to influence for an aerospace manufacturing company: they need to ensure their products generate sufficient revenue to cover production costs and deliver a return on

investment (Mengistu et al., 2024), which is often seen as conflicting with sustainability. Therefore, companies should work towards aligning business value and societal value (Dyllick and Rost, 2017).

The remaining three categories are of a lower systemic level, and this paper argues that they can be managed by companies, providing they have the capabilities to do so:

- 4- **Design process and organisation:** There is a need for organisational and process change to better align with sustainable design practices (Mallalieu et al., 2024), and change is a difficult and lengthy process. Companies have full responsibility to change and improve their ways of working, although constrained by the type of products they design.
- 5- **Behavioural and cognitive influences:** Decision-making towards sustainability can be very difficult due to a lack of knowledge or visibility on the consequences of a decision. Capability development is a strong focus in the field of SPD (Hallstedt et al., 2020), and cognitive barriers significantly hinder the implementation of SPD (Mallalieu et al., 2024). Companies should increase their people's capabilities and support decision-making towards sustainability through culture, training, incentives, and support methods.
- 6- **Technology, infrastructure and products:** Many technologies are promising to support the aviation's sustainability journey (Rohacs, 2022), but their feasibility remains uncertain, both economically and from an engineering point of view (Delbecq et al., 2023). Companies should engage in collaboration with value chain partners and focus on building engineering and data capabilities.

*RQ2. What are the capabilities needed to advance Sustainable Product Development in aerospace?*

The analysis of capability needs across the reviewed papers shows that companies should build capabilities across the entire spectrum of the product development process, focusing on assessing sustainability risk, sustainability impact, and achieving sustainability improvements. Papers frequently use the terms “Early design phases” and “designers”, which can be ambiguous, potentially including several product development phases and a broad range of individuals who may not identify as designers themselves. The capabilities needed to address categories 2- Regulatory frameworks and industry norms and 3- Business drivers and economic context were discussed to a lesser extent in the reviewed literature (see Fig. 4). This could be explained by the presence of potential causal effects between the challenge categories, e.g., supporting designers in decision-making (category 5- Behavioural and cognitive influences) can also support them in overcoming regulatory (2-) and economic (3-) challenges. However, the study's focus on design and engineering activities within aerospace companies may have contributed to the limited discussion of those system levels.

Although SPD research suggests that decision-makers at all levels of the organisation need training and support (Hallstedt et al., 2023), the literature from this review focuses mostly on operational and tactical levels. Therefore, most papers reviewed in this paper take a “bottom-up” approach, which supports engineers to design sustainably despite potentially unsustainable industry targets or company strategy. However, there is growing evidence that top-down approaches can be highly effective, as shown for example by Rauter et al. (2023) and in aerospace sustainability conducted in collaboration with public authorities (Pishdadian et al., 2025). In a sector characterized by long product lifecycles, strategic thinking may also be more embedded within tactical and operational activities than in other industries, blurring the boundaries between organisational levels.

This paper identified 11 top-needed SPD practices, which are listed in Table 5, spanning over a wide range of product development stages. The capability analysis highlighted the importance of building capabilities at all organisational levels, which has also been discussed in previous SPD research (Hallstedt et al., 2013; Mallalieu et al., 2024). The

**Table 7**  
Comparison of the SPD taxonomy with existing frameworks.

Taxonomy dimension	PESTEL dimensions	Engineering change issues ( Jarratt et al., 2010)	Barriers to circular economy ( Kirchherr et al., 2018)
<i>Evidence used for framework design</i>	<i>Conceptual</i>	<i>Conceptual</i>	<i>Empirical</i>
Socio-ecological impact	Environmental, Social	/	/
Regulatory frameworks and industry norms	Legal, Political	/	Regulatory
Business drivers and economic context	Economic	Cost	Market
Design process and organisation	/	Company structure	/
Behavioural and cognitive influences	/	Company culture, Attitudes	Cultural
Technology, infrastructure and products	Technological	/	Technological

14 SPD methods and methodologies found in the systematic review were analysed and related to the capability needs. Most prescriptive supports explicitly aim to integrate sustainability into product development and enhance product sustainability performance, with a strong emphasis on life cycle thinking and systems engineering approaches. However, three critical research gaps persist:

- Most supports are aimed at one person or one target group as a decision-maker and do not explicitly support horizontal and vertical communication (across functions and hierarchy). Ensure that sustainability influences decisions across organisational levels is a recurring issue in SPD. Several authors have proposed methods to facilitate this collaboration (e.g., Schulte and Hallstedt, 2018; Watz and Hallstedt, 2022), while other approaches focus on ensuring decisions are widely accepted through quantification of consensus among a variety of stakeholders (Wu et al., 2025). It is necessary to further develop these approaches for the aerospace context to address the current research gap.
- Mechanisms for trade-off management and prioritisation remain underdeveloped. Navigating trade-offs in design is a recurring challenge in SPD, with, for example, Parolin et al.'s (2025) recent work that provides a structured approach, although not tested in the aerospace context.
- The reviewed papers offer limited support to systematically mitigate sustainability risks. Tools that support handling sustainability risks do not get a lot of visibility, as they might be merged into other purposes of SPD tools, such as “assessment” or “prioritisation” (Vicente and Camocho, 2024). Previous research, however, shows that risk management has different mechanisms from sustainability assessments (e.g., Schneider et al., 2024; Schulte and Knuts, 2022), and such approaches could be further validated and tailored for aerospace products.

#### *Implications, limitations and future work*

In terms of theoretical contributions, this paper advances SPD research by conceptualizing challenges as a multi-level, systemic phenomenon through a taxonomy that includes both internal and external factors, multiple perspectives (policy, organisational, engineering), and all product development stages. Its alignment with PESTEL dimensions, circular economy barriers, and engineering change barriers from the literature indicates applicability to other industrial sectors. Our findings highlight the need to approach SPD broadly in the context of aerospace, not only focusing on the early stages of design, but thinking from strategic planning to the late stages of design, and it requires building capabilities across all organisational levels. Finally, applying the framework of SPD practices presented by Vilochani et al. (2024b) confirms its relevance in the aerospace sector and reveals the most critical capability development needs for this context, pointing out areas where SPD research needs to focus.

Regarding practical implications, this study offers guidance for aerospace companies seeking to advance SPD. Companies may use the taxonomy proposed in this study to identify challenges at organisational, cognitive, and technical levels, and we encourage them to seek support regarding systemic challenges through collaboration in research and industry networks. Additionally, we recommend that companies assess their maturity against the 11 critical capabilities identified in this paper to prioritize capability-building efforts and allocate resources. Furthermore, companies should test the applicability of SPD methods identified in this review, specifically targeted at their least mature capabilities, and consider embedding tools in their processes to ensure sustainability is systematically considered in design decisions.

Insights into the reviewed SPD methods and methodologies are limited, as this study adopted a conceptual approach without empirical testing. Moreover, there is uncertainty about the actual impact of the identified capability needs on product sustainability performance, where further research is needed (Vilochani et al., 2024b).

Future work could investigate the practical value of this taxonomy and critical capability needs in industry and aim to understand further how these findings are perceived by practitioners. Moreover, future work should investigate the applicability of this research in other industrial contexts and compare the critical capability needs with other industrial sectors, which are expected to present many similarities based on the discussion above. This research shows that future SPD support development for the aerospace industry should adopt a more ambitious and holistic scope that addresses organisational and strategic dimensions of SPD capability building and focus on developing supports that target the most critical capability needs identified in this review. Based on our findings, we propose the following research agenda:

- i) *Disseminate the SPD challenge taxonomy and critical capability needs* to SPD practitioners and R&D managers in the aerospace industry. This will spread knowledge and support them in structuring their SPD actions, while verifying the relevance in the industrial context. Moreover, companies could measure their maturity in different capabilities using our findings to identify areas of weakness and efficiently plan for future interventions.
- ii) *Analyse gaps and needs from an industrial perspective.* Mapping gaps and challenges in detail across product development stages allows to identify stage-specific constraints, decision-making levers, and organisational responsibilities influencing SPD integration. This is about using appropriate research methods (e.g., action research) to understand who is involved, when sustainability-related decisions are made, which constraints apply to each stage, and which helps to identify actionable levers to advance SPD in aerospace.
- iii) *Map, combine, and further develop existing support methods* for SPD from industries other than aerospace that could fill the most critical gaps, namely trade-off management, mitigate sustainability risks, and support cross-functional engagement around SPD. A future SPD methodology should support aerospace manufacturing companies in engaging different organisational levels and adopting a strategic sustainability perspective and a full lifecycle perspective.

## 5. Conclusion

Through a systematic literature review, this study analyses 51 papers and provides a comprehensive overview of the current state of Sustainable Product Development (SPD) in the aerospace industry, addressing key challenges and capabilities. The field of SPD in aerospace is rapidly evolving, with most research published from 2021 and a strong concentration of studies from Europe. While research approaches and levels of analysis are diverse, recent studies increasingly focus on the use phase, with holistic approaches and social sustainability perspectives remaining less addressed.

This paper introduces a six-category taxonomy of SPD challenges that aligns with established frameworks in related fields and can help practitioners identify and address barriers to sustainable product development. While companies can directly manage technical, structural, and human challenges through capability building, understanding the broader context of socio-ecological, regulatory, and economic factors is essential for effective SPD interventions. To advance SPD in aerospace, companies should build capabilities across all product development phases, with a focus on assessing sustainability risks, sustainability impacts, and implementing improvements. The literature tends to emphasise bottom-up efforts, supporting engineers and designers, and advocates for a holistic, lifecycle, systemic approach of sustainability. This study identified 14 SPD methods tailored to aerospace, covering a broad range of situations. However, these support methods are standalone and fragmented, highlighting the need for better support in method selection to effectively drive sustainable product development.

By synthesising state-of-the-art knowledge, this paper offers a comprehensive synthesis of current research for sustainable product development in the aerospace industry. The proposed six categories of SPD challenges help researchers, practitioners, and policymakers understand and manage barriers to sustainability. The study also outlines eleven actionable capabilities across product development stages, guiding academia and companies in targeting their actions. Additionally, this paper examines SPD support methods found in the review that are tailored to aerospace, highlighting the need for better integration and selection support. While grounded in aerospace, the findings offer insights applicable to other industries undergoing sustainability transitions. Limitations to this research reside mainly in the research methods used and the nature of the data analysed. Many of the insights from this systematic literature review were derived from non-explicit content or inferred knowledge within the papers, which required interpretation throughout the review process similarly to processes for qualitative data analysis.

Future research in Sustainable Product Development should further support companies in addressing structural, cognitive, and technical challenges. This research shows that future SPD support development for aerospace should adopt a more ambitious and holistic scope that addresses the organisational and strategic dimensions of SPD capability building and focus on developing supports that target the most critical capability needs identified in this review. Two main research directions emerge from this paper. First, sharing the SPD challenge taxonomy and critical capability needs with SPD practitioners and R&D managers will support companies in prioritisation and decision-making for sustainable product development. Second, this research showed gaps in aerospace-tailored SPD support, which can be resolved through exploring practices in other industrial sectors, as well as combining and further developing existing methods from sustainable material selection guides to holistic sustainability impact assessments.

#### CRediT authorship contribution statement

**P.L.Y. Léonard:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **S.I. Hallstedt:** Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization. **G. Dokter:** Writing – review & editing, Supervision, Conceptualization.

#### Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Copilot to spell-check the manuscript. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

#### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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#### Appendix A. Supplementary data

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