

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Integrating sustainability in aerospace product development: challenges and pathways for change

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Gothenburg, Sweden, 2026

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Cover: The illustration consists of a light bulb containing the Earth, surrounded by gears, clouds, airplanes and a circular arrow. It symbolises sustainability, aerospace, engineering and innovation. Image generated by Pauline Léonard using GPT-5.3, April 2026.

Printed by Chalmers digital printing,  
Gothenburg, Sweden 2026.

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## **Abstract**

This thesis explores sustainable product development in the aerospace industry, an inherently complex sector with long product lifecycles, advanced technology, high safety standards, and an urgent need to become more sustainable. The aim of this thesis is to clarify the challenges associated with integrating sustainability in aerospace product development, and to propose how aerospace design practice could change to ensure further sustainability integration.

The research conducted for this thesis work employs a multiple case study approach with two main aerospace companies, which participated in all empirical studies in this thesis. Using a qualitative research approach, four studies were conducted. Together, they provide an understanding of: i) current sustainability integration in aerospace product development and underlying reasons, ii) challenges for further sustainability integration, iii) capability needs and main levers to overcome sustainability integration challenges.

The findings indicate that, despite many constraints, aerospace manufacturing companies can significantly influence the sustainability impact of the products they design. Developing products towards sustainability requires new capabilities to effectively assess sustainability performance, navigate trade-offs, and mobilise relevant stakeholders throughout the product development process. Sustainability should become a driver for product development decisions, influencing which projects are realised and what concepts are selected.

The study advances scientific knowledge by providing in depth empirical insights into sustainability integration barriers and leverage points for advancing sustainable product development. This research supports aerospace practice by providing a structured taxonomy of challenges, an overview of necessary capabilities, and levers to help practitioners further integrate sustainability into product development.

## **Keywords**

Aerospace, Engineering design, Sustainability, Sustainable Product Development



# List of Publications

## Appended publications

This thesis is based on the following publications:

[**Paper A**] **Léonard, P. L. Y.**, Hallstedt, S. I., Nylander, J. W., Isaksson, O. (2024). Design Aspects of Importance in a Sustainability Transition. *Proceedings of NordDesign 2024, Reykjavik, Iceland, 12-14 August 2024*. <https://doi.org/10.35199/NORDDESIGN2024.12>

The author of this thesis was the lead author of this paper and led the work in all stages of the study. She was responsible for the literature review and study design, i.e., selection of case companies, participants, and planning of the semi-structured interviews. She executed the interviews, analysed and synthesised the results. She led the writing process of the paper, responded to reviewers, and presented at the conference.

[**Paper B**] **Léonard, P. L. Y.**, Hallstedt, S. I., Dokter, G. (2026). Capability Needs for Sustainable Product Development in Aerospace: A Systematic Literature Review. *Sustainable Production and Consumption*, 64, 191-203. <https://doi.org/10.1016/j.spc.2026.02.0042>

The author of this thesis was the lead author of this paper and led the work in all stages of the study. She was responsible for the literature review and study design, i.e., selection of case companies and participants, and planning of the semi-structured interviews. She executed the interviews, analysed and synthesised the results. She led the writing process of the paper, responded to reviewers, and presented at the conference.

[**Paper C**] **Léonard, P. L. Y.**, Hallstedt, S. I., Isaksson, O., Kipouros, T., Mallalieu, A. (2025). Key elements to navigate sustainable product development in aerospace. *Proceedings of the Design Society, Volume 5: ICED 2025, 2191-2200*. <https://doi.org/10.1017/pds.2025.10233>

The author of this thesis was the lead author of this paper. She supported the design and execution of the workshops and was responsible for analysing results. She was responsible for the design, execution, and analysis of the interviews. She led the writing process of the paper, responded to reviewers, and presented at the conference.

[Paper D] **Léonard, P. L. Y.**, Hallstedt, S. I., Dokter, G. (in press). Who drives sustainability in product design? A case study in aerospace. *Proceedings of the Design Society, DESIGN2026*.

The author of this thesis was the lead author of this paper and led the work in all stages of the study. She was responsible for the design of the study, including the selection of case companies, study participants and planning for the workshops and interviews. She led the execution and analysis of the qualitative data collection methods and coding activities. She led the writing process of the paper, responded to reviewers and is expected to present at the conference.

# Acknowledgments

I would like to thank my academic supervisors, Sophie Isaksson Hallstedt and Giliam Dokter, for their guidance in conducting this research. You have been kind and supportive on this journey to become a researcher. It has been a challenge to adjust to academic approaches after years of effective report writing and firefighting in industry, and I sincerely appreciate your patience in guiding me through this change.

I would like to thank my industrial supervisor, Johanna Wallin Nylander, for believing in me and supporting me in realising this research project. You and our sustainability team make me feel like I have a group of cheerleaders behind me, always having positive feedback and ready to provide support when I need it.

I would also like to thank my other colleagues at GKN Aerospace. My journey from materials engineering to sustainable product development brought me to many different teams and managers, and I am grateful to still receive support and recognition from all of you.

Additionally, I would like to thank all of my co-authors and the Systems Engineering Design research group at Chalmers University of Technology for their continuous support and exchange on research and early steps of a PhD.

Finally, I want to thank my friends, family and my partner who have supported me throughout my PhD journey. You helped me stay grounded, provided much-needed escapes from reality, and did so always with positivity and kindness.

This research was supported by the Swedish Governmental Agency for Innovation Systems (VINNOVA) through the SUSTAIN project (SUStainable life cycle Thinking in the Aerospace Industry), grant number [2024-01283].



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# Acronyms

**DRM** Design Research Methodology

**DS-I** Descriptive Study I

**DS-II** Descriptive Study II

**OEM** Original Equipment Manufacturer

**INCOSE** International Council on Systems Engineering

**PS** Prescriptive Study

**RC** Research Clarification

**RQ** Research Question

**SPD** Sustainable Product Development

**SRQ** Sub-Research Question

**TRL** Technology Readiness Level



# Chapter 1

## Introduction

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. Historically, the aerospace industry's growth was made possible by technological and regulatory improvements, which rendered flight safer and more affordable (Spren, 2020), as well as urbanisation and a growing middle-class population, which made flying more accessible (Addepalli et al., 2018). The civil industry is expected to continue to expand, which will result in increased carbon emissions, which are estimated to double by 2050 in business-as-usual scenarios for the aviation sector alone (ICAO, 2025). The military aircraft industry is also rapidly growing, as worldwide military expenditures increased by 9.4 per cent in 2024 only (Liang et al., 2025).

Increasing sustainability challenges, however, extend beyond greenhouse gas emissions alone. NO<sub>x</sub> emissions, local air pollution, noise pollution, and resource dependency are some examples of the many sustainability challenges that will continue to grow in importance (European Commission, 2022). There is also high uncertainty around the non-CO<sub>2</sub> effects of aviation, which might double or triple the warming effect of aviation compared to considering direct CO<sub>2</sub> emissions alone (Lee et al., 2021). Consequently, the industry growth will have negative consequences on the planet and society unless substantial transformations in design, production, and operational practices are implemented across the aerospace sector. This implies that a radical shift in aircraft systems design must happen to align future aerospace products with the sustainability expectations of the coming decades.

Achieving a successful transition to a sustainable society requires a strategic and systematic approach that considers ecological, social, and economic dimensions together. Sustainable development requires that both society and nature must be sustained and not systematically and increasingly degraded (Broman & Robèrt, 2017).

Product development plays a pivotal role in accelerating the sustainabil-

ity transition (Gaziulusoy et al., 2013), and companies can develop products towards sustainability within a 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 & Isaksson, 2017). Implementing SPD requires changing product development practices (Mallalieu et al., 2024), which includes structures, processes, methods, and capabilities to ensure the product meets market needs, technical requirements, and business goals. While various forms of SPD support exist, their efficient implementation in the industry remains a challenge (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 & Hallstedt, 2022).

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. In the aerospace innovation process, value is being created through improvements in efficiency, customer experience, and environmental sustainability (Pereira et al., 2021). But 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). The use phase of a civil aircraft accounts for more than 99 per cent of its lifetime carbon emissions (Rahn et al., 2022), an impact that is locked in very early in the design process when the type of aircraft and fuel used are determined. These characteristics make early design decisions disproportionately impactful for sustainability and difficult to reverse once a product is in service.

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. It is an ongoing challenge to define and represent sustainability criteria that are both compliant with a strategic sustainability perspective and sufficiently precise to guide designers (Hallstedt et al., 2023a). 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). Only a few initiatives aim to integrate all sustainability dimensions as a driving force in the initial stages of design (Filippatos et al., 2024).

Implementing SPD in the aerospace industry is not a clearly defined, solvable, and testable problem, which can therefore be considered as “wicked” (Rittel & Webber, 1973). SPD does not have a *clear stopping rule* (Rittel & Webber, 1973): because systemic consequences cannot be fully predicted or bounded, there is no finite point at which one can verify “the system is

sustainable” or “SPD is sufficiently implemented”. Moreover, to “achieve” sustainability would require bringing all its dimensions to a satisfactory level, and some would argue that creating new products that might not be needed by society is already trespassing this threshold. Then, there is *no ultimate test* (Rittel & Webber, 1973) to evaluate the effectiveness of a SPD solution, as the results of capability building on the resulting product sustainability impact cannot be fully evaluated in advance. This is especially difficult in the context of aerospace, where product development cycles can last a decade. Finally, *problem understanding and solution development are intertwined*, as defining the problem implies a preferred solution (Rittel & Webber, 1973). Therefore, advancing SPD requires an understanding of a broad range of topics, i.e., organisations, decision-making mechanisms in design, the product development process, and its management.

## 1.1 Research aim and research questions

The long-term goal of this research is to enable aerospace product development teams to develop solutions with improved sustainability. The initial focus of this thesis was to understand context-specific challenges to SPD in the aerospace industry. As the research progressed, the scope expanded to understanding the main levers to advance SPD, which requires knowledge of the product development process, the management of product development, and decision-making mechanisms in design.

The aim of this thesis is to clarify the challenges associated with integrating sustainability in aerospace product development, and to propose how design practice could change to ensure further sustainability integration. Two Research Questions (RQs) and six Sub-Research Questions (SRQs) are defined to guide this research in achieving the aim:

**RQ1. What are the key challenges of integrating sustainability in aerospace product development, and why?**

**SRQ1-1.** To what extent is sustainability currently integrated in aerospace product development?

**SRQ1-2.** How can sustainability integration challenges be categorised to support companies in effectively mitigating them?

**SRQ1-3.** Why do aerospace companies encounter sustainability integration challenges in product development?

RQ1 is descriptive and intends to capture the challenges that companies and practitioners encounter when advancing sustainable product development. It requires understanding the current state-of-practice (SRQ1-1), to categorise sustainability integration challenges (SRQ1-2) and explain why such challenges are present (SRQ1-3).

**RQ2. What could change in aerospace product development practice to deliver more sustainable products?**

- SRQ2-1.** What capabilities are needed to address sustainability integration challenges in aerospace product development?
- SRQ2-2.** What are the main levers to accelerate the integration of sustainability in aerospace product development?
- SRQ2-3.** In what ways should the key stakeholders involved in product development collaborate to design products towards sustainability?

RQ2 is of a prescriptive nature and focuses on identifying the changes necessary to design practice to accelerate sustainable product development. It intends to capture capability needs for organisations and product development teams (SRQ2-1), to clarify the main levers to accelerate the implementation of sustainable product development (SRQ2-2), and to understand the role of product development stakeholders in realising sustainable products (SRQ2-3).

## 1.2 Scope and assumptions

Some delimitations need to be listed to clarify the scope of this thesis. This research focuses on product development activities for the design of aircraft systems and subsystems. When referring to “aerospace” in this thesis, it includes physical systems and subsystems of commercial aircraft, business jets, and fighter jets. Therefore, the research scope includes both civil and defence aerospace industries. The space industry and digital products are out of scope. While the results of this research might have broad implications for many stakeholders (e.g., policy makers or airlines), the core focus of this research is on aerospace manufacturing companies and how they can change their design practices.

This thesis approaches product development broadly. This includes design activities, e.g., planning, conceptual design, detailed design, and gate assessments. It also includes supporting processes, i.e., strategic planning, programme management, and technology development. Portfolio management, testing, and production are out of the scope of this thesis. Finally, while acknowledging that aerospace is a global industry, Swedish companies were chosen as the main scope for this research. This thesis is based on two main assumptions:

- *Aerospace manufacturers can have a lot of influence on the sustainability impact of the solutions they design.* While acknowledging a need for systemic change that includes new regulations and policies, this thesis assumes that acting at the company level will have a significant impact on product sustainability.
- *Companies changing their product development practices will accelerate the sustainability transition.* Although this assumption is based on a robust logic, there are no examples yet of companies that have fully implemented SPD and are capable of developing truly sustainable products.

## 1.3 Thesis structure

This chapter has briefly introduced the reader to the problem and focus of this research. Chapter 2 outlines the theoretical background to the studied topic. Chapter 3 presents the research design and methodology adopted in this research. Chapter 4 presents a summary of the appended papers, along with highlighting their contribution to this thesis. Chapter 5 discusses the findings with respect to the research questions and the validity of the results. Chapter 6 concludes the main findings and presents the way forward. The reference list is provided at the end, followed by the appended papers on which this research is founded.



# Chapter 2

## Theoretical background

This chapter gives a theoretical background to this thesis and provides an overall description of the research area that this research is part of. An introduction to the aerospace industry is covered in Section 2.1. Section 2.2 introduces product development and some typical activities and processes in the context of the aerospace industry. Section 2.3 introduces and defines sustainability and sustainable product development, describing its role, key factors and current status in the aerospace sector.

### 2.1 The aerospace industry

The aerospace industry is a complex, global, strategically important sector that designs, manufactures, operates, and supports aircraft, spacecraft, and related systems. Aerospace typically includes three segments: i) *civil* (commercial aviation, business jets, regional aircraft), ii) *defence* (fighter jets, transport aircraft, defence systems), and iii) *space*. This section introduces the aerospace industry within the scope of this thesis and focuses on sustainability in aircraft systems and subsystems development.

Aviation has been tightly regulated since its earliest days, evolving from 18th and 19th century local and international rules on balloon flight to today's extensive, harmonised legal frameworks governing safety, operations, and liability (Spreen, 2020). As aircraft capabilities increased and cross-border flying became routine, national laws and international treaties grew in parallel, making aerospace one of the most heavily regulated industries in the world (Spreen, 2020). The aerospace industry has experienced significant technological and structural changes over the last few decades. Historically, different segments operated with distinct dynamics, but these have converged into tightly inter-linked markets over time. Consolidation has been a major trend over the last few decades, and small and mid-tier manufacturers often specialise or exit markets due to scale pressures, turning aerospace into a few dominant players

supported by extensive supplier networks (Gélain, 2021).

From an engineering product development perspective, the aerospace industry has shifted significantly. In the past, engineers largely defined products by pushing technical limits, while cost, industrialisation, and risk were addressed later (Gélain, 2021). Modern aerospace product development is now inseparable from programme management, systems engineering discipline, industrial readiness, and global supply chains (Spreen, 2020). As a result, today's engineering decisions must align with business strategy, market demand, certification risk, supply-chain capability, and long-term operational costs, meaning that the “best” design is not always the most advanced technically, but the one that delivers the greatest overall (Gélain, 2021). The combined influence of factors such as production constraints, supplier maturity, quality assurance, regulatory compliance, certification and financial exposure all shape what can be engineered and when, meaning product development is now as much a managerial and coordination challenge as a technical one (Spreen, 2020).

Commercial aviation represented approximately 2 per cent of global greenhouse gas emissions in 2019, but forecasts suggest an escalation due to the 3.6 per cent expected annual average growth rate of the passenger market over the next three decades (ICAO, 2025). This rapid growth is possible thanks to the technological and regulatory improvements, which enabled safer and more affordable flights. This industry will represent as much as 20 per cent of man-made greenhouse gas emissions by 2050 if no significant action is taken. 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. 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.

New regulations and policies are already being launched, such as the EU's Green Deal (European Commission, 2022) and the EU's Critical Raw Materials Act (European Commission, 2023), enforcing a transition towards a circular economy and more regional value chains. These regulations will most likely have an impact on the 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 requires closer attention to sustainability, with the risk of overemphasising the reporting itself rather than driving change. In addition to policies and regulations, aerospace organisations (e.g., ICAO, 2025, ACARE, 2020) and authorities (e.g., EEA, 2023) are driving the sustainability transition by setting long-term aspirational goals related 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 management (IAEG,

2025). Altogether, there are several actors that push and drive the change in the aerospace industry towards more sustainable solutions. While aerospace has set long-term decarbonisation targets, progress against these goals has been limited, and it is likely that other sustainability impacts are also not being reduced as rapidly as needed.

The historical example of cobalt showcases how integrating sustainability into product development previously would have strengthened the industry's economy today. Older engine generations used many cobalt-based alloys, a critical metal that is predominantly mined in politically unstable regions of the world. Mining conditions cause many social sustainability issues, such as exploitation, child labour, dangerous and unregulated working conditions, and severe health impacts on local communities. A major historical shift occurred in the late 1970's, when cobalt prices surged dramatically due to increased geopolitical instability in Central Africa (Stephens, 1981). This supply risk caused cobalt prices to spike sharply, making the metal too expensive and unreliable for aerospace manufacturers who relied on it for turbine engine alloys.

Today, the industry is heavily focused on technology development. Many studies compare different technological innovations (e.g., Dhara and Lal Jeyan, n.d., Bravo et al., 2022, Rohacs, 2022) and their potential to reduce the climate impact of civil aviation. Other research focuses on the sustainability impact of specific innovations, such as the electrification of propulsion systems (Adu-Gyamfi & Good, 2022) or sustainable aviation fuels (Tanzil et al., 2021). There is, however, evidence that technology cannot keep up with the growth of air travel demand for the period up to 2050 (Haan, 2010), and deeper societal transformations must take place (Gössling & Cohen, 2014). If technological progress alone is insufficient to address sustainability challenges, it is necessary to rethink how aircraft are conceived and designed in the first place.

## 2.2 Product development in aerospace

Product development is the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product (Ulrich & Eppinger, 2012). Aerospace faces distinctive obstacles that constrain product development activities and shape how aircraft are designed today. Aerospace design is a synthesis of trade-offs among competing priorities: cost, weight, size, performance, safety, power, payload, range, noise, reliability, and so on.

The development of aerospace products can take from a few years to a decade, depending on the level of innovation, and is constrained by standards, regulations, and certifications. The certification of aircraft is extremely expensive and rarely done from scratch. This limits the adoption of radical innovations that can enable a more sustainable flight, such as electric or hydrogen flight. In addition, the operational lifespan in the civil industry averages around 26.5

years (Elsayed et al., 2019). For instance, the aircraft Boeing 747 was certified in the late 60's, and its derivative aircraft systems, building further on the original aircraft certification, have been in production until 2022. Aerospace products designed today will still be in use in 2050. To significantly improve the sustainability impact, there is a need to welcome radical technology shifts without compromising flight safety and business risk (Hallstedt et al., 2023a). This industry also faces slow development in technologies and materials that support a circular economy (Rodrigues Dias et al., 2022).

The need to use advanced materials and manufacturing methods is another sustainability challenge that the industry is facing (Hallstedt & Isaksson, 2017). Materials for aerospace products need to be thoroughly certified for safety reasons and are often expensive. Specific alloys are scarce and critical from an availability and sustainability perspective, and are typically 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 do not necessarily reduce material use or waste. It is particularly challenging to comprehend and utilise the design space to make materials and manufacturing processes more sustainable.

### 2.2.1 The aerospace product development stakeholders

Product development involves a wide range of internal stakeholders at companies, who refer to different functions. Table 2.1 shows an overview of the key functions for sustainable product development (Vilochani et al., 2024b) and for product development drivers (Majava et al., 2015) side by side. Strategic management, engineering, and product management are identified as having the most influence on product development drivers.

Aerospace companies typically operate under rigorous systems engineering processes, where functions such as airworthiness and certification, system safety, configuration management, integration and test, and programme management exert substantial influence over product development decisions. These functions act as gatekeepers for technical maturity, risk acceptance, and regulatory compliance, making them critical contributors from the earliest stages of planning through to retirement (Gélain, 2021). In addition, technology development functions are deeply intertwined with product development because long development cycles and high-performance targets require continuous advancement of materials, manufacturing processes, and digital engineering capabilities (Hallstedt et al., 2023a). Moreover, sustainability has become increasingly integrated in aerospace decision-making. This introduces new roles that participate directly in trade-offs during conceptual and detailed design.

In addition to internal functions, external stakeholders play a significant role in shaping product development activities. Aviation stakeholders form a complex, multi-level decision-making hierarchy (Al Sarrah et al., 2020). Consequently, key stakeholders, such as regulatory committees, aerospace

**Table 2.1:** Comparison of key functions for sustainable product development (Vilochani et al., 2024b) and product development drivers (Majava et al., 2015).

<b>Key functions for sustainable product development</b>	<b>Key internal stakeholders for product development drivers</b>
Strategic management	Management (Tier 1)
Product and service innovation	Engineering (Tier 1), Product management (Tier 1)
Sales and marketing	Sales (Tier 2), Marketing (Tier 2)
Supply chain management and operations	Sourcing (Tier 2), Operations (Tier 2), Logistics (Tier 3)
Compliance and standardisation	Quality (Tier 2), Legal (Tier 3)
After sales	Customer care (Tier 3)
Market intelligence & business development	Not in model
Change management	Not in model
Technology development	Not in model
Information technology	Not in model
Sustainability	Not in model

manufacturers, and airlines, often delay decisions regarding environmental sustainability or pass on their responsibility ‘to one another’ (Singh et al., 2022). The Original Equipment Manufacturers (OEMs) capture requirements from passengers, airlines, and national governments. They must operate and develop in alignment with airworthiness authorities such as EASA in Europe or FAA in the USA.

Different types of Tier-1 OEMs exist. Civil airframe OEMs, e.g., Airbus, Boeing, Embraer, design and manufacture commercial aircraft used for passenger and cargo transportation. Defence airframe OEMs, e.g., Lockheed Martin, BAE Systems, Dassault Aviation, SAAB, develop and produce military aircraft tailored to defence and security missions. Aero-engine OEMs, e.g., Rolls-Royce, General Electric, Pratt & Whitney, Safran, design, build, and support the engines that power civil and military aircraft. Equipment OEMs, e.g., Honeywell Aerospace, Leonardo, Thales, supply critical onboard systems and avionics that enable aircraft operation, safety, and performance. Finally, maintenance, repair, and overhaul OEMs, e.g., Lufthansa Technik, ST Engineering Aerospace, HAECO, provide specialised services to inspect, maintain, repair, and extend the life of aircraft and their components.

The Tier-1 OEMs are often both system integrators and developers of technologies and components. In this context, the supplier’s responsibility can vary greatly. It ranges from being a contractor and following transactional business models, to being a partner with shared investment, collaborative business models, and sharing technical and financial risk, e.g. GKN Aerospace. The OEMs expect such partners to propose new and more effective technologies, and this requires a systems integration perspective.

## 2.2.2 The product development process in aerospace

A product development process is the sequence of steps or activities that an enterprise employs to conceive, design, and commercialise a product. Some organisations define and follow a precise and detailed development process, while others may not even be able to describe their process (Ulrich & Eppinger, 2012). Aerospace product development includes several concurrent processes. Technologies are researched and matured through the technology development process and by researchers and research engineers. Products are designed using selected mature technologies, and the design process starts from an initial idea and ends with a certified design ready for production. In the aerospace industry, design is at the start of the life cycle process, which spans from a product idea through its development, production, and retirement.

Design can be viewed as a process of making decisions towards solving a problem and seeking solutions (Isaksson et al., 2022). Design engineers often face wicked problems without an obvious way forward, which led to the development of “design thinking” to solve such challenges. Design thinking builds on five phases: empathise, define, ideate, prototype, and test (Isaksson et al., 2022).

Structuring product development comes from the need to get better at conceiving, developing, and launching new products that give companies a durable competitive advantage (Cooper, 2015). Gate assessments act as a quality control checkpoint between each stage. In short, the stages are where the work is done, and the gates ensure that the quality is sufficient (Cooper, 1990). In industries with a systems engineering approach, such as aerospace, risk and safety management are embedded within the gate assessment process. Each gate serves as a decision point ensuring technical maturity, safety readiness, resource adequacy, and acceptable residual risk before proceeding. This approach ensures that progress is clearly visible and ensures the readiness to proceed (INCOSE, 2023). Typical goals of decision gates are to confirm that: i) the maturity is within a defined threshold, ii) the project satisfies the business case, iii) the resources are sufficient to continue development, iv) the unresolved issues are addressed, and v) the risk for proceeding is acceptable.

Process models exist that allow for a better understanding and management of design practice. Ulrich and Eppinger’s (2012) generic model includes place in six steps: planning, concept development, system-level design, detail design, testing and refinement, and production and ramp-up. In this model, the product is first defined at a system/architecture level before being split into subsystems for detailed design. In the context of aircraft system design, literature describes three main stages, starting from requirements and ending with fabrication:

- *Conceptual design*: encompasses sizing of the most promising overall aircraft concept and proof of its feasibility. Has a typical duration between 4 to 6 months for a business aircraft and 9 to 12 months for a mid-size airliner (Torenbeek, 2013). The basic questions of configuration arrangement, size, weight and performance are answered. It is an iterative

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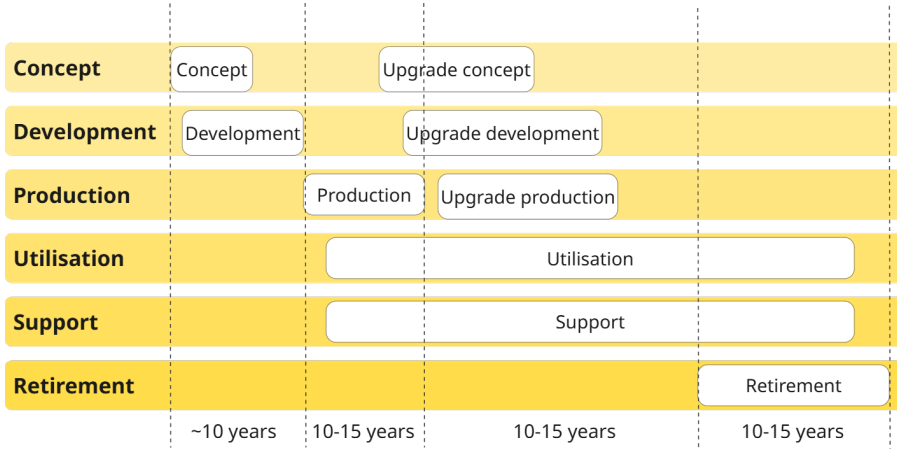
process where new ideas and problems emerge (Raymer, 1992).

- *Preliminary design*: aims at specifying the design concept at the main component level, sometimes including subsystem trades. Preliminary design typically lasts between 12 and 16 months. It begins when the major changes are over. The specialists in areas such as structures, landing gear, and control systems will design and analyse their portion of the aircraft (Raymer, 1992).
- *Detail design*: subsystems are designed, the actual structure of the aircraft is fabricated and tested, specialists determine how the aircraft will be manufactured (Raymer, 1992). This development phase is entered soon after the aircraft is committed to production and lasts between two and three years (Torenbeek, 2013).

The design of aero-engines starts with a similar phase of conceptual design. Customer requirements define the capability requirements of the airframe and power system, typically including thrust and specific fuel consumption (Jones et al., 2002). In this context, “customer” can mean the aircraft manufacturer or a military operator, e.g., the UK Ministry of Defence. From this limited data, a possible engine solution is defined. The aerospace industry adopts a systems engineering approach. Practitioners within a project team take a holistic, balanced, life cycle approach to support the successful completion of system projects (INCOSE, 2023). The “completion” includes realisation, use, and retirement of engineered systems. According to the International Council on Systems Engineering (INCOSE) handbook (INCOSE, 2023), commercial aerospace systems use all types of system development models. In practice, a sequential approach is often adopted for the whole aircraft and engine system because certification requires gated progress. An incremental/evolutionary approach can be applied for subsystems that can be updated or receive new components/features, which is the case for aero-engines. Finally, small, software-heavy components can adopt agile approaches where rapid iterations are possible.

Figure 2.1 shows a typical case of the system engineering development process for civil aircraft or engine development, with 10 years of design and up to 30 years of utilisation. It is typical to upgrade an aircraft or engine system mid-life to solve deficiencies encountered during usage or add new functionality. Since the beginning of the 2000’s, many countries require that planning for retirement is part of the system definition during concept and development stages, which makes the OEMs accountable for proper disposal (INCOSE, 2023).

In the context of aerospace, technology development plays a significant role IN product development. Technology Readiness Levels (TRLs) were introduced in the mid-1970’s by the National Aeronautics and Space Administration as an approach to allow a more effective assessment and communication of the maturity of new technologies. Mankins (2009) describes further how the TRLs are commonly defined by a combination of nine levels, which are characterised by a set of specific activities and deliverables. TRLs1-3 correspond to a research stage, from observing basic principles to analyses and experimentation on a



**Figure 2.1:** Overview of the system engineering development process adapted for civil aircraft and engine development. Adapted from (INCOSE, 2023).

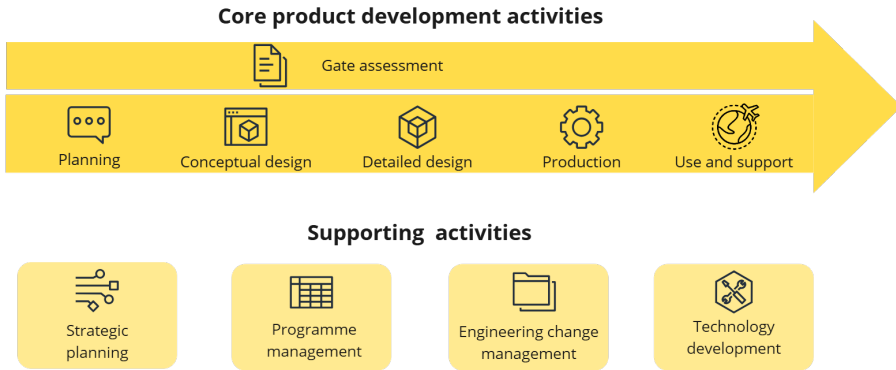
concept. TRLs4-6 correspond to engineering development, from validating a prototype in a laboratory environment to system demonstration in a relevant environment. Finally, TRLs7-9 relate to product demonstration, integration and qualification (Mankins, 2009). In aerospace, TRLs are not just a maturity scale; they are directly connected to how aerospace companies structure and plan their product development activities. TRL6 is a critical stage where a prototype has been tested in a relevant environment and is often a minimum maturity threshold to insert a technology in a product or system.

### 2.2.3 Aerospace product development from a sustainability perspective

To develop solutions towards sustainability, it is necessary to adopt a broad view on product development, not only considering design activities but also supporting activities. Figure 2.2 shows an overview of aerospace product development activities in the context of SPD, inspired by Vilochani et al. (2024b), INCOSE (2023), and Ulrich and Eppinger (2012).

System integration, verification, and validation are activities that should occur throughout the design process, not only at the end (INCOSE, 2023), which is why they are not represented as distinct phases in this process. In the context of aerospace, several companies can jointly develop a system and are entering the product development process concurrently. The core aerospace product development activities are defined below:

- *Planning*: takes place before a product development project is formally approved and launched. It begins with opportunity identification guided by the corporate strategy and aims to identify the target market for the product, business goals, key assumptions and constraints, and preliminary



**Figure 2.2:** A view on aerospace product development activities for sustainable system development, inspired by Vilochani et al. (2024b), INCOSE (2023), and Ulrich and Eppinger (2012).

technology selection (Ulrich & Eppinger, 2012). For system development, this also includes formulation of requirements at the system level and derivation of subsystem requirements (INCOSE, 2023).

- *Concept development:* in this phase, the needs of the target market are identified, alternative concepts are generated and evaluated. It includes the development of a preliminary system architecture and refinement of requirements (INCOSE, 2023). In comparison to Raymer’s (1992) nomenclature, this entails both “conceptual design” and “preliminary design”, i.e., encompasses sizing of the most promising overall aircraft concept, proof of its feasibility, and specifying the design concept at the main component level.
- *Detailed design:* further development of the selected concept, testing, and validation. The designs of subsystems are finalised (Raymer, 1992) and are certified to be ready for production and use. This stage aims to mature the system concepts to meet stakeholder needs and requirements in a manner that is supportable over the desired span of product life (INCOSE, 2023).
- *Production and launch:* begins with the approval of the design and its qualification for use. In production, the system, its enabling systems, and related documentation are realised (INCOSE, 2023).
- *Product support:* evaluation of experiences from product use, customer support, and removal of product from operation at end-of-life. Product modifications are often introduced during this stage to remedy deficiencies, enhance capabilities, or extend the system’s life (INCOSE, 2023). This is the case in the aerospace industry: it is frequent for OEMs to launch a new “generation” of the system after 10-15 years of production. In the fighter jet business, life cycles can be longer, and there can be more iterations of upgrades.

Aerospace product development is also complemented by supporting activ-

ities. These run in parallel to the main product development activities and support them in various ways, e.g., providing input, direction, resources, or approval. The following list of supporting processes is inspired by Vilochni et al.'s (2024b) nomenclature:

- *Strategic planning*: formulation and deployment of business and innovation strategy.
- *Programme management*: management of product development portfolio, management of product lifecycle, and allocation of resources.
- *Engineering change management*: control of product information, requirements, and design elements to maintain consistency throughout the lifecycle.
- *Technology management*: identification, development, and management of new technologies.

*Gate assessment* is conducted parallel to all core product development and technology development activities.

## 2.3 Sustainable product development

This chapter describes the field of Sustainable Product Development (SPD) with fundamental concepts, its relation to neighbouring research fields and state-of-the-art SPD literature.

The definition of sustainability traces back to the Brundtland Commission, which defined the concept of sustainable development as “to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs.” (Nations, 1987). With its focus on fulfilment of human needs now and in the future, the definition has been widely adopted, but gives no specification of which type of needs are concerned. Therefore, the concept of the triple bottom line was based on the Brundtland report’s three pillars: environmental, social, and economic considerations (Elkington & Jeurissen, 2000). These three pillars can be seen as inter-nested, where a thriving economy relies on a thriving society, relying itself on a thriving planet. The Framework for Strategic Sustainable Development further conceptualises sustainability through the funnel metaphor, which illustrates how ecological and social constraints tighten over time as resources are depleted and societal expectations increase (Broman & Robèrt, 2017). In this narrowing space, organisations that address only selected aspects of the triple bottom line risk suboptimisation, whereas a holistic, principled perspective is needed to avoid being pushed toward the funnel’s closing walls.

Using this view for sustainability means there is space for economy and society to grow, but this must be within boundaries so that the growth does not jeopardise the stability of Earth’s natural systems. Those critical impact levels are called planetary boundaries. In 2023, six of the nine boundaries were transgressed, suggesting that Earth is now well outside of the safe operating space for humanity (Richardson et al., 2023). With this overall picture in mind,

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it becomes easier to understand how these issues appear at the product level.

### 2.3.1 The role of product development in the sustainability transition

The production and consumption of products significantly impact society and the environment. The role of product design for sustainable development has been a research area that has developed considerably over the last 30 years (Bhamra & Hernandez, 2021). Considering ecological, social, and economic dimensions altogether is essential for the transition to a sustainable society (Broman & Robèrt, 2017), which can be achieved by developing products that better meet fundamental sustainability principles (Hallstedt, 2017). This is a complex but necessary task in which manufacturing companies must participate to develop solutions that preserve natural and social systems while enhancing long-term success and competitiveness (D. Maxwell & van der Vorst, 2003). This, in turn, calls for increasing capabilities to be resilient (Urbaniec, 2014) and the ability to create value for stakeholders (Li et al., 2021).

Addressing the product development level is crucial in the context of the sustainability transition, as it includes the key business functions, strategic transformations, technological advancements, and social meanings of new products and services (Masui et al., 2003). These dynamics are increasingly understood by the investment sector (Schulte & Hallstedt, 2018), but there is a gap between a company's ambitions to be more sustainable and actual integration of sustainability (Schulte & Hallstedt, 2017). While it is not uncommon that products are referred to as being "sustainable" or "more sustainable", products cannot be sustainable or unsustainable in themselves. Sustainability is a systems property, and products can only be part of a sustainable system or contribute to/counteract a system's transition towards sustainability (Hallstedt et al., 2025). This is evident from Dyllick and Rost's (2017) three phases describing how to move towards true product sustainability:

- *Phase 1*: requires a holistic approach that considers the entire product life cycle and integrates economic, ecological, and social impacts.
- *Phase 2*: shifts from reducing harm to generating positive environmental and social impacts, strives for absolute improvements on products with regard to their sustainability performance.
- *Phase 3*: shifts from creating private customer value to generating public value. Products actively contribute to enhancing social wellbeing and environmental health rather than merely minimising harm.

Phase 3 can also be seen as a requirement for a product to have a "positive impact", which Gebler et al. (2022) defines as: "*A positive impact reduces pressure on planetary boundaries, increases human wellbeing and/or generates sustainable value*". When all three dimensions of sustainability are considered in parallel, it prevents unintended consequences and suboptimisation.

To maintain a systems perspective without getting lost, it is possible to

relate all the different symptoms of unsustainability to a few underlying root causes, upstream within cause-and-effect chains. These are referred to as Sustainability Principles: *“In a sustainable society, nature is not subject to systematically increasing . . . (1) . . . concentrations of substances extracted from the Earth’s crust, (2) . . . concentrations of substances produced by society, (3) . . . degradation by physical means, and people are not subject to structural obstacles to . . . (4) health, (5) influence, (6) competence, (7) impartiality, and, (8) meaning-making”* (Broman & Robèrt, 2017).

Similar to Dyllick and Rost’s (2017) phase approach, this thesis considers product sustainability on a scale. On one end is insular and relative sustainability, which is product-centric and focuses on implementing improvements compared to a baseline from a triple bottom line perspective. On the other end is absolute and systemic sustainability, which complies with the fundamental sustainability principles (Broman & Robèrt, 2017) or does not overstep a predefined boundary of irreversible change (e.g., planetary boundaries). While compliance with sustainability principles might not be possible in today’s industrial context, they allow a backcasting approach. Backcasting begins by defining the long-term vision and then asks what shall be done today to get there (Dreborg, 1996). The framework for strategic sustainable development is a procedure that supports organisations in applying these principles, i.e., in the execution of backcasting planning and redesign for sustainability (Broman & Robèrt, 2017). With this view, it is of the utmost importance that companies set a vision of success and strive to achieve it, and relative, insular sustainability is not the destination but is on track towards true sustainability.

### 2.3.2 Scope and evolution of sustainable product development

Sustainable product development was first defined in 1995 by van Weenen as *“meeting the elementary demands among present and future generations through product functions and its systems, considering the resource availability and distribution”* (van Weenen, 1995). D. Maxwell and van der Vorst (2003) further developed the concept of SPD as the process of making products which achieve a balance between environmental protection, social equity and economic prosperity. Products developed in this context need to fulfil traditional criteria as well as sustainability requirements. Sustainable product development can be applied to existing products, but ideally at the concept stage, where greater opportunities for the development of a more sustainable solution may be realised (McAloone & Bey, 2009). Nowadays, sustainable product development is generally defined as the integration of sustainability issues in the various activities associated with engineering practice (Gagnon et al., 2012), more specifically, the integration of a strategic sustainability perspective into early product innovation stages (Hallstedt, 2017).

Selecting the right verb between “integrate” and “implement” sustainability or SPD can be guided by the term definitions in the Cambridge Dictionary. To

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*integrate* is defined as "to combine two or more things in order to become more effective" (Assessment, 2026). Sustainability can be *integrated* into product development, i.e., it is combined with the other drivers, criteria, or requirements, allowing design to become more effective. To *implement* is defined as "to put a plan or system into operation" (Assessment, 2026). The aim of this research is, therefore, to further *implement* sustainable product development in the industry.

In this thesis, sustainable product development is considered as a broad term, not only covering design activities but also organisational functions such as strategy, technology, or change management. Design, including technology and product development, is core to sustainable product development. Other areas of management, such as business, strategy, or supply chain, are also key functions that can block or accelerate sustainable design.

Many fields of design research can be considered part of the SPD umbrella, such as ecodesign, design for sustainability, design for end-of-life, or lifecycle design (Bhamra & Hernandez, 2021). The field of design for sustainability is very broad, and has progressively expanded from a technical and product-centric focus towards large-scale, system-level changes in which sustainability is understood as a socio-technical challenge (Ceschin & Gaziulusoy, 2016). New design approaches have emerged, progressively adopting a more systemic perspective and including more aspects of sustainability. Green design was the first initiative to address environmental issues, primarily through incremental, product-level interventions such as eco-material selection, cleaner production, and biomimicry. Ecodesign introduced a focus on the whole product life-cycle, from extraction of raw materials to final disposal (Ceschin & Gaziulusoy, 2016). This life-cycle approach has been supported by lifecycle assessment methods, which quantify environmental impacts to enable meaningful design decision-making (Ramani et al., 2010). Eco-efficiency is also one of the earliest concepts within sustainable design. While it focuses on reducing impacts, the eco-efficiency concept involves no long-term vision or strategy. However, in this approach, the links between resource consumption and waste emissions are not well related to the sustainability state, and increases in eco-efficiency may lead to increases in consumption levels and hence overall sustainability impact (Bjørn & Hauschild, 2012). Therefore, recent perspectives often seek to widen typical scopes to also include consumption patterns, business models, and people as active stakeholders. Examples of more systemic approaches are, e.g., design for product service systems (Ceschin & Gaziulusoy, 2016).

Despite the creation of new design disciplines and trends in state-of-the-art, industrial practice remains a step behind, and efficiently implementing sustainable product design remains a challenge for many industries (Faludi et al., 2020). Moreover, adopting holistic, system approaches can be particularly difficult for companies that have just started to implement environmental, product-level approaches such as ecodesign. 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 (Hallstedt et al., 2023a). Manufacturing

companies have comparatively low sustainable product development capability level with key practices not systematically integrated, particularly with regard to product requirements, product design and development, portfolio management, and organisational awareness (Vilochani et al., 2024a). Further research is needed to bridge the gap and further support product development companies to integrate sustainability in decision-making and everyday activities.

### 2.3.3 Key enablers for sustainable product development

Significant research efforts have been accomplished to support companies in developing more sustainable solutions, and this section aims to provide an overview of such works, synthesised in key enabler categories. Hallstedt et al. (2013) identified eight key elements to implement a strategic sustainability perspective in the early product innovation process. Vilochani et al. (2024b) conducted a systematic literature review on management practices for Sustainable Product Development, which resulted in the identification of 61 key practices, spanning across different product development stages and organised in 11 segments. Reviews were also performed in the adjacent fields of ecodesign (Schäfer & Löwer, 2020) and project management (Sabini et al., 2019) that shed light on the evolution of the sustainable product development field.

#### *Assessment of product sustainability performance in design*

Several researchers have highlighted the need for companies to assess product sustainability to monitor their progress throughout development and measure the efficiency of sustainability measures (e.g., Sabini et al., 2019). Sustainability assessment models can support design teams in their decisions and can be qualitative, quantitative, or a mix of both (Hallstedt et al., 2023b). Assessing the sustainability impact of technologies plays a crucial role in improving the environmental and social impact of products and processes (Parolin et al., 2024b). Beemsterboer et al.'s (2025) work on the effectiveness of lifecycle assessments in design further demonstrates the role of sustainability assessments in product development. The environmental analysis may not lead to a direct and significant reduction of the product's environmental impact, but it contributes to capability building and affects the outcome of other design projects positively. In short, one should not only evaluate the effectiveness of sustainability assessments on the product impact itself, but also on their ability to transform practice (Beemsterboer et al., 2025).

Assessing a solution's sustainability performance is a complex task that requires the consideration of multiple aspects that cover sustainability in a broad sense. Reaching high sustainability performance involves a balance between maximising economic, social, and environmental performance (Pintea & Achim, 2010). A recent review by Mengistu et al. (2024) classified factors commonly used in literature for sustainability assessments into the three sustainability pillars and nine primary themes: economic factors (quality and reliability, manufacturability, cost, and financial gain), social factors (functionality, usability, and social well-being) and environmental factors (resource utilisation effect-

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iveness, waste and emissions, and end-of-life management). Filippatos et al. (2025) propose a holistic approach that integrates sustainability dimensions with traditional performance requirements in the context of aviation, resulting in five pillars: safety, environmental impact, cost, social aspects, and circular economy. This multitude of dimensions is why sustainability is particularly difficult to address, and companies need further guidance to navigate related trade-offs (Parolin et al., 2024c).

Increasing the ability to assess the sustainability performance of solutions can be achieved through competence building, knowledge sharing with the value chain, usage of support tools (Hallstedt et al., 2013), and employing sustainability criteria (Hallstedt, 2017). Assessments can be used to identify and reduce the negative sustainability impacts of the products, but could also be used to improve the sustainability performance towards a strategic vision. To assess sustainability at early design stages is particularly important, but it presents challenges to avoid issues such as reductionism (Lövdahl et al., 2024).

#### *Systematic integration of sustainability in design decisions*

The majority of the environmental impacts of a product are decided in the early phases of product development (Graedel et al., 1995). There, important decisions are made by various stakeholders that influence the full life cycle of a product, which is why the early phases present greater opportunities for the development of solutions towards sustainability (D. Maxwell & van der Vorst, 2003).

To achieve the implementation of SPD in early design phases, stakeholders need to systematically include sustainability in decision-making. This is supported by the integration of sustainability in product engineering processes and in the business strategy. Decision-makers on all organisational levels require capabilities that empower them to integrate sustainability in their processes (Hallstedt et al., 2023b). It is key to increase decision makers' understanding of sustainability, which requires providing them with demonstrated business and sustainability value of different alternative solutions (Byggeth et al., 2007). Knowledge management and training can support sustainability awareness for managers, cascading down to their employees (Weina & Yanling, 2022). The role of design engineers is highlighted in design-related disciplines such as ecodesign (Schäfer & Löwer, 2020), but it also involves individuals at tactical and strategic levels of a company.

Despite a strong focus of literature on early design stages, several authors highlight that the systematic integration of sustainability in the product development process as a whole is key for successfully developing products towards sustainability and systems (Hallstedt & Thompson, 2011). As the product development process is quite broad, there are multiple approaches aiming to integrate sustainability in decision-making. Integration in product development phases such as product requirements (Watz, 2022), risk management (Schulte, 2021), portfolio management (Villamil Velasquez, 2023), and technology development (Parolin et al., 2024a) is a promising direction to increase the prioritisation of solutions with a better sustainability performance.

*Organisational and human-behavioural aspects*

The implementation of sustainable product development methods in the industry is low despite significant research efforts in the field. SPD methods and tools can be improved to facilitate their adoption in industry, e.g., to be less complex, easier to implement, not requiring special training or clearly fitting the needs of designers (Wallace, 2011). Sustainability tools or methods also need to consider all 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., 2023a).

Adopting a multi-level perspective is necessary to understand change on different levels, typically divided in three levels (Geels, 2019): (i) *macro*, e.g., culture, macro-politics, and macro-economics, where change is usually slow and cannot be forced by single actors, (ii) *meso*, e.g., technology, science, and business activities, where the status quo is often enforced, and (iii) *micro*, where new innovations can be explored and tested, which may or may not be in line with the current socio-technical systems. Product development companies play a key role in systems innovation, because they can envision and create the solutions on the micro-level that can shake established systems on the meso-level and, over time, contribute to change on the macro-level (Schulte, 2021).

To support the adoption of sustainable design practices using design methods, Mallalieu (2024) has identified five key barriers. The first barrier is related to the prescriptive nature of design methods combined with the influence of human-behavioural aspects. There is a paradox in which the value of design methods can be seen best once they are adopted, while people are resistant to change if they do not see the value in it. Second, design methods need to be adapted to different contexts, i.e., situations, organisations, and products, and those contexts can be particularly complex. Third, design needs to adopt lifecycle thinking and a systemic approach to sustainability, but this is not how design is currently practised and perceived by practitioners. Fourth, people are often biased and make decisions that are ‘satisfactory’ based on their own perception of what this means. There is a risk that organisations will pick sustainable design practices that do not address the full complexity of sustainability without being aware of this problem. Finally, companies often have insufficient information and data capabilities, which limit the appropriate adoption of design methods, potentially leading to inefficiencies or reductions.

The need for both ‘soft’ and ‘hard’ approaches to overcome adoption barriers is discussed in similar fields to sustainable product development, such as sustainable innovation performance. Rauter et al.’s 2023 research shows the need to take a complementary perspective, using both formal controls (guidelines, objectives) and social controls (shared norms, values), and highlights the large potential impact of managerial practices.

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### 2.3.4 Sustainable product development in the aerospace industry

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 challenges and capability needs. 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 whole value chain to adopt SPD practices, from aircraft manufacturers to material suppliers and process developers.

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 (Gericke et al., 2017). Despite these innovation efforts, aerospace systems remain costly and technologically advanced 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.

Hallstedt et al.'s (2023a) longitudinal study with an aerospace company revealed that it is still a challenge to define and represent sustainability criteria sufficiently compliant with a sustainability perspective and sufficiently precise to guide engineers in design and development. 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). As a result, few initiatives aim to integrate all sustainability dimensions as the primary driving force in the initial stages of design. Recent works, e.g., Filippatos et al., 2025, Schilling et al., 2025, and Kwok et al., 2025, propose new approaches to adapt current development processes and integrate sustainability assessments alongside technical and economic requirements. Such approaches could benefit from being further tested and validated in the aerospace context.



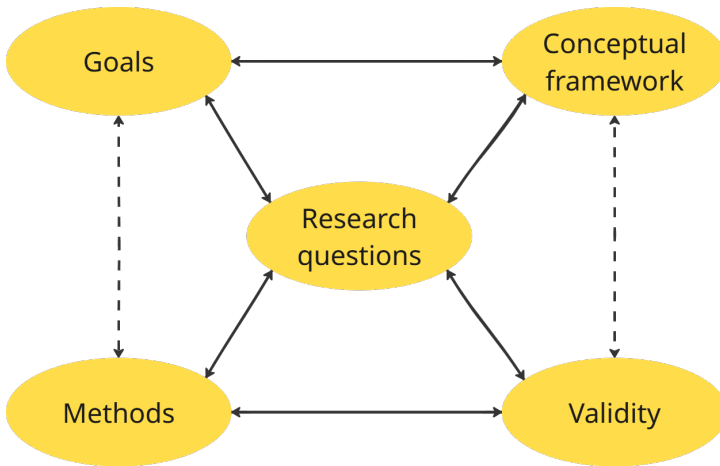
## Chapter 3

# Research design and methodology

This chapter introduces the research design and methodology employed in this thesis to work towards answers to the research questions presented in Section 1.1. An interactive qualitative research approach (J. A. Maxwell, 2013) was applied, guided by the structure of the Design Research Methodology (DRM) (Blessing & Chakrabarti, 2009). Section 3.1 describes the qualitative approach applied for this research. Section 3.2 introduces the DRM and its role in structuring this thesis. Sections 3.3, 3.4, 3.5, 3.6, 3.7, and 3.8 describe the different steps within the qualitative research approach, namely goals, conceptual framework, research questions, methods for data collection, data analysis, and validity. Finally, section 3.9 discusses ethical considerations.

### 3.1 Research approach

This research adopts a qualitative research approach, which is particularly suitable when a complex concept or phenomenon needs to be explored and understood (Creswell, 2014) or a “wicked problem” such as the implementation of SPD. With a qualitative approach, researchers have the opportunity to raise new research questions, or even challenge the questions already asked, revealing deeper insights into management, organisations, and society, which are critical to understanding and potentially shaping our world (Bansal & Corley, 2011). Qualitative approaches to research are unique in their ability to uncover deep processes in individuals, teams and organisations, and understanding how those processes unfold over time (Bluhm et al., 2011). This is especially relevant in the context of this thesis, which requires a deep understanding of aerospace manufacturing companies and their barriers to sustainable product development.



**Figure 3.1:** Interactive model of qualitative research design (J. A. Maxwell, 2013).

This thesis is grounded on J. A. Maxwell’s (2013) model for qualitative research design shown in Figure 3.1. Five essential components constitute the interactive model, and the RQs are the central focus. The other four components, i.e., goals, conceptual framework, methods, and validity, are interconnected, but must not be conducted in a certain order. In this model, the RQs influence other components while being affected by them. It is common in this approach that the RQs are modified or expanded while doing the research. The interactive model was used both at the research level and the individual study level. In the research level, it guided the direction and execution of the research presented in this thesis, and its use is further detailed in the following sections of this chapter.

## 3.2 Research methodology

This research combines J. A. Maxwell’s (2013) iterative approach with DRM by Blessing and Chakrabarti (2009). It allows for this research to be simultaneously flexible and reflective, while academically rigorous and structured. The DRM helps in achieving more rigour in design research, i.e., aiming to improve design practice, management, education, and their outcomes. It supports researchers in the formulation and validation of models and theories about a phenomenon in design, as well as the development and validation of support developed based on these models and theories.

The DRM is a particularly suitable methodology to conduct this research for several reasons. First, the DRM requires obtaining an overview of existing research, which is highly relevant in the growing field of SPD. Second, it aims to increase the use of research in practice, which is a recurring issue in the field of SPD, where support tools, methods, and practices are not sufficiently

implemented in the industry. Finally, it aims to increase scientific rigour, which is particularly difficult to achieve in a multidisciplinary field such as sustainability.

The DRM consists of four iterative stages described in Table 3.1 (Blessing & Chakrabarti, 2009). In the Research Clarification (RC) stage, researchers find literature-based evidence of a gap in order to formulate a realistic and worthwhile research goal, as well as an initial description of the desired situation. In the Descriptive Study I (DS-I) stage, the researchers seek to identify influencing factors and gain a deep understanding of the existing situation. In the Prescriptive Study (PS) stage, the researchers further elaborate their description of the desired situation and how addressing one or more factors of the existing situation would lead to the desired situation. In PS, the researchers use their understanding of various interconnected influencing factors obtained in the DS-I and their view of the desired situation to develop a support in a systematic way. The developed support is then evaluated in the Descriptive Study II (DS-II) stage.

<b>Stages</b>	<b>Basic means</b>	<b>Main outcomes</b>
Research clarification	Literature analysis	Goals
Descriptive study I	Empirical data analysis	Understanding
Prescriptive study	Assumption, experience, synthesis	Support
Descriptive study II	Empirical data analysis	Evaluation

**Table 3.1:** Stages of the Design Research Methodology, basic means and main outcomes (Blessing & Chakrabarti, 2009)

This thesis consists of a review-based RC stage, a comprehensive DS-I, and an initial PS. In the DRM nomenclature, this corresponds to a type II study. Table 3.2 shows an overview of the different stages of the DRM and how they relate to the different papers included in this thesis. The RC was mostly conducted through the process of drafting the research proposal for funding acquisition, and through papers A and B, which review literature from the SPD and aerospace fields. All papers have a strong focus on the DS-I stage as they aim to gain a better understanding of the status of SPD in aerospace from different perspectives. Finally, the PS stage is addressed initially by most papers as they outline key factors to be addressed to change the current situation and clarify the vision of a desired situation.

	RC	DS-I	PS
Paper A	Provides evidence of lack of systematic and holistic approach in design practice	Provides an initial understanding of the integration and consideration of sustainability aspects in design	
Paper B	Provides evidence of a gap in the literature to address sustainability strategically in aerospace	Provides deep understanding of the SPD advancements and remaining challenges in the aerospace context	Identifies key influencing factors to develop products towards sustainability
Paper C		Describes the desired situation and proposes a set of critical capabilities that companies should develop	Outlines strategies to further enable sustainable solutions, and shows priorities through causal links
Paper D		Clarifies the formal and informal roles of key stakeholders in the product development process	Outlines several gaps in collaboration that need addressing and in what ways they could be solved

**Table 3.2:** Papers included in the thesis and their relation to the DRM.

### 3.3 Goals

Goals are essential to research design. They help guide design decisions to ensure the research is worth doing and justify why the results and conclusions matter (J. A. Maxwell, 2013). For the *intellectual goals*, this thesis aims to advance the field of SPD in the aerospace industry, a complex sector with long product lifecycles and high technical requirements. This means to understand the particular context of aerospace, its barriers to SPD, and to identify influences and processes by which sustainable products can be realised. It aims to provide deep insights and recommendations on how research can further support companies in their SPD implementation journey.

As *practical goals*, this research seeks to provide actionable solutions to enhance the aerospace design team’s ability to develop products towards sustainability. This research also supports sustainability specialists in promoting and integrating sustainable product development in their organisations. The objective is not only to improve design practice but also to promote the value of sustainable solutions, encouraging their broader adoption within the industry.

Regarding *personal goals*, this research is driven by a strong commitment to sustainability and innovation in aerospace, aiming to develop this author’s own expertise in SPD while contributing to the broader sustainability transition.

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## 3.4 Conceptual framework

In J. A. Maxwell's (2013) approach, the conceptual framework is made of concepts, assumptions, expectations, beliefs, and theories that support and inform the research.

### *Epistemology*

The philosophical worldview is a general philosophical orientation about the world and the nature of research that a researcher brings into a study, and is a major component of a research approach. The philosophical worldview is based on the researcher's discipline, research community, experience, and cultural environment (Creswell, 2014). For this research, I have adopted a combination of pragmatism and critical realism.

Critical realism focuses on identifying and understanding the underlying causal mechanisms of an event (J. Maxwell & Mittapalli, 2010). It combines two perspectives: i) there is a real world that exists independently of our perceptions and theories; ii) our understanding of this world is inevitably our construction, rather than a purely objective perception of reality, and no such construction can claim absolute truth (J. A. Maxwell, 2013). In this thesis, this worldview particularly influenced the design of descriptive studies. It stems from the view that to study SPD in aerospace comprehensively, it is necessary to understand the situation from different organisational levels, individual perspectives, and through a variety of data collection setups.

This thesis also takes a pragmatic stance, which focuses on consequences and solutions to problems (Creswell, 2014). While the descriptive studies aim to gain an understanding of the current SPD advancement in aerospace, this research is oriented towards real-world practice. This particularly transpires in the analysis and communication of the descriptive study results, which are intentionally practical and actionable for the aerospace industry. In both worldviews, researchers acknowledge there are multiple perspectives and use all approaches available to understand the problem, which might be qualitative, quantitative, or mixed methods (Creswell, 2014, J. Maxwell and Mittapalli, 2010).

### *Experiential knowledge*

In traditional research, the researcher's background and identity have been treated as bias that needs to be eliminated from the design. J. A. Maxwell (2013) advocates that explicitly incorporating one's identity and experience in research allows for more insights and validity checks. While the author of this thesis is a PhD student now, she has been employed as an engineer and sustainability specialist in the aerospace industry for five years prior, and has witnessed challenges to implementing sustainable product development. Aware of this, the author of this thesis systematically peer-reviewed her research designs to limit my bias, while using my experience to gain richer insights into causes and effects related to sustainable product development in the studied organisations.

### *Prior theory and research*

Using existing theory in qualitative research can help make sense of an observed phenomenon and shed light on particular events, phenomena, or relationships that might otherwise go unnoticed. According to J. A. Maxwell (2013), to be genuinely qualitative research, a study must take account of the theories and perspectives of those studied, rather than relying entirely on established theoretical views of the researcher's perspective. In this thesis, existing theory is presented in Chapter 2 and was used to structure and make sense of sustainable product development barriers and enablers in the aerospace industry. Theories and perspectives of the studied individuals and organisations were included through either inductive or abductive research designs (Section 3.6).

## **3.5 Research questions**

This research is part of a project guided by four research questions: i) What are the sustainability-related challenges in aerospace product and technology development? ii) In which ways can a sustainable lifecycle approach support product and technology development for aerospace solutions (i.e., with complex lifecycles)? iii) How can a sustainable lifecycle approach be implemented for product and technology development for aerospace solutions? iv) How can sustainable product development be a competitive advantage for the Swedish aerospace industry?

This licentiate thesis focuses primarily on answering the first question, as well as bringing an initial understanding of the second and third questions. Each paper included in this thesis has been designed with its own set of research questions to answer or hypotheses to be tested. Due to the interactive and inductive nature of qualitative research, the final questions presented in this thesis were finally set after a significant amount of data collection and analysis had been done. This includes synthesising and combining the goals and outcomes of the four papers appended to this thesis. The questions explored in this thesis are shown in Table 3.3, along with the contributions of different papers to the RQs. Papers A, B, and C contributed to answering RQ1 and its related sub-questions and Papers B, C, and D contributed to answering RQ2. The contribution of each paper to this thesis is further discussed in Chapter 4.

## **3.6 Methods for data collection**

A variety of data collection activities were undertaken to answer the research questions, as shown in Table 3.4. This section further describes the characteristics of the methods employed in the context of this research.

	Paper A	Paper B	Paper C	Paper D
<b>RQ1. What are the key challenges of integrating sustainability in aerospace product development, and why?</b>	X	X	X	(X)
<b>SRQ1-1.</b> to what extent is sustainability currently integrated in aerospace product development?	X	(X)		
<b>SRQ1-2.</b> How can sustainability integration challenges be categorised to support companies in effectively mitigating them?		X	(X)	
<b>SRQ1-3.</b> Why do aerospace companies encounter sustainability integration challenges in product development?	(X)	(X)	X	(X)
<b>RQ2. What could change in aerospace product development practice to deliver more sustainable products?</b>		X	X	X
<b>SRQ2-1.</b> What capabilities are needed to address sustainability integration challenges in aerospace product development?		X		
<b>SRQ2-2.</b> What are the main levers to accelerate the integration of sustainability in aerospace product development?		(X)	X	
<b>SRQ2-3.</b> In what ways should the key stakeholders involved in product development collaborate to design products towards sustainability?				X

**Table 3.3:** Contribution of the appended papers to the research questions. Direct and partial contribution to answering a question is marked X and (X) respectively.

	Literature review	Semi-structured inter-views	Workshops/focus group discussions	Case study
<b>Paper A</b>	Industry reports and regulations (narrative)	<b>3 interviews:</b> 3 SPD practitioners		3 companies
<b>Paper B</b>	Academic literature (systematic)			
<b>Paper C</b>		<b>2 interviews:</b> 2 SPD practitioners	<b>6 workshops (2-5 participants):</b> 13 researchers 5 SPD practitioners 3 students 2 business analysts 2 educators	2 companies
<b>Paper D</b>		<b>8 interviews:</b> 4 customer managers 2 product managers 1 project manager 1 project portfolio manager 1 SPD practitioner 1 technical authority	<b>2 focus group discussions (2 participants):</b> 4 SPD practitioners <b>4 workshops (2-9 participants):</b> 6 engineers 3 project managers 2 programme managers 2 project portfolio managers 1 SPD practitioner 1 product insertion manager 1 customer manager	2 companies 4 product development projects (sub-case)

**Table 3.4:** Overview and data collection methods for each paper included in this thesis.

### 3.6.1 Literature reviews

Several types of literature reviews were used in this thesis. The project started identifying topics of interest and using relevant literature to identify the state-of-the-art with respect to what problems are already solved and what remain to be solved. The literature review followed a narrative approach. After defining the initial research questions, publications were retrieved based on their titles and abstracts. The initial search string on Scopus contained “Sustainable product development” and was used in different variations, with the addition of the following words: “definition”, “circularity”, “design”, and “aerospace”. Both Google search and Google Scholar were also used to explore industrial goals, reports, and regulations focusing on “aerospace” and “sustainability” or “environment”. In paper B, a Systematic Literature Review was conducted to analyse state-of-the-art knowledge while strengthening clarity of scholarly communication, validity by decreasing risk of bias, and transparency/auditability (Kwok et al., 2025). The study applied the PRISMA framework (Page et al., 2021) and followed the three-phase methodology proposed by Biolchini et al. (2005): planning, execution, and results analysis.

### 3.6.2 Case studies

The research conducted for this thesis work employs a multiple case study approach at two main companies, SAAB and GKN Aerospace, shown in Table 3.5. The case companies were selected with a theoretical sampling approach (Walsh et al., 2015), aiming to cover two very different cases that will allow more reliable comparisons (Yin, 2019). SAAB and GKN Aerospace have a global footprint as Tier 1 suppliers and are representative of different focus areas within the aerospace business. SAAB is mostly oriented towards the defence business and has an OEM role for military applications, i.e., manufacturing and designing aircraft systems. GKN Aerospace manufactures and designs components and subsystems, mainly for the civil aviation sector. Both companies also have business related to maintenance, repair and overhaul, and are manufacturing of parts for other OEMs.

**Table 3.5:** Description of the case companies.

Company	Role within aerospace	Number of employees	Division
SAAB AB	OEM, MRO, Manufacturer	26,000	Aeronautics, Linköping, Sweden
GKN Aerospace Services Limited	Strategic partner, MRO, Manufacturer	16,000	Engines, Trollhättan, Sweden

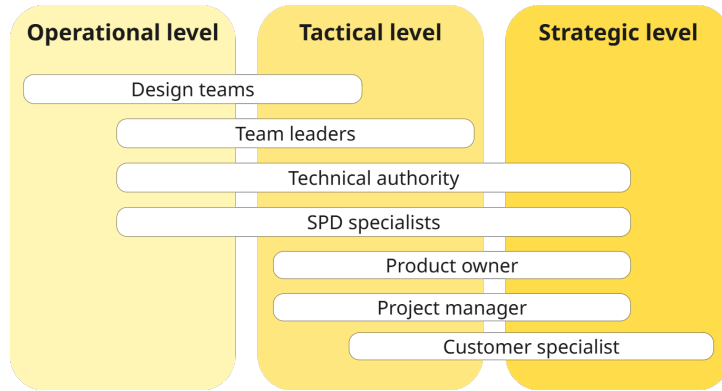
The case studies were conducted at the company level (Papers A and C) and at the project level (sub-cases in Paper D), where two product development projects within each case company were studied. To select sub-cases, the theoretical sampling approach was used to cover projects at different stages of maturity. The case study approach allows for a deep understanding of organisations, their current practices, and their decision-making processes (Yin, 2019). This approach is particularly relevant in the context of SPD. A multi-case approach enables a stronger theoretical foundation and generalizability (Eisenhardt & Graebner, 2007). Multiple case studies, in Yin (2019), can be seen as linear and replicable, where cases are planned ahead of time, and each case repeats the same design. However, one of the most critical challenges with this approach is to move from surface observations to deep explanations. Dubois and Gadde (2014) argue that the discovery of deep structures is more likely to occur in continuous movements back and forth. In this thesis, the goals and research questions were planned ahead and identical among the case companies. A few aspects differed, mostly related to setup for data collection (e.g., online versus in-person, length of the discussions) and roles of study participants, which resulted from a more abductive, flexible design.

### 3.6.3 Interviews and group discussion

Interviews are the most frequently used data collection method in this thesis. This method was selected for its ability to collect current and historical information related to the integration of sustainability in product information. This is particularly suitable in this context, as the studied phenomenon is difficult to directly observe (Creswell, 2014). SPD is complex and takes place at various organisational levels continuously. Moreover, there are only a few individuals at aerospace companies who are deeply knowledgeable about product development, and the research questions in this thesis required targeting specific roles at the case companies. This context with few informants made quantitative research methods unsuitable, and questionnaires undesirable due to their typically low response rate (Flick, 2009). Interviews were therefore selected as a method to cover a broad range of individuals with experience from a variety of product development projects, while accommodating practical limitations such as participants' availability.

Participants were selected with a purposeful sampling with a “typical case” strategy (i.e., to describe what is typical) and a “snowball” strategy (i.e., identify cases of interest) (Palinkas et al., 2015). The interviews were typically semi-structured with a mix of open, theory-driven (Pawson, 1996), and confrontational questions. An overview of all the roles interviewed and their organisational level within the case companies is shown in Figure 3.2.

In Paper A, expert interviews were employed. To understand SPD in aerospace, 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



**Figure 3.2:** Overview of the roles of the study participants and the organisational level at which they work.

of these processes. Expert interviews have the capacity to reconstruct both types of knowledge and are suitable for exploration and theory formulation (Flick, 2009). These interviews were theory-driven, having a strong link to theoretical frameworks, and the participants were allowed to both learn and teach (Pawson, 1996).

Paper C used two group interviews with SPD experts. The group format was used instead of individual interviews to encourage discussing potential contradicting opinions and perspectives (Flick, 2009). The interviews were built on previous data collection activities and utilised the structure-laying technique to structure the concepts. In this process, participants have the opportunity to visually structure concepts and their causal links. This method is especially suitable for revealing and organising existing knowledge, as well as shaping the contents of subjective theory (Flick, 2009). In paper D, interviews were conducted with individuals occupying strategic and tactical roles in product development at the case companies. These interviews adopted an inductive approach with open-ended questions.

In Paper C, I led focus group discussions, a method inspired by focus group and group discussion methods. The aim of this mixed format is to encourage an exchange of opinions and to allow participants to correct each other, only after receiving a specific introduction (Flick, 2009). Workshops were also conducted in Papers C and D with researchers and practitioners.

### 3.7 Methods for qualitative data analysis

This thesis followed fundamental principles for qualitative data analysis, i.e., data reduction, data display, and conclusion drawing/verification (Miles et al., 2018). The analysis was conducted in an iterative manner, which included comparison and moving back and forth between the qualitative data sources

several times. Emerging results were continuously discussed and validated among co-authors.

In Paper A, the data reduction and display were activities in which study participants were actively involved during the interviews. During the discussion and the questions, I shared my screen while recording participants' responses in a predefined template, providing them the opportunity to review and validate the emerging results.

In papers B, C, and D, a more structured coding approach was applied. In-vivo coding was used to analyse academic papers (Paper B) and interview data from transcripts (Paper D) in an inductive setup. The codes were then synthesised using terms from the analysed paper or the informant to reduce researcher bias. Paper C used a combination of hypothesis coding, concept coding, and causal coding (Miles et al., 2018) to classify and understand links between different concepts.

Papers C and D applied the Gioia methodology to ensure methodical rigour and transparency in data analysis (Gioia et al., 2012). While most suitable for inductive research, the Gioia methodology was employed in Papers C and D to analyse the data and separate 1st and 2nd order codes and visually represent the data analysis process.

## 3.8 Validity

In qualitative research, validity is based on determining whether the findings are accurate from the researchers' standpoint, the participant, or the readers of an account (Creswell, 2014). It refers to the trustworthiness, correctness, or credibility of a description, conclusion, explanation, or interpretation (J. A. Maxwell, 2013). While validity focuses on the trustworthiness of the research, the concept of "quality" is broader and relates to the scientific rigour and value of the study.

Following J. A. Maxwell's (2013) approach for qualitative research, major threats to validity were identified for each research question and its associated methods for the design of each study. During the planning and execution of the research, major threats to validity and reliability were identified and are shown in Table 3.6. This section describes these risks and the measures that were taken to mitigate them.

**Table 3.6:** Validity threats related to data collection methods, and strategies to deal with them.

Methods	Validity threats	Strategies
Case study + all qualitative methods	<p><b>Lack of rich data:</b> Research is based on a small number of case companies and informants</p>	<p>Triangulation to increase methodological rigour and data quality (Bluhm et al., 2011) and long timelines to enable multiple verification of theories and rectification. Participants and cases are carefully selected to provide rich insights and high quality data.</p>
Case study	<p><b>Overgeneralisation:</b> Drawing broad conclusions from limited or non-representative data.</p>	<p>Multi-case approach for stronger theoretical foundation and generalizability (Eisenhardt &amp; Graebner, 2007).</p>
All qualitative methods	<p><b>Participant bias:</b> Participants may change their responses or behaviour in systematic ways due to being part of a study.</p>	<p>Building strong researcher-participant relationships to reduce socially desirable responding and member checking (J. A. Maxwell, 2013).</p>
All	<p><b>Researcher bias:</b> The researcher’s values, assumptions, or expectations can distort data collection or interpretation.</p>	<p>Principles of data coding and transparency were applied (Bansal &amp; Corley, 2011) in order to clarify the informant’s and the researcher’s positions separately. Peer review of data interpretation and coding patterns.</p>
All	<p><b>Selection bias:</b> The results are not representative because of how data sources were chosen.</p>	<p>Literature review was conducted systematically, and participant selection was peer-reviewed.</p>
Case study + all qualitative methods	<p><b>Source or method bias:</b> Using only one type of data source or method inflates or distorts results.</p>	<p>Triangulation to increase methodological rigour (Bluhm et al., 2011).</p>

To establish methodological rigour, qualitative researchers are often recommended to consider incorporating one or more forms of triangulation into their research design (Köhler, 2016). Triangulation essentially means that researchers look at a phenomenon from different angles to explore and understand it deeply. Described as one of the best practices in qualitative research (Bluhm et al., 2011), this can mean that researchers might combine different data or sources of information, utilise different methods to harness their respective strengths, integrate multiple theories to understand a phenomenon, employ different researchers to add different lenses and expertise, collect information at different times, and several other strategies (Köhler, 2016).

The author of this thesis has targeted data collection efforts towards a variety

of individuals who represent all organisational levels at the case companies. Figure 3.2 presents the role of all industrial participants who have contributed to this thesis and locates them on a scale of organisational levels. While data collection efforts have mainly focused on the tactical level, this research also included participants at the operational and strategic levels, which ensures triangulation of the results and a deep understanding of challenges and enablers to SPD in the aerospace context. High-quality qualitative data often include variation that allows the researcher to understand a phenomenon from multiple angles, and targeting a broad range of individuals increases variability and diversity of perspectives.

### 3.9 Ethical considerations

Good research practice is central to the quality of research and to its benefit to society and the world. Conducting research in a responsible way and according to good research practice requires knowledge about ethical principles and rules and the ability to implement them in practice (Council, 2024). Conducting good research must follow four fundamental principles:

- *Reliability* in ensuring the quality of research, reflected in the design, methodology, analysis, and use of resources.
- *Honesty* in developing, undertaking, reviewing, reporting, and communicating research in a transparent, fair, full, and unbiased way.
- *Respect* for colleagues, research participants, animals, cultural heritage, and the environment.
- *Accountability* for the research from idea to publication, for its management and organisation, for training, supervision and mentoring, and for its wider impacts.

In this thesis, the study objects are large organisations and individuals within them. The main ethical consideration from a human-individual point of view is that the study objects are confidential and no personal data is recorded or disclosed. Each organisation and individual was asked to consent to participating in the studies and to be recorded. Moreover, participants were anonymised systematically and were given at least two weeks of notice before externally sharing data related to the studies through publications or presentations.

## Chapter 4

# Summary of appended papers

The outcomes of the research conducted to address the research questions are summarised in this chapter. The results of this effort are published in four appended papers. This chapter contains a summary of each paper, discusses their relation to the thesis, and states the contribution of the author of this thesis.

## 4.1 Paper A

### Design aspects of importance in a sustainability transition

*Published as*

Léonard, P. L. Y., Hallstedt, S. I., Nylander, J. W., Isaksson, O. (2024). Design Aspects of Importance in a Sustainability Transition. *Proceedings of NordDesign 2024, Reykjavik, Iceland, 12-14 August 2024*. <https://doi.org/10.35199/NORDDDESIGN2024.12>

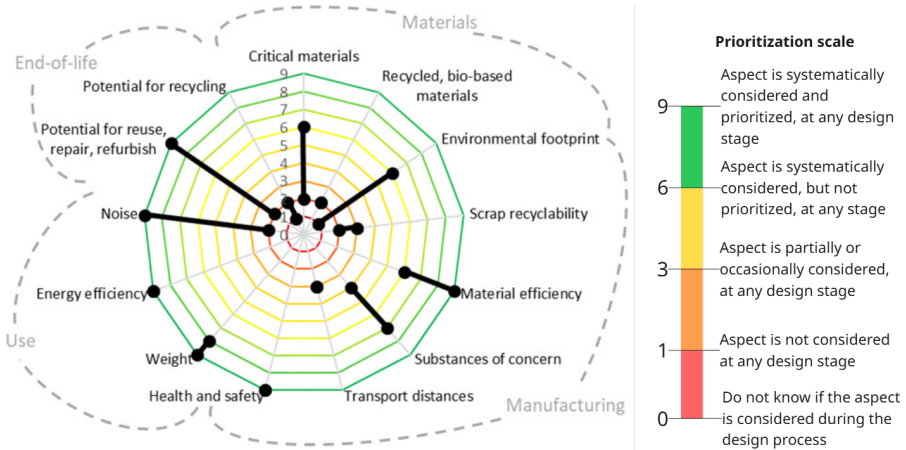
*Summary*

This study examined the prioritisation of sustainability aspects across the development process of three different aerospace companies and aims to clarify the underlying reasons. Through expert interviews, this paper explores the following hypotheses:

- H1.** Engineering design activities, aimed at mitigating sustainability impact and developing more sustainable solutions, are not adopting a holistic sustainability approach.
- H2.** There are variations among aerospace companies regarding which sustainability aspects are prioritised and why, due to the type of products they develop and their role in the value chain.

Three expert interviews were conducted with practitioners engaged in implementing sustainable product development within their organisations. Each interviewee works at a different aerospace company, each having different roles in the value chain: component designer, defence OEM, and civil OEM. The interview participants were asked to: i) evaluate 13 sustainability criteria derived from literature, ii) assess the integration of these criteria at early, detailed and re-design stages of product development, iii) explain their rationale, and iv) discuss the need for future research in sustainable product development.

Figure 4.1 summarises findings from the study. Four criteria, 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 as they are tied to generating economic value. Another four criteria had low importance, i.e., potential for recycling, recycled/bio-materials, scrap recyclability, and transport distances. Low-importance aspects were all found to relate to the concept of circular economy, which is not yet mature in aerospace. The main challenge to integrate those “low-importance” criteria in design is that their value is not clear or recognised for the case companies or their stakeholders. The remaining criteria (i.e., critical minerals, substances of concern, noise, and environmental footprint) were identified as aspects of growing importance. They are increasingly important to work with due to external constraints (regulations, requirements), as the case companies acknowledged that a better integration of sustainability in early design stages is desirable to enable more anticipation of future demands. Aspects of growing importance typically come with business opportunities, where substantial



**Figure 4.1:** Companies' level of prioritisation of sustainability aspects in aerospace product development. Each aspect is ranked from 9 to 0 for each case company. The highest and lowest levels are represented with black dots connected by a line.

financial savings could be made. Alternatively, those aspects may also support benchmarking new products. Aspects of growing importance are seen to be more innovative, and this study indicates that they are currently more explored in early product design.

This study has provided some indications of challenges and knowledge gaps regarding what sustainability aspects are prioritised when, and why, in the context of the Swedish Aerospace industry. Within the scope of this research, several areas remained unexplored and would be worthy of further investigation. It is necessary to gain a better understanding of decision-making drivers in product development and what can increase the prioritisation of sustainability criteria.

#### *Relation to thesis*

This paper contributes to the *Research clarification* and *Descriptive study I* stages of this thesis. The study shows that design activities do not systematically adopt a holistic sustainability approach. It provides empirical evidence of a gap in current practice and answers SRQ1-1: “to what extent is sustainability currently integrated in aerospace product development?”. This paper also provides an initial understanding of why certain sustainability aspects are prioritised while others are not, providing an initial answer to SRQ1-3: “Why do aerospace companies encounter integration challenges when pursuing sustainable product development?”. This understanding is foundational in identifying influencing factors to develop products towards sustainability, and this paper’s findings relate directly to answering RQ1: “What are the key challenges of integrating sustainability in aerospace product development, and why?”.

## 4.2 Paper B

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

*Published as*

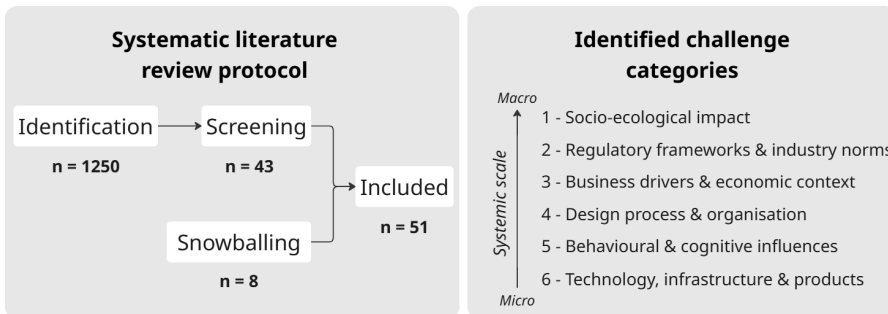
Léonard, P. L. Y., Hallstedt, S. I., Dokter, G. (2026). **Capability Needs for Sustainable Product Development in Aerospace: A Systematic Literature Review.** *Sustainable Production and Consumption*, 64, 191-203. <https://doi.org/10.1016/j.spc.2026.02.0042>

*Summary*

Building on paper A, which clarifies the lack of sustainability integration in practice, this study aims to provide a comprehensive overview of sustainable product development literature for the design of aircraft systems and subsystems. Aerospace literature typically focuses on technological development and might lack a holistic and systemic view of sustainable design. Through a systematic literature review, a selection of 51 papers was analysed 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?

The review protocol and main findings of this study are summarised in Figure 4.2. After identification and classification of nearly 200 challenges from literature, a taxonomy of six challenge categories is proposed: 1- Socio-ecological impact, 2- Regulatory frameworks and industry norms, 3- Business drivers and economic context, 4- Design process and organisation, 5- Behavioural and cognitive influences, 6- Technology, infrastructure and products. The developed taxonomy presents similarities to other frameworks within economics, design, and circularity, suggesting its applicability to other industrial sectors.



**Figure 4.2:** Overview of method and main findings of Paper B: systematic literature review protocol and identified challenge categories.

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While aerospace companies face systemic challenges, this study argues that most can be addressed by developing the necessary capabilities. These capabilities are required across the entire spectrum of the product development process, with a focus on assessing sustainability risk, evaluating sustainability impact, and guiding sustainability improvements. This study outlines 11 critical capability needs. Although existing aerospace SPD methods address most of those critical needs, our analysis revealed three main capability gaps, detailed below:

- Ensure appropriate communication across departments and hierarchical levels concerning SPD.
- Manage trade-offs within and across the sustainability requirements (e.g., social vs. environmental, or quality vs. cost).
- Systematically identify and mitigate potential sustainability risks across the product lifecycle.

This study advances the field of SPD by providing a sector-specific synthesis of challenges, capabilities, and support methods within the aerospace industry. It contributes a taxonomy and clarification of capability needs that align with broader sustainability literature, and it provides a foundation for future cross-sectoral research and methodological development. Companies may use the taxonomy proposed in this study to identify challenges at organisational, individual, and technical levels. Practitioners should seek support regarding systemic challenges through collaboration in research and industry networks. The critical capabilities identified in this paper support practitioners in identifying gaps, prioritising capability-building efforts, and allocating resources.

#### *Relation to thesis*

This paper contributes to all stages of the research conducted in this thesis: *Research clarification*, *Descriptive study I*, and *Prescriptive study*. It builds on the empirical findings of Paper A and further explains why some sustainability aspects are considered or not in aerospace design. After Paper A identified gaps in state-of-practice, Paper B sises the state-of-the-art in SPD for aerospace.

The literature review collects further evidence of the lack of a holistic sustainability integration, answering SRQ-1-1: “to what extent is sustainability currently integrated in aerospace product development?” and contributes to the Research clarification stage.

The systematic approach allows for a deep and holistic understanding of the SPD advancements and remaining challenges in the aerospace context, contributing to the *Descriptive study I* and answering RQ1: “What are the key challenges of integrating sustainability in aerospace product development, and why?”. It proposes a taxonomy of sustainability integration challenges, which supports answering SRQ1-2: “How can sustainability integration challenges be categorised to support companies in effectively mitigating them?”. Paper B also provides a conceptual explanation of why they are present, initially answering SRQ1-3 “Why do aerospace companies encounter sustainability integration

challenges in product development?”.

Finally, the paper proposes a set of critical capabilities that companies should develop to improve product sustainability performance, answering SRQ2-1: “What capabilities are needed to address sustainability integration challenges in aerospace product development?”. It describes the desired situation and the different levers that aerospace companies can use to advance sustainability integration, which provides an initial answer to SRQ2-2: “What are the main levers to accelerate the integration of sustainability in aerospace product development?”. Paper B’s findings support the *Prescriptive study* phase of this research and answer RQ2: “What could change in aerospace product development practice to deliver more sustainable products?”.

## 4.3 Paper C

### Key elements to navigate sustainable product development in aerospace

*Published as*

Léonard, P. L. Y., Hallstedt, S. I., Isaksson, O., Kipouros, T., Mallalieu, A. (2025). Key elements to navigate sustainable product development in aerospace. *textitProceedings of the Design Society, Volume 5: ICED 2025*, 2191–2200.<https://doi.org/10.1017/pds.2025.10233>

*Summary*

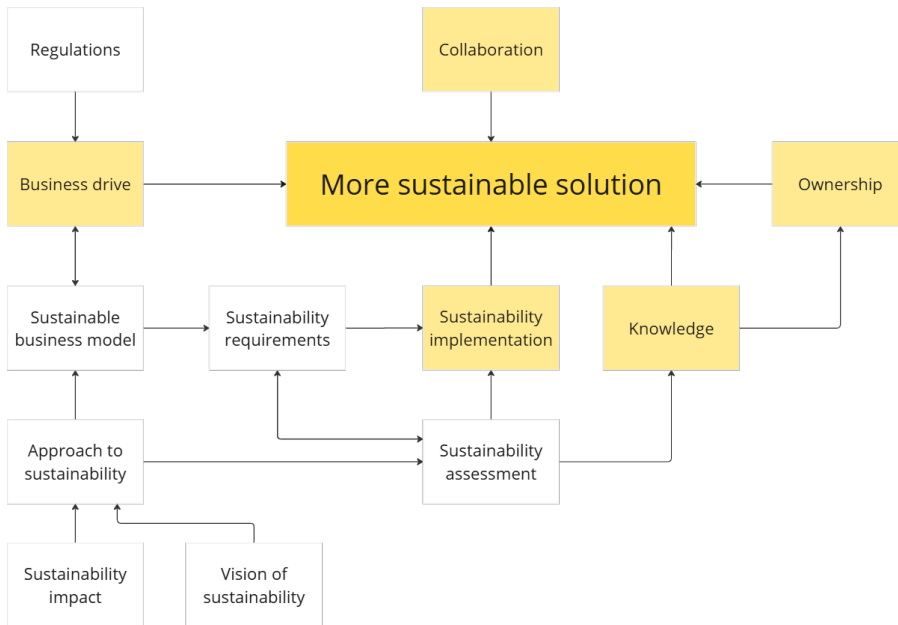
Building on Papers A and B, this study aims to gain a deeper understanding of the levers to accelerate the development of sustainable products in the aerospace industry. This industry deals with context-specific challenges, such as strict safety and quality regulations to which new aircraft systems have to comply. There is an overall lack of sustainability proactiveness in aerospace, and manufacturing companies believe that enabling sustainable solutions is beyond their scope. This study gathers input from both researchers and practitioners to answer the following questions:

- RQ1.** What are the key elements needed to design for sustainability in the aerospace industry?
- RQ2.** What strategies can further enable the development of sustainable solutions in aerospace technology and product development projects?

Six focus group discussions were used to explore barriers and means to design for sustainability in aerospace. Participants are sustainable product development specialists from the aerospace industry and researchers within design for sustainability. A semi-structured interview was then conducted with SPD experts from the two case companies presented in this thesis, which was qualitatively analysed and refined through a structure-laying technique.

This paper proposes an initial impact model (see Figure 4.3) and identifies five key elements essential to design for sustainability in aerospace. Currently, companies experience insufficient *business drive* (i) to prioritise the development of more sustainable solutions. They lack *implementation of sustainable practices* (ii) in their product development processes. Results show that individuals at operational and tactical levels lack *sustainability knowledge* (iii) and do not have sufficient *ownership* (iv) to take action. Lastly, *collaboration* (v), both internally in companies and with the value chain, is not established sufficiently to address sustainability challenges.

Several solutions to enable the development of sustainable solutions were identified, providing valuable insights for future research. This study suggests extending stakeholder analysis in the development of business models, i.e., moving beyond immediate customer needs and considering future trends. This approach can facilitate the creation of more sustainable business models while ensuring successful solutions. Our findings show that sustainability should not



**Figure 4.3:** Proposed impact model with key elements towards sustainable solutions in aerospace, based on findings from Paper C. An outgoing arrow means an element enables another.

only be integrated into business model development but also in management practices, decision-making, and day-to-day activities, which aligns with findings from previous research discussing the integration of SPD at operational, tactical, and strategic levels. Adopting a strategic sustainability approach that focuses on opportunities is essential, along with managing trade-offs between sustainability aspects and other metrics.

#### *Relation to thesis*

This paper contributes to the *Descriptive study I* and *Prescriptive study* stage of this study by identifying influencing factors to develop products towards sustainability. These findings strengthen the outcomes of Papers A and B with empirical evidence of the need to understand the business value of sustainable solutions, to transform routines and processes at companies, and for design teams to build capabilities.

This study contributes to answering RQ1: “What are the key challenges of integrating sustainability in aerospace product development, and why?” through empirical identification of such challenges. It provides a practitioner’s view on how barriers and enablers can be categorised, which completes Paper B’s answer to SRQ1-2: “How can sustainability integration challenges be categorised to support companies in effectively mitigating them?”. The practitioner’s perspective allows for a deep understanding of why those challenges are encountered, answering SRQ1-3: “Why do aerospace companies encounter

sustainability integration challenges in product development?”.

This paper outlines key factors to move forward and provides a sense of priority through the demonstration of causal links, answering SRQ2-2: “What are the main levers to accelerate the integration of sustainability in aerospace product development?”. It also briefly discusses capability needs and collaboration needs to most effectively design a product towards sustainability. Therefore, this paper contributes to RQ2: “What could change in aerospace product development practice to deliver more sustainable products?” by discussing the impact of different levers.

## 4.4 Paper D

### Who drives sustainability in product design? A case study in aerospace

*Published as*

Léonard, P. L. Y., Hallstedt, S. I., Dokter, G. (in press). Who drives sustainability in product design? A case study in aerospace. *Proceedings of the Design Society, DESIGN2026*.

*Summary*

Building on Papers B and C, this paper aims to explore further the topics of ownership and responsibility related to sustainable product development. Stakeholders can influence product sustainability in many ways, but their formal roles may not reflect their actual power or impact. Moreover, existing stakeholder analysis for sustainability often focuses on either internal or external actors, rarely adopting a systemic perspective. To address these challenges, this research investigates the stakeholder landscape in aerospace sustainable product development, aiming to clarify who holds influence and how design teams can engage them effectively. Using a case study approach and mixed methods to gather insights from different functions within aerospace companies, this paper addresses the following research questions:

- RQ1.** Who are the stakeholders involved in product development that can significantly impact product sustainability?
- RQ2.** How can design teams engage with these stakeholders to realise sustainable products?

Data was collected through workshops and interviews to gather perspectives from three main groups of practitioners: sustainability specialists, design teams, and product strategy and management, capturing perspectives across operational, tactical, and strategic levels related to design. Moreover, four product development projects at different companies, maturity stages, and levels of novelty were examined to analyse stakeholder dynamics in diverse contexts. This study applied elements of the Change Agent Infrastructure framework to explore stakeholder roles in sustainable product development.

Eight important stakeholder groups were identified, shown in Figure 4.4. Four of them were consistently identified across the project use cases: *product and technology development*, *product management*, *customers*, and *suppliers*. The remaining four stakeholders showed context-dependent influence. *Customer programmes* are especially important in the early stages of design to get buy-in from customers. *Senior leadership* and *regulatory stakeholders* appeared to be more influential in cases involving the development of novel technologies, e.g., additive manufacturing. Only one use case project named *sustainability management* as important, indicating a potential gap in integrating sustainability expertise across product development projects. *Procurement* did not emerge as a key stakeholder in this study, despite previous research highlighting

		Initiators	Subjects	Convincers	Change owners	Sponsors	Blockers	Solution builder	Documenters
Internal	Customer programs	X		X		X	X	X	
	Product and technology development	X						X	X
	Product management		X	X	X		X	X	
	Senior leadership				X	X			
	Sustainability specialist	X		X	X				
External	Customer	X	X		X		X	X	
	Regulatory stakeholder	X				X	X		
	Supplier		X				X		

**Figure 4.4:** Role of identified main stakeholders in developing sustainable products. An "X" shows when at least one quote describes the stakeholder as taking a specific role in the Change Agent Infrastructure framework. .

its important role in bringing in sustainability.

*Product and technology development* have multiple roles: they are the main solution builders and documenters, and can also act as initiators. Findings suggest that design teams need to strengthen their relations to convincers, i.e., *customer programmes*, *product management* and *sustainability management*. These stakeholders are instrumental in aligning sustainable products with a business case and in convincing other actors of the need for change, hence the importance of including a managerial perspective into SPD research. Beyond early-stage engagement, our findings suggest that design teams must continuously engage with change owners and blockers, especially in aerospace product development projects, which require multiple approval stages.

Our study found limited collaboration between "initiators", i.e., *customer programmes*, *product and technology development*, *sustainability management*, *customers* and *regulatory stakeholders*. Sustainable ideas often emerge within isolated stakeholder groups and are either passed down to design teams or escalated to strategic decision-makers. Design teams have little direct contact with the other initiators when it comes to generating ideas for sustainable innovations, and this fragmented communication hinders co-creation.

#### *Relation to thesis*

This paper contributes to the *Descriptive study I* and *Prescriptive study* stages of this research. This study supports answering RQ1: "What are the key challenges of integrating sustainability in aerospace product development,

and why?” by clarifying the formal and informal roles of key stakeholders in the product development process, discussing their responsibilities and their importance to influence product sustainability. This study enables a deeper and more nuanced understanding of current practice and encountered challenges in the industry. It also supports answering SRQ1-3: “Why do aerospace companies encounter sustainability integration challenges in product development?”, by showing that product development teams need support from other functions to be able to ideate and realise sustainable solutions. Although it is demonstrated in literature, there is a lack of awareness of the importance of sustainability experts and procurement in sustainable product development.

This paper identifies which collaboration gaps need addressing and in what ways they could be solved, answering SRQ2-3: “In what ways should the key stakeholders involved in product development collaborate to design products towards sustainability?”. Paper D shows that further research is needed to facilitate the integration and collaboration of key stakeholders in the design process. This contribution supports other papers in answering RQ2: “What could change in aerospace product development practice to deliver more sustainable products?”

# Chapter 5

## Main results and discussion

The aim of this thesis was to clarify the challenges associated with integrating sustainability in aerospace product development, and to propose how design practice could change to ensure further sustainability integration. This chapter summarises and discusses the main findings to answer the RQs sections 5.1 and 5.2. Then, the limitations following from the methodological and analytical choices of the research design are presented in section 5.3. Finally, the validity of the findings is discussed in Section 5.4.

### 5.1 Key challenges of integrating sustainability in aerospace product development

The research presented in this thesis has explored the diversity and complexity of challenges that the aerospace industry faces when integrating sustainability in product development. The sections below present the main findings and provide answers to SRQs 1-1, 1-2 and 1-3 before discussing the results of RQ1.

#### 5.1.1 SRQ1-1: To what extent is sustainability currently integrated in aerospace product development?

Through three case studies and a systematic literature review, this research shows that aerospace companies struggle to adopt a holistic, lifecycle-oriented understanding of sustainability, limiting their ability to address impacts beyond the apparently dominant use phase.

Papers A and B show that current research and practice do not adopt a holistic sustainability approach and focus mainly on the use-phase climate impact. Using recycled and recyclable materials and reducing transportation distances are not considered in current design practice. Findings from Paper

A show that avoiding critical minerals and substances of concern, as well as reducing noise, are important product development drivers in the defence business, but not in the civil business. Social sustainability is not well integrated in product development in other industries as well, as functions outside design activities manage social sustainability aspects (Mesquita & Missimer, 2021) and social data is perceived as complex and difficult to access (Lövdahl, 2026).

The lack of a holistic approach and lifecycle approach is a recurring issue in the field of SPD (Lövdahl et al., 2024). Reducing the complexity of sustainability to a few selected aspects is likely to result in suboptimisation, where targeted improvements can cause new or more severe problems in relation to aspects or life cycle phases that were not considered (Lövdahl et al., 2024). These findings echo the challenges identified by Bhamra and Hernandez (2021): despite growing awareness, industries continue to struggle with adopting holistic and systemic sustainability practices. Although its products have significant environmental and social impacts across the entire lifecycle, design efforts remain concentrated on a narrow subset of issues, leading to missed opportunities for transformative change. The difficulty practitioners face in addressing sustainability holistically reflects what the Framework for Strategic Sustainable Development describes as a lack of principle-based, whole-system thinking (Broman & Robèrt, 2017).

### 5.1.2 SRQ1-2: How can sustainability integration challenges be categorised to support companies in effectively mitigating them?

Paper B proposes a taxonomy of six categories of integration challenges. Initially explored in Paper A through interviews with SPD practitioners, then formulated from a conceptual perspective in Paper B. The categories were then further explored empirically in C and D through interviews and discussions with participants from all product development organisational levels. To answer SRQ1-2, this section provides an overview of the six sustainability integration challenge categories identified in this research and the studies designed to explore them.

- *Socio-ecological impact (Papers A and B)*: Relates to the environmental and social impact of aerospace. This includes pollution of nature, degradation of nature by physical means, and people's health and well-being. Sustainability issues belong to the macro-level since they relate to system-wide ecological and social conditions.
- *Regulatory framework and industry norms (Papers C and D)*: Relates to governance, international policies, and regulatory frameworks. This includes industry norms, needs of aviation stakeholders, regulatory compliance, and safety standards. This challenge category can be considered both macro- and meso- level, where change cannot be forced by a single actor.
- *Business drivers and economic context (Papers A, B, and C)*: Challenges

of an economic nature. This includes customer demand, fuel prices, competitor actions, setting requirements on product performance and cost, and reaching business goals. This challenge category can be considered both macro- and meso- level, where change cannot be forced by a single actor and depends on macro-economics and macro-politics.

- *Design process and organisation (Papers B, C, and D)*: Structural challenges, primarily linked to the aerospace design process. This relates to how design is structured, conducted, and coordinated, but also the company structure. This challenge category is found at the micro- and meso-level, as it is within a company's influence to change but constrained by project partners and industry norms.
- *Behavioural and cognitive influences (Papers B, C, and D)*: Relates to human judgment, uncertainty, and resistance to change. This includes bias, competence, assumptions, communication challenges, weighing trade-offs, and interpreting data. This challenge category is found at the micro- and meso-level, as it is within a company's influence to change but constrained by education, culture, and available decision-making support.
- *Technology infrastructure and products (Paper B)*: Relates to the physical, technical, and systemic limitations of aerospace design and production. This includes challenges related to available infrastructure, methods, and data, technical limitations (e.g., weight, thrust), and the readiness and feasibility of technology. This challenge category is found at the micro- and meso-level, as it is both within a company's influence to change, but constrained by project partners, industry norms, and available technology.

The classification of sustainability integration challenges has similarities to other known frameworks within economics (PESTEL), design (Jarratt et al., 2010), and circularity (Kirchherr et al., 2018). It advances SPD development research by conceptualising challenges as a multi-level, systemic phenomenon through a taxonomy that includes both internal and external factors, multiple perspectives, and all product development stages.

### 5.1.3 SRQ1-3: Why do aerospace companies encounter sustainability integration challenges in product development?

All papers included in this thesis contribute to answering SRQ1-3 from different perspectives. Industrial and regulatory approaches are described in Paper A, and Paper B focuses on academic literature. The empirical data collection in Papers A, C, and D also allowed diverse perspectives on the question, e.g., design teams, researchers, sustainability specialists, and customer strategists.

#### *Socio-ecological impact*

The inclusion of sustainability criteria design is closely connected to economic sustainability (Paper A). Criteria which are explicitly connected to generating business value are often highly prioritised in design. New criteria are being integrated when companies identify the opportunity for financial

savings or need to comply with new requirements or regulations.

A holistic, lifecycle perspective is not frequently adopted in the aerospace context due to the large, visible environmental impact of the use phase (Papers A and B). The use phase of a civil aircraft or of its subsystems, i.e., maintenance, fuel production, and fuel combustion, accounts for more than 99 per cent of the total lifecycle global warming potential (e.g. Rahn et al., 2022, Léonard and Nylander, 2020). Studies show that the production and combustion of fossil fuels contribute to more than 95 per cent of other lifecycle environmental impacts, e.g., freshwater eutrophication, ozone depletion, and mineral depletion. As aircraft engines' exhaust contains substances dangerous to human health, the use phase is also very detrimental to social sustainability for people living or working near airports. The use phase of fighter jets also dominates the lifetime climate change impact, although they fly less. While findings show that the main environmental challenges are in the use phase, previous studies need to be examined with critical thinking, and a holistic and strategic sustainability approach to identify hotspots without hidden trade-offs or rebound effects.

#### *Regulatory framework and industry norms*

Aviation has been tightly regulated since its earliest days to govern safety, operations, and liability, and aerospace is one of the most heavily regulated industries in the world today (Spren, 2020). Regulations should set ambitious targets, but remain realistic, i.e., they need to be both technically and economically feasible. Current sustainability-related regulations typically result from agreements between regulatory bodies and aerospace companies, and such lobbying has consistently weakened sustainability targets (Gössling & Cohen, 2014). However, the aviation sector is subject to national laws when doing business in certain countries, e.g., REACH, limiting chemical use in the EU and environmental protection compliance in the UK. This scattered regulatory landscape presents some similarities to other industries, such as the shipbuilding industry, which also operates in a global context and experience long lifecycles (Bouyssou et al., 2023).

#### *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 (Paper B). Aircraft remain in service for several decades, which means that aircraft fleets are replaced slowly and manufacturers have fewer opportunities to introduce new products. For civil aviation, it means that fuel efficiency must be sufficiently improved to compensate for the high development and production costs. Material efficiency is also a highly prioritised aspect as it enables direct reduction of manufacturing costs (Paper A). Developing disruptive innovation is especially risky : any failed innovation is very expensive, and aerospace companies avoid risks unless the value is clear. This challenge might evolve over time, as companies further update digital product development. Using more digital prototyping, simulations and modelling approaches can support the development of disruptive innovations by speeding up development, reducing

risk, predicting issues and reducing sustainment costs (Ferrari & Willcox, 2024).

However, the value brought by sustainable products is often hard to grasp for decision-makers, resulting in low prioritisation of projects with sustainable design goals (Papers A and C). There are, however, sustainability criteria that are not directly quantifiable in economic terms, yet paramount in aerospace. Product safety is such an example. Being able to fly safely has contributed to the growth of the aviation industry in the past, and maintaining this standard is key to ensuring more passengers want to fly.

#### *Design process and organisation*

Aerospace has a very structured product and technology development process, in which it is necessary to further integrate and implement sustainable practices (Paper C). These findings align with other industrial sectors: Vilochani et al.'s (2024b) systematic review shows that SPD management practices are poorly integrated across product development phases. This can be achieved through formal controls, which can take the form of specific, isolated practices and tools, e.g., a checklist or corporate-level controls, e.g. an innovation strategy framework (Rauter et al., 2023).

There is, however, another layer of complexity related to product development stakeholders. While product sustainability is the formal responsibility of the product development team, realising and prioritising the development of such solutions requires the involvement of a broad range of internal stakeholders (Paper D). In short, the design team does not control the levers needed to deliver sustainable products. Collaboration is not facilitated due to organisational barriers, which call for systemic organisational changes as highlighted by Mallalieu et al. (2024).

#### *Behavioural and cognitive influences*

The presence of knowledge gaps is discussed in Paper C. Working with sustainability includes challenges in terms of decision-making, as it often includes new trade-offs, which increases complexity. Resolving such trade-offs is a decisive activity as the prioritisation of aspects in trade-off decisions largely determines the pace of sustainability efforts (Lövdahl, 2026). It is not evident which criteria should be used to evaluate sustainability, and communicating the value of sustainable solutions is difficult (Hallstedt et al., 2023b). There is also a prevailing techno-optimism, where actors expect technological innovation to address current and future sustainability problems. However, since technological mitigation levers alone are not sufficient for reaching the most ambitious climate targets, the trade-off between the evolution of air traffic and the allowed climate impact of aviation needs to be considered (Delbecq et al., 2023).

The concept of ownership and responsibility is further discussed in Papers C and D. Some practitioners believe that subsystems have little influence on overall sustainability and might not put the effort into integrating sustainability at the component or technology level, which is essential to address (Hallstedt & Thompson, 2011). Despite rigorous product development processes, some individuals or teams might choose to bypass certain aspects they deem less crit-

ical in time-sensitive projects (Paper C). This causes sustainability assessments to be left out or performed at the last minute before a gate.

#### *Technology, infrastructure and products*

Some technologies, such as additive manufacturing, further enable existing design sustainability practices, e.g., design for repair (Graziosi et al., 2024). There is evidence, however, that the pace of technology is not sufficient to address upcoming sustainability challenges. One example relates to the electrification of flight: while batteries are increasingly used in automotive and other ground vehicles, safety, drag, and weight concerns prevent their use in aircraft systems as of today. Paper C found that technical limitations are also related to the economy. Companies manage a portfolio of technology projects and might decide to slow or accelerate the development of a specific technology.

In addition to dealing with technology immaturity, design teams need to navigate trade-offs (Faludi et al., 2020). This requires managing with non-negotiable criteria, e.g., related to legislation, contracts, or budgets (Parolin et al., 2024c). In comparison to mandatory requirements, sustainability criteria are often considered “nice to have” and clearly not put at the same level as technical criteria. Paper B found a gap in the aerospace literature on the topic of trade-offs, which leaves companies to down-prioritise sustainability or potentially suboptimise designs by choosing less impactful priorities.

#### **5.1.4 RQ1: What are the key challenges of integrating sustainability in aerospace product development, and why?**

Companies directly affect the environment and society, and today’s products are far from being “truly sustainable”. These sustainability impacts span the entire aircraft lifecycle, and it is a challenge for aerospace companies to navigate the breadth of sustainability. Companies have efficiently integrated some sustainability aspects which ensure high safety in flight and low fuel consumption. Many other sustainability aspects are, however, not considered in today’s practice due to the lack of a holistic, strategic approach to sustainability.

The findings presented in this thesis show that most aerospace literature acknowledges regulations as a constraint to which companies must comply and cannot challenge. Aerospace companies mainly face regulatory challenges in the support and maintenance of products regarding chemical use, which might accelerate the retirement of existing products (Paper A) and there is very little research on how aerospace companies can address those issues (Paper B). However, companies could and should lead the sustainability transition themselves: aerospace companies can act as agenda-setters by establishing new standards that will impact future regulations and norms (Paper C). Enforcing new environmental regulations is particularly challenging for the aerospace industry, which creates a state of inertia that prevents the rethinking of established business paradigms and regulations. This phenomenon aligns

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with what Goldstein et al. (2023) describe as a lock-in, a situation observed across many sectors where established technologies, institutions, and routines reinforce one another and make change difficult. These findings also align with the multi-level perspective on transitions, which implies that product development companies need to understand and anticipate change on the macro- and meso-level (Schulte, 2021, Schulte, 2021).

Achieving sustainability-driven innovation in aerospace is particularly complex, as the sector operates under rigid technical, economic, and safety constraints that directly affect which new products are developed and how. Today, the opportunity to develop products towards sustainability in aerospace is constrained by a combination of high risk aversion and difficulties in perceiving clear value from sustainable design choices (Papers A, B, and C). Organisational decision-making is strongly shaped by short-term financial pressures that overshadow the long-term value potential of sustainability investments (Eccles et al., 2014). Organisations operating in high-risk, high-cost contexts tend to favour incremental improvements over transformative solutions (Ram & Sheth, 1989), even when long-term sustainability benefits are evident.

The design process of an aircraft system allows for high reliability, but it becomes challenging when sustainability needs to be integrated. The current product development process is highly structured, fragmented across stakeholders, and lacks the organisational mechanisms needed to support cross-functional sustainability decision-making (Papers B, C, and D). Sustainability can be further integrated in the current product development process and strategy, but its potential will be limited due to organisational challenges. These findings reflect socio-technical systems perspectives, where tightly coupled organisational routines and role structures limit the uptake of new sustainability-oriented practices. Moreover, there is a risk that sustainability gets integrated as a compliance routine, which limits creativity and reduces its transformative potential.

Decision-making towards sustainability can be very difficult due to a lack of knowledge or visibility on the consequences of a decision. There are challenges related to potential lack of knowledge, engagement, or ownership when it comes to sustainability (Papers B, C, and D). The results of this research suggest that behavioural and cognitive challenges are not aerospace-specific, as similar issues have been identified in other industrial contexts (Mallalieu et al., 2024). Due to the very structured product development process in aerospace, encouraging individuals to take ownership of product sustainability might require officially assigned roles that come with explicit responsibilities, authority, and accountability.

Finally, many technologies are promising to support the aviation's sustainability journey, but their feasibility remains uncertain, both economically and from an engineering point of view. As shown in Paper B, the aerospace literature predominantly focuses on driving technical progress while ensuring that new technologies meet economic and safety requirements.

Collectively, these challenges explain why sustainability is only partially

integrated in today's aerospace product development practice. Many of these challenges occur at the macro- and meso-levels, but this thesis argues that companies can- and should take a proactive stance in the sustainability transition by transforming their own processes, routines and structures.

## 5.2 Pathways for future product development practice

In this thesis, pathways towards sustainability integration in aerospace product development have been explored through Papers B, C, and D. The sections below present the main findings and provide answers to SRQs2-1, 2-2, and 2-3 before discussing the results for RQ2.

### 5.2.1 SRQ2-1. What capabilities are needed to address sustainability integration challenges in aerospace product development?

Through a systematic literature review and empirical data collection at aerospace companies, this research identified a wide range of capability needs. In the challenge to provide sustainable solutions, aerospace companies need to address new types of needs, which will require developing new capabilities. Hallstedt et al. (2023b) define SPD capabilities as "Skills and knowledge in the field of SPD, exercised through support methods and tools applied in routines and organisational processes, that enable firms to coordinate activities on strategic, tactical and operational organisational levels to accelerate towards a sustainability transformation and make use of their assets". The synthesis of all results outlines four main gaps in capabilities.

#### *Design team's capability to assess product sustainability performance*

While there is some literature focusing on holistic sustainability performance assessments, this view is rarely adopted in the industrial context (Paper A). Moreover, few academic works adopt a risk and opportunity perspective on sustainability (Paper B). Previous research has shown the benefits of performing sustainability assessments on overall capability building in a company (Beemsterboer et al., 2025). Therefore, companies need to develop their capabilities to anticipate and assess the sustainability impact of their products in development (Hallstedt et al., 2023b) and to mitigate potential sustainability risks across the products' lifecycle (Hallstedt et al., 2015)(Papers B and C). Mitigating sustainability risk is important for design teams, but this responsibility can also be extended to change owners, i.e., product management, senior leadership, sustainability management, and customer programmes (Paper D).

#### *Design team's capability to navigate sustainability-related trade-offs*

Some of aerospace SPD research gives visibility to sustainability-related

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trade-offs (e.g., social vs. environmental, or quality vs. cost), but available support is limited when it comes to managing them and prioritising among them (Paper B). This is also true in non-aerospace specific literature (Parolin et al., 2024c). It is a priority for aerospace companies to develop their capabilities to navigate sustainability-related trade-offs in design, but further support from research is needed to achieve this goal (Paper C).

#### *Design teams' capability to collaborate and be creative*

Most of aerospace SPD research does not focus on supporting communication between departments and hierarchical levels (Paper B). Design teams need to increase their capabilities to collaborate with other stakeholders across functions and hierarchy (Papers C and D). Furthermore, design teams need to gain capabilities to know which stakeholders to involve and when in the product development process for the successful realisation of sustainable products (Paper D). This lack of capability is not only due to skill and tool gaps within the design teams, but also due to a larger lack of capability to co-create at the organisation level (Paper D). Design for sustainability requires a wide involvement of stakeholders, i.e. large structural changes in how products are designed today.

Finally, to be able to design sustainable products, design teams need to be innovative and propose concepts with increased novelty (Jeoh, 2024). A significant challenge to this approach is that the business value of radical concepts is difficult to assess. This capability to be creative might be especially important for OEMs, which have more freedom to be novel, while subsystem designers must seek richer partnerships to allow them more freedom in design.

#### *Sustainability specialist capability to change the product development process*

Sustainability specialists are instrumental in the integration of sustainability in product development, and their capabilities need to be built to facilitate this process. As described by Beemsterboer et al. (2025) in relation to life cycle assessments, integrating SPD tools into product development not only supports decision-making but also contributes to building capabilities in the whole organisation. With the end goal of reducing sustainability impact, using SPD support can lead to substantial changes in product design, practices, people, and organisation (Beemsterboer et al., 2025).

Therefore, sustainability specialists need to have customised tools, methods, and guidelines available that can be easily implemented (Paper B). They also need to develop capabilities in understanding and communicating the value of sustainable products to act as convincers throughout their organisations (Papers C and D). This would further support design teams and participate to behaviour changes necessary to adopt sustainable design methods.

### 5.2.2 SRQ2-2. What are the main levers to accelerate the integration of sustainability in aerospace product development?

This research identified a list of four main levers to accelerate the integration of sustainability in aerospace product development using results from Papers B and C. Paper C investigated the SPD practitioner’s perspective on what the main levers and key factors are to develop products towards sustainability, and Paper B conceptually identified capability needs to integrate sustainability in product development.

*Lever 1: Integrate sustainability and life cycle thinking into the product development process*

The current processes and methods do not integrate sustainability holistically or systematically. Consequently, sustainability is treated as secondary and “nice to have” rather than a driver for product development (Paper A). Integrating sustainability in the product innovation process will increase the consideration of such criteria in decision-making, hence supporting development towards sustainable solutions. Findings from Papers B and C suggest that a successful implementation of SPD in the aerospace context is complex: it needs to fit reasonably within existing structures yet push the boundaries to really drive change. Additionally, it should limit the design space and guide towards a sustainable solution without impeding on innovativeness or creativity. Sustainability can also be used to force out-of-the-box thinking: a backcasting approach from an ambitious sustainability vision can stimulate creativity (Broman & Robèrt, 2017).

To support sustainability integration in product development, companies should seek to implement SPD methods and tools (Paper B) (Faludi et al., 2020, Hallstedt et al., 2013). They also need to implement relevant design guidelines to address the sustainability hotspots (Paper B)(Andriankaja et al., 2015) and use criteria to measure the sustainability performance of products during development (Paper B)(Hallstedt et al., 2013, Schäfer and Löwer, 2020). Doing so requires identifying, developing, selecting, and/or combining relevant methods, tools, guidelines, and indicators. All integration of new SPD support comes with a cost for companies, and lowering this cost is essential to increase the level of implementation (Faludi et al., 2020). This can be achieved through: i) alignment with customer demand, business strategy, and regulations, ii) adaptation SPD support to the company’s internal processes and roles, iii) supports having a high practical value (Faludi et al., 2020, Mallalieu et al., 2024).

Achieving an integration of sustainability in specific product development phases or decision-making processes requires first defining sustainability criteria (Watz, 2022). Integrating sustainability into the product requirement list would support using sustainability as a driver, planning product and development more efficiently towards reducing the sustainability impact (Hallstedt et al., 2013) (Paper C). The aerospace industry follows a structured systems engineering

approach that uses requirements as a baseline for verification and validation of the design, which makes requirement definition practice important to change (Paletti et al., 2024). In this context, it is also essential to integrate sustainability into gate assessments to ensure it is part of the mandatory deliverables (Papers B and C). Product development in the aerospace industry is driven by increasing fuel efficiency and safety in flight, two aspects tightly connected to sustainability. There are, however, many other important sustainability aspects which are not considered as design drivers today, and further integrating sustainability requires to consider the sustainability performance of products during the gate assessments.

SPD literature emphasises the need to implement SPD at “early design stages”. Those “critical stages” were identified in Papers B and C to relate to the planning, conceptual design, programme management, and technology development stages. Generally, in aerospace, these four stages of product development correspond to three different organisational units, namely technology, product development and product management. These findings reinforce the theory that SPD implementation requires multi-level transformation of the organisation. This research suggests that integrating sustainability criteria in decision-making requires better connecting them to business value. Further work is needed, however, to describe more accurately which decision-making activities are the most critical to address first.

*Lever 2: Facilitate collaboration across functions, decision-making levels and value chain actors in product development projects*

Papers C and D identified that these organisations are structured in a way that does not facilitate the development of solutions towards sustainability. The need for increased collaboration between the design teams and other functions, organisational levels, and actors of the value chain is also discussed in SPD literature (e.g., Sabini et al., 2019, Schäfer and Löwer, 2020). How stakeholders should collaborate to develop products towards sustainability is further discussed in Section 5.2.3.

*Lever 3: Develop the design team’s capabilities to design products with better sustainability performance*

The capability to design products with better sustainability performance is tightly connected with the capability to integrate sustainability in product development, which is further explained in section 5.2.1.

*Lever 4: Taking a proactive stance in the sustainability transition*

Papers B and C have outlined the importance of challenging industry norms to drive change across the aerospace sector. Companies could be proactive, joining research and industry networks, and pushing for regulatory change. This requires setting new standards by showcasing what is possible and how far the industry could go. That also requires taking risks to develop radically new products and technologies.

As described by Broman and Robèrt (2017), a particularly interesting aspect is that proactive companies might actually turn to politicians and ask

for harsher legislation, regulation or tax. This would not only increase the general pace of change but also allow them to gain relative advantages for themselves. In the aerospace context, increasing Lever 4 is most effective if driven by large organisations, preferably original equipment manufacturers. Smaller companies or upstream value chain actors might not have the economic power to drive this change alone and should seek an alliance with other partners.

### **5.2.3 SRQ2-3. In what ways should the key stakeholders involved in product development collaborate to design products towards sustainability?**

Changing existing structures is necessary to implement sustainable design practices (Mallalieu et al., 2024). Papers B, C and D show that this change can be facilitated by increased internal communication on sustainable product development. This is also supported by previous literature in the field of SPD (e.g., Hallstedt et al., 2013).

Paper D investigated the structural and relational aspects of product development practice, discussing roles and responsibilities in realising sustainable products. Findings show that design teams should further collaborate with initiators, convincers, and value chain stakeholders. The “initiators” refer to sustainability management and customer programmes, and further collaboration among them and design teams could support in ideating more sustainable product concepts that are more aligned with a business need (Paper D). Design teams should also be able to further mobilise “convincers”, i.e., product management, sustainability management and customer programmes (Paper D). This is essential in the process of product realisation. Further work is needed, however, to identify how and when each stakeholder should be mobilised in relation to the product development process. Aligned with these findings, previous research has shown that including a managerial perspective in SPD research is instrumental in aligning sustainable products with a business case and in convincing other actors of the need for change (Schulte & Knuts, 2022).

Key external stakeholders, i.e., customers, suppliers and regulatory bodies, were identified as important stakeholders in Paper D. Collaborating with external stakeholders in the value chain is essential to achieve circularity, hence sustainability, and should be further explored in the aerospace context (Dokter et al., 2025).

### **5.2.4 RQ2. What could change in aerospace product development practice to deliver more sustainable products?**

This research has identified two broad categories of changes required to deliver more sustainable products: changing the product development process and changing individual and organisational capabilities.

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*Change the product development process*

Findings from this thesis point towards four specific stages of the product development process that should be addressed: planning, conceptual design, programme management, and technology development.

By changing the planning process, the main goal should be to include sustainability as a decision driver in project portfolio management. Projects with the largest potential to minimise negative sustainability impact should be systematically prioritised. Additionally, realising sustainable products requires adopting a long-term, holistic vision. Therefore, leading sustainability criteria could be used to assess a solution's sustainability performance, while enabling a lifecycle perspective, and could allow tracking the progress throughout the product development process.

In the conceptual design and technology development stages, the product development should be changed so that sustainability becomes a decision driver in concept selection. This means that a threshold of sustainability compliance should be defined, so that product development projects would successfully pass a review only if the product is within requirements. This integration should also include iterative sustainability assessments, which evolve as the product concept matures, using similar sustainability criteria throughout the whole product development process.

Changing the product development process should aim to foster collaboration by structurally embedding it. Collaboration takes place mostly at the operational level, i.e., in day-to-day tasks, but can be facilitated by planning and restructuring at tactical and strategic levels of the organisation. From a product development process perspective, collaboration can be facilitated by adding roles and tasks in the typical product development process that would force the intervention of specific stakeholders at specific times.

To change the product development process requires acting at the tactical levels of aerospace manufacturing companies. To conduct this change would require the mobilisation of product development management and sustainability experts, as well as the engineering change management function, as it requires the transformation of current practices. This change needs to be aligned with business strategy, but also needs to come with a set of operational tools and methods to facilitate decision-making. To change the product development process can be done initially at the micro-level, i.e., through exploration of new innovations before deployment at the business level.

It is common practice to attempt to integrate sustainability through formal controls, ensuring a systematic consideration of sustainability in the process, with clear roles and responsibilities. However, tools, checklists, or procedures cannot fully prescribe how employees execute complex sustainability innovation tasks, what sustainability-related ideas they submit, and which internal and external stakeholders to integrate (Rauter et al., 2023). Another limitation of this approach comes from the risk that sustainability gets integrated as a compliance routine. Applying SPD principles does not systematically guarantee

that products are designed with improved sustainability performance (Watz & Hallstedt, 2022). Additionally, advancing collaboration and overcoming organisational silos might be particularly challenging in the aerospace context. Engineers are often separated into two or more units (e.g., technology and product development, business areas), which further divides the engineering workforce. There are also several organisational layers between a design team, strategic decision-makers, and stakeholders in the value chain. Therefore, it is also required to change capabilities within aerospace organisations.

#### *Change individual and organisational capabilities*

While changes to the product development process define when and where sustainability should be considered, the effectiveness of such changes ultimately depends on the individual and organisational capabilities to act on them. Even when sustainability criteria are formally integrated into planning, concept selection, and decision-making, developing sustainable products still requires effectively assessing sustainability performance, navigating trade-offs, and mobilising relevant stakeholders throughout the product development process.

Holistic sustainability assessments and risk and opportunity perspectives are rarely applied in aerospace product development practice. Understanding lifecycle impacts and potential sustainability risks across a product lifecycle could allow for the sustainability criteria to be used proactively rather than retrospectively. Therefore, design teams need capabilities to assess and anticipate product sustainability performance.

Current practice offers limited support for explicitly recognising and prioritising sustainability alongside established decision criteria. Decision-makers need further guidance to decide which aspect to prioritise to most effectively improve product sustainability performance with constrained resources and time, i.e., capabilities to navigate sustainability-related trade-offs.

Designing for sustainability often requires broader stakeholder involvement than traditional product development, including actors from different organisational units, hierarchical levels, and value chain positions. Current limitations are not solely due to skill gaps within design teams but also reflect a broader lack of organisational capability to support co-creation. Design teams, therefore, need capabilities to further involve key stakeholders in product development activities. Engineers and strategists also need to think “outside of the box” to step away from incremental improvements that would not be sufficient to counteract the sustainability impact of the industry.

Sustainability specialists need to further develop their capabilities to communicate sustainability value and act as internal convincers. Their support in translating sustainability challenges and opportunities into implications for operational, tactical, and strategic decisions is essential in supporting behavioural change within the organisation.

SPD capabilities are exercised through routines, practices, and organisational processes. Consequently, developing individual and organisational capabilities should be seen as a complementary and reinforcing effort to changes in the

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product development process, ensuring that sustainability integration becomes embedded in everyday design practice rather than remaining dependent on formal controls alone.

## 5.3 Limitations

The findings of this thesis are the result of a series of methodological and analytical choices, which entail limitations that are further discussed in this section. This research is centred on the aerospace industry, and more specifically on the design of aircraft systems and subsystems. This impacted the design and execution of the conceptual framework, research questions, and methods. While grounded in general sustainable product development literature, insights applicable to other industries are limited or have little validity due to the research design, hence limiting generalisability.

This research also focused on two aerospace companies headquartered in Sweden, which further narrows down the scope of generalisability. While the companies were carefully selected to represent different actors of the aerospace value chain, two case companies might not be sufficient to understand the full breadth of the aerospace business. This thesis also contains a limited amount of grey literature, i.e., research and information produced outside of traditional commercial or academic publishing, which could have provided further insights into different contexts. Having cases based in a different continent and having a different role in the value chain, such as a civil airframe original equipment manufacturer, would increase further generalisability of this research.

The number of study participants and the format in which they were engaged in the research involve limitations. Sustainability specialists were continuously engaged in the research. Engineers, for example, were only included in studies through workshops and group discussions. Some managerial roles, e.g., R&D manager or innovation strategist, were not participants in the four studies in this paper. The participant selection, therefore, limits insights related to certain parts of the case companies.

Finally, this research is mainly of a descriptive nature and involves no empirical testing of the identified factors required to integrate sustainability in aerospace product development. Additionally, there is uncertainty about the actual impact of these factors on product sustainability performance.

## 5.4 Validity

This section discusses the internal validity of the findings for the research question. Similar validity mitigation approaches were followed for both research questions. A variety of methods were employed to understand the key challenges, including literature reviews, semi-structured interviews, and workshops. Performing such triangulation allows for a deeper understanding

of the studied phenomenon and increases the rigour and quality of qualitative research (Bluhm et al., 2011). During research planning and execution, close attention was paid to all product development stages included in the scope of this thesis, as well as all organisational levels of the studied organisations. This approach minimised validity threats related to acquiring rich data, method bias, and source bias.

To handle researcher bias, rigorous coding and transparency procedures were applied. The research design and results were regularly peer-reviewed. Moreover, study participants were given the opportunity to provide feedback on the data analysis and interpretation. In Paper A, interviewees participated in an online meeting to discuss the results and interpretations prior to their publications. In paper B, the qualitative data from the literature were rigorously compiled and coded and were sent to the publisher along with the article. In Paper C, this feedback was integrated in the research design using the structure-laying technique (Flick, 2009). In Paper D, the Gioia methodology (Gioia et al., 2012) was applied to allow transparency of first and second order codes.

As this thesis is mainly based on the case study of two aerospace companies, overgeneralisation is a risk. While the two case companies are based in Sweden, they have facilities across the globe. They also deal with customers and suppliers from all over the world. This means that they need to manage similar business drivers and constraints as any other aerospace company in the world. Additionally, the two case companies have different core businesses and roles in the value chain, increasing the generalisability of the results.

# Chapter 6

## Conclusions

In this concluding chapter, the contributions to knowledge and practice are laid out in Section 6.1 and 6.2. Additionally, ideas for future work are presented in 6.3

The aim of this thesis was to clarify the challenges associated with integrating sustainability in aerospace product development, and to propose how design practice could change to ensure further sustainability integration. The findings from the four appended papers demonstrate that integrating sustainability in aerospace product development requires new methods and capabilities, along with significant changes to companies' existing processes and structures.

This research showed that aerospace companies have efficiently integrated some sustainability aspects that ensure high safety in flight and low fuel consumption. However, they struggle to integrate more sustainability aspects in product development, resulting in a lack of a holistic, strategic approach to sustainability (Paper A). Further integrating sustainability is constrained by regulatory, economic, structural, technical, and cognitive barriers (Paper B). This thesis investigated the underlying reason behind this lack of sustainability integration, revealing that a part of design decisions is dominated by short-term economic value, strict regulations, and risk aversion. Long product lifecycles and the complexity associated with sustainability impacts add to those challenges (Papers B and C). Aerospace organisations and typical projects are also not set up to facilitate collaboration, which limits lifecycle and system level thinking, resulting in unclear sustainability ownership, knowledge gaps, and trade-offs (Papers C and D).

In exploring the argument that aerospace manufacturing companies can have a large influence on the sustainability impact of the solutions they design, this thesis identified several pathways through which companies can actively exercise this influence. Developing sustainable products requires new capabilities to effectively assess sustainability performance, navigate trade-offs, and mobilise relevant stakeholders throughout the product development process

(Papers B, C, and D). Design teams need to develop more novel and creative concepts and/or collaborate closely with OEMs to drive the radical changes necessary to significantly improve the industry's sustainability impact (Paper D). Individuals in aerospace organisations should also be empowered to understand and communicate the value of sustainable solutions, supporting in building culture and securing strategic support (Paper D). This research shows the importance of aerospace companies to change their product development processes. Sustainability should become a driver for product development decisions, influencing which projects are realised and what concepts are selected (Papers B and C). Therefore, the main findings from this thesis suggest that sustainability should be structurally embedded so that considering sustainability wouldn't be sufficient in itself, but each product or project would need to comply with a certain sustainability threshold to be able to pursue development. Embedding collaboration into the product development process could also further support the ideation and realisation of sustainable products (Paper D).

In summary, the findings show that the challenges to integrate sustainability in aerospace product development are diverse, and an intervention is required at different levels. It is necessary to change the current product development process and to build capabilities. The value of sustainability criteria must be clarified to further integrate into design decision-making. Companies need to take a proactive stance in the sustainability transition and support design teams in building new capabilities to deliver products with better sustainability performance. These systemic and interconnected challenges cannot be resolved through isolated tools or methods. Instead, they point to the necessity of a new, holistic methodology capable of steering sustainability integration throughout the aerospace product development process.

## 6.1 Contributions to science

This research contributes to the growing body of literature on SPD within the aerospace industry, an inherently complex sector with long product lifecycles. SPD is not yet fully and effectively implemented in industry, and requires a deep understanding of organisations, decision-making mechanisms in design, the product development process, and its management. This research contributes to knowledge and theory in the field of SPD by conceptualising sustainability integration challenges as a multi-level, systemic phenomenon. The findings challenge narrow approaches to sustainable product development and highlight the need to approach SPD broadly in the context of aerospace from a product development process perspective.

Through case studies, the findings allow for a deep understanding of the particular context of aerospace and the barriers to SPD. This thesis contributes to empirical insights into current sustainability integration in aerospace design, challenges to further integration and why they are present, and discusses the main levers to move forward. It provides insights into decision-making mechan-

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isms and identifies influences and processes by which sustainable products can be realised.

Although grounded in the aerospace context, insights from this research may be applicable to other sectors with technically advanced products and long product lifecycles. The sustainability challenges taxonomy is aligned with PESTEL dimensions, circular economy barriers, and engineering change barriers from the literature, indicating applicability to other industrial sectors. Capability needs and main levers for developing sustainable products are also aligned with SPD literature. These insights reveal significant gaps between state-of-the-art and state-of-practice and highlight the need for support in clarifying the business value of sustainable products and driving further SPD implementation.

## 6.2 Contributions to practice

A radical shift in aircraft systems design must happen to align future aerospace products with the sustainability expectations of the coming decades. This study offers guidance for aerospace companies seeking to advance SPD.

This research offers support to SPD practitioners, i.e., individuals responsible for the integration of sustainability in their company's product development activities. They may use the categorisation of sustainability integration challenges to identify barriers at organisational, cognitive, and technical levels. It is recommended to seek support regarding systemic challenges through collaboration in research and industry networks. Additionally, SPD practitioners can assess their company's maturity against the capabilities needs identified in this thesis to prioritise capability-building efforts and allocate resources. SPD practitioners should seek to implement sustainability into critical product development stages, i.e., planning, conceptual design, programme management, and technology development. This should be conducted through formal controls, e.g., gate assessments and product requirements, and through social controls, e.g., training and culture.

To be able to initiate and realise sustainable products, design teams need to foster collaboration across departments and hierarchical levels. This also means to mobilise key internal stakeholders with decisional power, i.e. strategic, leadership roles in research and development. Design team members are recommended to develop their capabilities for anticipating product sustainability performance, managing trade-offs, and mitigating sustainability risks. Despite a structured and constrained product development, our findings encourage aerospace designers to ideate novel and creative solutions towards sustainability.

From a managerial perspective, it is necessary to clearly attribute sustainability responsibility and provide time and tools to design teams to work with it. This requires a shift from short-term economics to creating long-lasting value through sustainable products. Additionally, managers can help to abate organisational silos and foster more novel, creative solutions towards a sustainable

aerospace industry.

### 6.3 Future work

Future work should seek to empirically test the identified levers and capability needs to examine their actual impact on product sustainability performance. Through action research, future research could plan an intervention aiming at integrating sustainability in decision-making, focusing on one or several of the identified critical stages of the product development process defined in this thesis. This requires to defining sustainability criteria, defining a compliance level for each, mapping which ones are applicable at which stages of design, and developing a framework to monitor these indicators throughout product development. Furthermore, future research could implement changes to the product development process, e.g. a sustainability compliance threshold, in selected case projects.

To accelerate building capabilities effectively in aerospace organisations, future research should seek to map, combine, and further develop existing support methods for SPD. This would support closing identified gaps in this research, e.g., trade-off management, mitigation of sustainability risks, and support cross-functional engagement around SPD.

Future research could also seek to develop a new design methodology to implement in the current aerospace product development process to support decision-making towards sustainability. Such methodology needs to further guide design teams in sustainability-related trade-offs by clarifying which are important sustainability criteria and what their value is. Future tool development should also seek to increase the design team's ability to collaborate with other stakeholders at different organisational levels, to adopt a strategic sustainability perspective, and think creatively despite constrained design spaces.

The scope of this thesis is intentionally narrow, with two Swedish-based aerospace companies, focusing on the design of aircraft systems and subsystems. Future research could, therefore, test and refine the findings with other aerospace companies, or in broader contexts with systems approaches and long product lifecycles, such as the ship industry, the rail industry, or the defence and military industries.

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