An Introductory Study of the Sustainability Transition for the Aerospace Manufacturing Industry

Sustainable Production through Advanced Manufacturing, Intelligent Automation and Work Integrated Learning, J. Andersson et al. (Eds.)

doi:10.3233/ATDE240200

An Introductory Study of the Sustainability Transition for the Aerospace Manufacturing Industry

Pauline L. Y. LÉONARD[a,1], Sophie I. HALLSTEDT[b], Johanna W. NYLANDER[a], Ola ISAKSSON[b]
[a] *GKN Aerospace Sweden*
[b] *Chalmers University of Technology*
ORCiD ID: Pauline L. Y. Léonard https://orcid.org/0009-0008-1469-058X, Sophie I. Hallstedt https://orcid.org/0000-0002-7382-1825, Johanna W. Nylander https://orcid.org/0009-0002-4998-9473, Ola Isaksson https://orcid.org/0000-0003-0373-3720

Abstract.
This paper explores the needs and clarify the sustainability challenges in relation to complex lifecycles within the aerospace field. It is an introductory study to understand how to improve the sustainability performance of aerospace solutions and aim to propose a comprehensive sustainability transition roadmap for the Aerospace industry in further research work.
Society is increasingly demanding that the aviation industry adopt more sustainable practices, resulting in the formulation of new regulations and policies to limit the sustainability risks of this strategic industry. Existing regulations, such as the EU's Green Deal and the EU's critical raw materials act, are already impacting the Swedish aerospace manufacturing industry. Furthermore, circular economy is gaining significant attention in the manufacturing industry in general and is increasingly considered in aerospace.
This exploratory and descriptive research is conducted with support of Swedish Aerospace manufacturers and aim to cover real industrial projects with products at different stages of development. The interviewed companies operate within both civil and governmental aerospace sectors, encompassing the entire spectrum of product development, from radically innovative technology introductions to enhancements made to existing systems and components.
This paper highlights current challenges and several focus areas on which the aerospace manufacturers have started to work on and will have in focus for the next 5-10 years ahead. Differences in approach have been identified between early product development phases with radical innovations and more advanced and mature product development. The stakes and priorities are different and it is reflected on how the companies are working with sustainability today. There is a need to balance efforts between developing the right future products, and also improving current ones, to lead the sustainability transformation in the aerospace industry.

Keywords.
Sustainability, complex lifecycles, sustainable product development, aerospace industry, sustainability transition

[1] Corresponding Author: Pauline Louise Yolande Léonard, pauline.leonard@gknaerospace.com, https://www.linkedin.com/in/paulineleonard1/

1. Introduction

1.1. Importance of a sustainability transition in aerospace

The aviation sector, responsible for 3.5% of global greenhouse gas emissions, is projected to experience continued growth, with an annual average of 4.1% over the next three decades [1]. But it has become evident lately that society's sustainability challenges are not limited to only climate impact and challenges are driving sustainable development in the global business that is aerospace. Achieving the 2050 net-zero vision, in addition to NOx emissions and noise reduction goals [2] will require many efforts in the entire value chain of aerospace products. The society is expecting the aviation industry to become more sustainable and new regulations and policies will be created in the future in order to limit the footprint of this strategic industry. Some regulations already exist that will affect the Swedish aerospace manufacturing industry such as the EU's Green Deal or EU's critical raw materials act, enforcing a more circular and more regional value chain [3].

Circular economy is gaining significant attention in the manufacturing industry in general, yet not in aerospace according to Dias et al [4]. The adoption of Circular Economy is recommended following criticism of the linear model, which causes issues such as increased pollution and deforestation, reduction of natural resources and loss of biodiversity, among others. Circular economy is a recommended approach for improving environmental sustainability, increasing the life cycle of products and generate economic and productivity gains resulting from the optimization of materials and reduction of waste.

While various methods and approaches for integrating sustainability in product design exist, efficiently implementing sustainable development remains a challenge for many industries [5]. Research has been initiated internationally, e.g the SUSTAINAir project to address the circularity aspects of material solutions in aircrafts.

Aerospace faces its own unique obstacles when it comes to developing sustainable solutions. Time perspective is one such challenge, as the development of aerospace products is often long, i.e. three to seven years in average, and limited due to standards, regulations and certifications. In addition, the operational lifespan in the civil industry averages around 26.5 years [6]. Given the urgency of a sustainable change, it is crucial to enable this transformation while balancing tactical and strategic goals. The need to use advanced materials and manufacturing methods is another sustainability challenge that the industry is facing [7]. Materials for aerospace products need to be thoroughly certified for safety reasons, and are often expensive. Specific alloys are many times scarce and critical from availability and sustainability perspective, and are not included in a circular loop, as well as frequently hard to substitute. Similarly, certain manufacturing methods, e.g. Additive Manufacturing, can be very energy-consuming, or generate a lot of scrap, e.g. forging and are difficult to replace while meeting current standards. Aerospace manufacturers are invested in research for design to optimize the life cycle of circular solutions by including repair and remanufacturing as design parameters [8]. The operating space to make materials and manufacturing processes more sustainable in aerospace is difficult to comprehend and use at its maximum. Therefore, there is a need to develop knowledge and capabilities in Aerospace industry to deal with the added complexity that sustainability challenges bring. Furthermore, there is a need to enable product development teams to develop resilient solutions and thereby actively contribute to the sustainability transition of aerospace industry.

1.2. Sustainability in product development

At present, the implementation of UN's 2030 sustainable development goals [9] have an impact on the products, systems, solutions and infrastructure that are needed. Production and decarbonisation are areas that need transformation to achieve these goals [10]. Through Clean Aviation, aerospace have emphasized the climate change challenge, but also recognising the development of new business models to handle energy and materials transformation. Sustainable development brings a range of new constraints and aspects to relate to, why the practices of product development continuously need to be adapted. The fact that the well-known insight that 80% of a product's sustainability impact over its life cycle is set already in the early design phases puts product development and its early phase decision making in focus. The understanding of sustainability challenges and opportunities are consequently critical to include already in the early phases of product development, e.g. in portfolio- and product requirement management [11, 12, 13, 14].

Sustainable product development, which relates to the integration of sustainability into the early phases of the product innovation process and includes a life-cycle thinking, is therefore an important measure in the development of a more sustainable product design and production. In a company, integrating sustainability aspects into product development is a complex task. This means: i) developing solutions that benefit from new technologies, i.e., new to the company and the market, with a high sustainability potential; ii) developing business models and solution that covers the full life-cycle and its value-chain; and, iii) managing and mitigating the risk associated with new technologies and new business models [15].

The challenge facing transportation industry in general, and aerospace in particular, will require a significant shift in products and technologies. Realizing such challenges requires equally a shift in thinking, acting and in the way of how to ensure confidence and robustness in the new approaches. This needs to be included in the design and development systems, routines and methods, something that is challenged by the systemic and holistic nature of sustainability. The understanding and designing of products to meet increased needs and expectations on sustainable products cannot be seen in isolation, but rather need to bridge design, technology, business and quality aspects with a complete life-cycle perspective.

In the challenge to provide sustainable solutions, it is expected that product developing companies need to simultaneously address new type of needs and integrate new type of technologies into functioning solutions. It is argued that this will require new practices that provide what will be referred to as capabilities, or more specifically, sustainable product development capabilities.

At present in the industry, there is a lack of understanding of the sustainability complexity of technology development. Providing sustainable solutions to the market is no longer only of strategic importance for aerospace, but rather business critical. While the industrially negotiated strategies in Europe [16] and the UK [17] outline actions necessary for reaching 2050 emission targets on Green House Gases and sustainability transformation are even wider. The Aerospace industry will also need to comply with other targets expressed in the new industrial strategy to meet the European Union's Green Deal [18]. One such area is the use of resources, where Circular Economy solutions and legislative actions are central. So in addition to the ambitious targets on emissions, industry needs to address also material resource targets. Such disruption in the business has not been seen in aerospace since the introduction of jet propulsion more than 60 years ago. Although aerospace is a high technology business, the number one priority for

aerospace has been, and still is, flight safety that practically have limited the ability to introduce too radical solutions into business. The safety levels of today are several orders of magnitude higher than the safety levels of early jet age, and a fundamental challenge is how to succeed with radical and disruptive changes while maintaining the high safety standards of today [19].

2. Method

This is mainly an exploratory study that aims to identify research problems, and understand how to improve the sustainability implementation of aerospace products, with a focus on industry leadership perspective. The.

The research is planned by inspiration from the Qualitative Research Design interactive methodology [20] as an exploratory study, where the aim is to identify components and patterns to create the conceptual framework for more in-depth studies in continues research. A semi-structured interview study was conducted in which three different companies participated. The three companies are all aerospace companies within Sweden and can provide a comprehensive view of sustainable product- and technology development in the aerospace industry. These companies were selected as they have aerospace solutions both within civil and defense industry, as well as products at different stages of development and therefore increase the understanding of how to accelerate the sustainability transition in a variety of situations. Development stages were represented by at least two out of the three companies:

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

The interview study targeted interviewees with a leading position in sustainability, in technology or product specialist, and in strategic development of the company. See Table 1.

Table 1. Roles of interviewees at the three companies

Company A	Company B	Company C
Sustainability lead Technology lead Strategy lead	Sustainability lead	Sustainability lead

The interview questions were grouped into two different overarching themes: sustainability transition and circular economy. The aim was to explore the needs and clarify the sustainability challenges in relation to complex lifecycles within the aerospace field. See list of interview question in Table 2.

In addition to the semi-structured interview, a list of current and upcoming regulations and policy instruments related to sustainability within the aerospace field was collected. Also, a review of initiatives in relation to sustainability from aerospace associations were conducted.

Table 2. List of interview questions

Theme I: Sustainability transition	Theme II: Circular economy
1) In which ways do you make sure your aerospace solutions are contributing to aerospace industry's sustainability transition? 2) Where is your company at in terms of sustainability transition? 3) What support do you need to achieve this transition? 4) On what sustainability aspects is your company focusing on today? What will it be in the long term? 5) What external factors are important for your company's future? 6) How do you evaluate sustainability performance of aerospace solutions today?	1) What is circular economy for you and your company? 2) How is circular economy implemented in your company today? 3) How do you work with sustainability across the value chain? 4) What is needed in order to develop solutions with more sustainable lifecycles?

3. Results and discussion

3.1. Regulations supporting the sustainability transition

There are several sustainability related regulations that affect the aerospace industry directly or indirectly, both national regulations and European regulations. There has been an increase of regulations in the last couple of years, as the climate has gotten increased attention in society. Many proposed regulations are also currently being considered and expected to be in force in the next few years.

The case companies, set in Sweden, are thereby directly affected by EU regulations, but also other regulations since they have sites and suppliers across the world.

Some of these regulations are focused on sustainability reporting, such as the Corporate Sustainability Reporting Directive (in EU) and proposal for Standardization of Climate-related disclosures (in US). While others regard sustainability in the supply chain for example regulations regarding due diligence and increased transparency in the supply chain (ex EU Corporate Sustainability Due Diligence Directive and Norway Transparency Act). EU critical raw material act [3] aims to secure the supply chain of critical materials in Europe encourages more circularity and the development of European suppliers. This has a big impact on the aerospace companies with their main suppliers outside of EU, long product lifecycles and high material quality demands.

There are also regulations regarding social aspect such as for example Conflict minerals regulation (in EU) or the proposal of Slave-Free Business Certification Act (in US), or financial aspect such as EU Taxonomy that sets a common classification for sustainable economic activities.

The increased number of new regulations and directives are putting increased attention on sustainability, however with the risk of overemphasising the reporting itself rather than on actually driving change. Two of the three companies have also committed to the Science-Based Target Initiative (SBTi) which implies that they work to measure climate impact and setting targets to reduce climate impact according to the Paris agreement.

3.2. Aerospace associations influencing the sustainability transition

3.2.1. International- on a global scale

The IAEG (International Aerospace Environmental Group) is an international organization in which aerospace companies from all continents are members. Their goal is to develop voluntary leading edge solutions across the value chain to promote a responsible and sustainable aerospace industry. Today they are a forum for sharing good practices concerning key issues and developing voluntary consensus standards around the environment. This organization does not currently have a roadmap, but is working on several focus areas that are: materials and substances declaration, greenhouse gases, emerging global regulations, environmental certification and supply chain [21].

The International Civil Aviation Organization (ICAO) is a United Nations agency and is the worldwide alignment of air regulations and procedures. Aviation safety and environmental protection (Climate change, aviation emissions, aircraft noise and local air quality) are in their global priorities. ICAO developed a carbon offsetting and reduction scheme that sets a baseline across the industry. It also quantified a large amount of sustainable aviation fuels and their potential towards carbon neutrality. In 2022, ICAO adopted a long term aspirational goal for international aviation of net-zero carbon emissions by 2050 [22].

In USA, the Federal Aviation Administration is committed to make aviation quieter, cleaner and more sustainable since 2023. Focus on aviation fuels, new technologies and operations efficiency, engage with communities on aviation noise [23].

3.2.2. International – on an Europe scale

ACARE, the Advisory Council for Aviation Research and Innovation in Europe has published their first roadmap including sustainability indicators in 2011 called "Flightpath 2050". Since then, after EU published the Green deal the roadmap has been revisited and updated in 2022 [2]. Several goals have been defined for short, medium and long term [24] to reach net zero carbon dioxide, significant reduction of NOx and particles, contrails cirrus formation, and reduce total climate impact of the aviation industry in Europe. Another of their sustainability goals is to "put the citizen at the center", hence enabling less inconvenience from the aviation industry such as noise and land change, as well as making the industry more socially inclusive and transparent.

EASA, the European Union Aviation Safety Agency publishes European aviation environmental reports regularly. It contains a roadmap for EU+ carbon neutrality by 2050. It also proposes a roadmap for noise exposure and NOx emissions reduction 2050. Air quality and aviation non-CO2 warming emissions are also addressed [25].

The report Destination 2050 – A route to net zero European aviation [26] describes pathways to net zero CO2 emissions in Europe and has been signed by several European airlines associations, councils as well as ASD. Improved technology and sustainable aviation fuels and hydrogen are key elements of the net zero roadmap. Figure 1 shows the effect of different measures in the future towards a net zero industry.

Innovair, the Swedish national innovation program for the aerospace industry has identified action areas to reduce the aviation's environmental impact, following strategies suggested by European and international strategies [27].

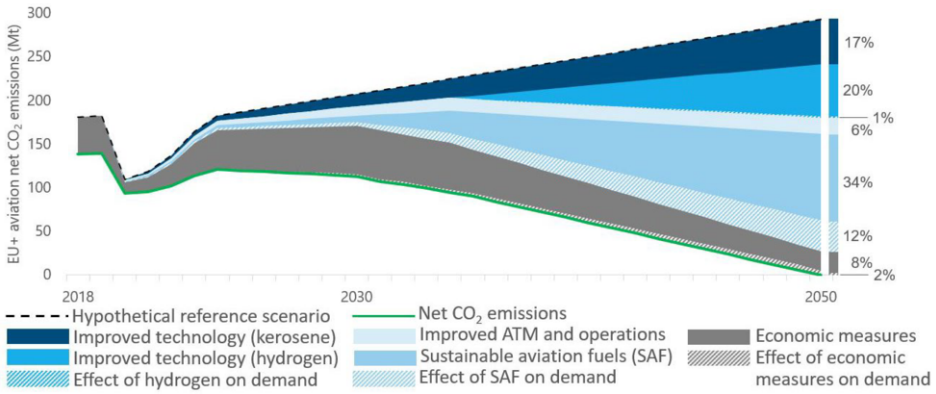

Figure 1. Net zero roadmap for European Aviation. Source: Destination 2050 report [26]

3.3. Interview results

Technology, sustainability and strategy leaders of aerospace manufacturing industry have been interviewed about the industry's sustainability transition and circular economy, see Table 2.

3.3.1. *Sustainability transition*

Figure 2 below presents a summary of the interview study on the topic of sustainable transition.

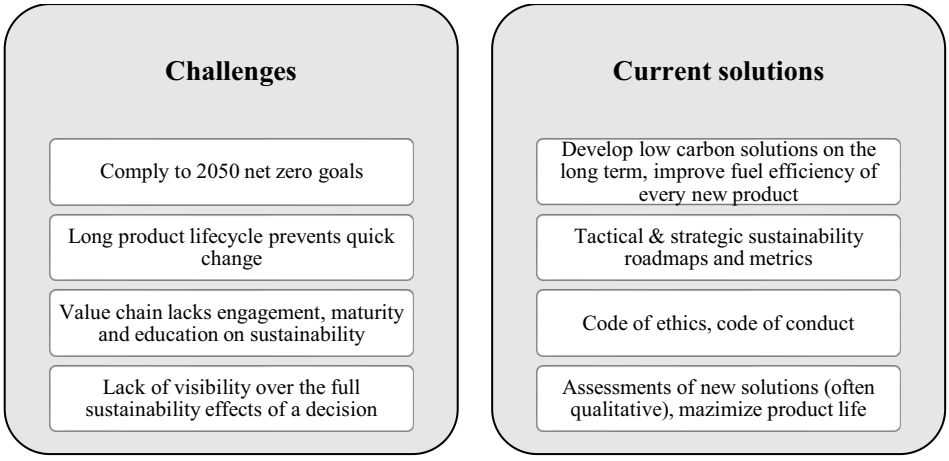

Figure 2. Challenges and current solutions to enable the sustainability transition in the aerospace industry

In terms of environmental transition, companies focus currently on carbon emissions from their own operations and energy consumption and a few other environmental metrics, such as water intensity and waste to landfill. Emissions of the whole value chain are more and more frequently evaluated and addressed through initiatives such as Science Based Targets. Substances of concerns are also an important compliance issue that current products on the market are facing. The industry keeps to date with the

world's sustainability transition with their external partners such as universities and research institutes and make sure that they are on the path to transition.

In terms of social sustainability, some interviewees sees it more as a continuous work for their companies than a transition. By gradually implementing more stringent code of ethics, supplier code of conducts, their business will become gradually more socially sustainable without the need for a fast transition.

In relation to product development, "*Aerospace has always had a focus on weight and efficiency*." (Sustainability lead, Company A). It is a strong focus for all solutions regardless they are at very innovative or not, at early or late development stages.

For aerospace manufacturers, long-term projects aiming to develop low carbon solutions are key to the sustainability transition of the industry. Research ongoing under the European program Clean Aviation is promising to significantly reduce the climate impact of aircrafts in flight. Hydrogen power, hybrid-electric or ultra-efficient aircrafts are being developed. This work is aligned with the European roadmap called "Fly the Green Deal" [2].

According to the leaders interviewed, reaching net zero by 2050 is a vision that likely will be very difficult to achieve for the aerospace industry due to the long lifecycle of their products. As the average life of an aircraft is 27 years, aircrafts sold in 2023 will only retire in 2050. Today's aircrafts are only certified to fly on blends of fossil and sustainable aviation fuels, which makes it highly unlikely that aircrafts in 2050 can fly fossil-free, even less likely carbon-neutral. Retiring aircrafts at an earlier age could be a solution if the business case allows it, however it poses other sustainability issues since tons of valuable materials will become waste with no possibility of life extension for the sake of climate neutrality.

The development of green aviation innovations such as electric or hydrogen appears to be currently more driven by the civil business. Meanwhile governmental business focuses on sustainability aspects that also have a strategic advantage, such as mineral criticality and noise of the aircrafts.

3.3.2. *Circular economy*

A summary from the interviews regarding circular economy is presented in Figure 3.

If climate change is high on the aerospace industry agenda, it is not necessarily the case for circular economy as of today. "*The goal is to have products in our portfolio that do not require any virgin raw material. […] We are far from that fully circular vision*" (Sustainability lead, Company A). To reach this, every life cycle phase should be optimized in terms of waste, and discarded materials should stay within the aerospace industry without downgrading.

Metal scrap is more often downcycled, and sold to a reselling company that does not guarantee for the materials to be circled back into aerospace-grade quality. Non-metallic scrap such as composites or plastics are in the best case today incinerated for energy recovery. Recycling of fibers in composite materials is being established but very large amount of waste are required to establish such contracts, and not all manufacturers reach the large volume necessary.

The strong focus on safety and lack of regulations hinders the development of some circular materials that might not reach required properties or might degrade during use. "*We are so focused on safety that it makes it more difficult to be circular, it is a costly exercise to recycle and recertify*." (Sustainability lead, Company A). Increase the amount

of recycled materials in purchased alloys is not on the trade-off list that is dominated by quality and cost.

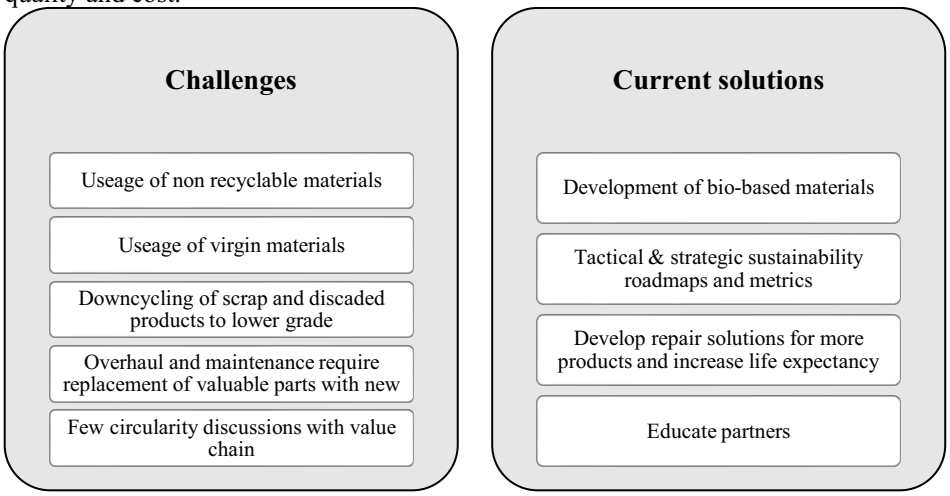

Figure 3. Challenges and current solutions to enable circular economy in the aerospace industry

The critical raw material act [3] is a concern expressed by some of the interviewees which see it very challenging to work with in their branch. The current offer in Europe is currently too limited to enable more circulation of critical raw materials within Europe. Critical elements are in vast majority coming from China, and aerospace alloys and parts come often from the USA where the aerospace business has been historically more established. However, it is important to highlight that it is not always well understood how to approach the critical raw material act and how much it will transform European aerospace manufacturers.

In the defense sector, "*Circularity is a business opportunity*" (Sustainability lead, Company B), that could provide more independence and flexibility in time of crisis and is therefore explored proactively both from an operational and eco-design perspective.

In the civil aviation engines sector, a contractual arrangement known as "power-by-the-hour" has increasingly dominated new contracts since 2010-2015. Previously, agreements involved a low upfront payment when purchasing the engine, but significant costs were incurred by airlines for overhauls and shop visits. With power-by-the-hour contracts, airlines pay a fee based on engine usage. This shift has posed a challenge for engine manufacturers, as shop visits are no longer a source of revenue but an expense. This led to the extensive development and implementation of repair solutions, which cost less than replacement of the entire damaged parts.

In terms of product development, companies working with immature technologies and radical innovation shifts are considering circularity at early design stages. It is not a driving requirement as of today because the current goal is to successfully demonstrate these innovations.

"*Sustainability and financial departments needs to work together on a business model for circularity*" (Sustainability lead, company C). In addition, it does not seem that the aerospace manufacturing industry is systematically discussing this topic when interacting with suppliers and customers and the value chain needs to be more educated about the importance of circularity.

3.3.3. *Roadmap*

The interviewees in the commercial sector emphasize that the industry needs to develop future low-carbon solutions is rooted in financial considerations. Achieving this goal requires aligning incentives for decision-makers and industrials forming powerful partnerships. As research projects and product development cycles in the aerospace industry are very long, the return on investment is not immediate. A significant obstacle at present is the lack of demand and compelling business case for developing such technologies, hence why governmental funding is crucial to drive development of innovative sustainable solutions. In the defense sector, the drive for a sustainability transition is not necessarily financial reasons but will come from customer demand. Company A and C leaders agree that creating international regulations on carbon emissions or fossil fuel usage taxes could drastically improve the "sustainable technologies" business case and affect how rapidly these solutions are being developed. On the other hand, company B's sustainability lead anticipates that future regulations "*might not support new technologies and limit what we can develop*".

In the coming years, the aerospace industry will continue to focus on mitigating their climate impact. If today this includes direct carbon emissions, it will also include in the future non-CO2 effects from flight such as persistent contrails and nitrogen oxides emissions. The industry's contribution to various environmental impacts will grow in importance in the future as well, referring to the nine planetary boundaries. Developing novel solutions will become necessary to take a broader perspective than weight and efficiency, incorporating other sustainability aspects into trade-offs considerations. Quantitative environmental evaluations such as lifecycle analysis will be more and more frequent. For aerospace companies driving radical innovation shifts, it is clear that circularity indicators such as recycled material content or recyclability will be high on the requirements of future solutions. The need is to understand how to connect these to business opportunities. For companies in the defense sector, circularity will also grow in order to support strategic independence. Aerospace manufacturers have circularity on the agenda but might not have identified the temporality of when and how to start implementing circularity. The Europe Critical Raw Materials act [3] will support faster development of European aerospace material supply.

The society's expectation and behavior towards flying will also strongly influence how the industry develops in the future. The flight industry has recovered since the COVID-19 crisis, and despite the high cost increase of flights overall, people are still flying and connecting around the world. It appears that despite the growing environmental and climate impact consciousness, many still take the opportunity to fly. Social development across the globe is expecting to enable continuous and strong growth in the aerospace industry, especially in Asia and African continents.

3.3.4. *Differences in product development phases*

The interview study identified differences in approach between early product development phases with radical innovations and more advanced product development.

Radical innovations aiming for more comprehensive sustainably and long-term impact, are viewed as the real enabler for net-zero and sustainability transition. Presently, efforts are focused on enabling these innovations rather than ensuring their immediate 100% sustainability. First, it is difficult to grasp the whole sustainability impact of these future technologies. Second, low maturity of the value chain does not enable more stringent decision-making. Third, there is a fear that making it more sustainable would

slow down the implementation of the innovation or make it too expensive. It is a problem both financially for the investment company and for sustainability as a whole, as more sustainable solutions would be further delayed. In contrast, current solutions and short-term product development address mostly compliance issues, which prevents long-term thinking. In addition, long lead times and cost of re-certification are seen to prevent the implementation of significant changes. Development resources are primarily focused on enhancing quality, meeting with regulations and managing supply risks.

4. Conclusions

This paper highlighted several focus areas on which the aerospace manufacturers have started to work on and will have in focus for the next 5-10 years ahead. See Figure 4.

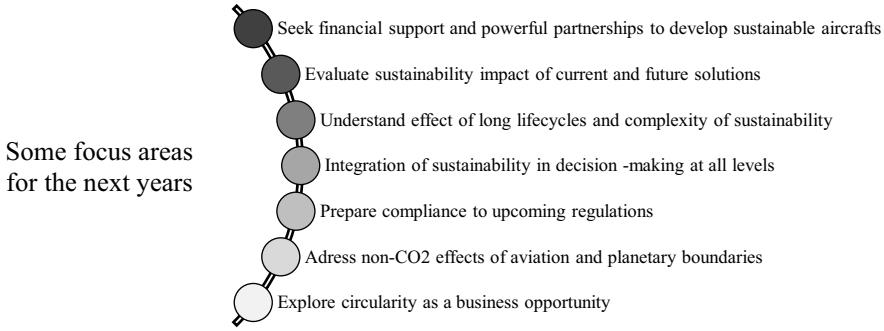

Figure 4. Some main sustainability focus areas in the aerospace manufacturing industry in the next years

These areas of focus are connected to current challenges that the industry is facing, such as comply with customer expectations, regulations and net zero targets. Long product lifecycles, lack of value chain engagement and complexity of sustainability are several challenges hindering the transition today.

The interview study identified differences in approach between early product development phases with radical innovations and more advanced and mature product development. The stakes and priorities are different and it is reflected on how the companies are working with sustainability today. There is a need to balance efforts between developing the right future products, and also improving current ones, to lead the sustainability transformation in the aerospace industry.

References

[1] ICAO. Future of Aviation [Internet]. International Civil Aviation Organization; 2015 [cited 2023 Oct]. Available from: https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx

[2] European Commission, Directorate-General for Research and Innovation, Fly the Green Deal: Europe's vision for sustainable aviation. Publications Office of the European Union; 2022. doi: 10.2777/732726

[3] European Commission, European Critical Raw Materials Act [Internet]. Publications Office of the European Union; 2023 Mar 16 [cited 2023 Oct]. Available from: https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661

[4] Rodrigues Dias VM, Jugend D, de Camargo Fiorini P, Razzino CdA, Paula Pinheiro MA. Possibilities for applying the circular economy in the aerospace industry: Practices, opportunities and challenges. Journal of Air Transport Management. 2022 Jul;102:102227. doi:10.1016/j.jairtraman.2022.102227

[5] Faludi J, Hoffenson S, Kwok SY, Saidani M, Hallstedt SI, Telenko C, et al. A Research Roadmap for Sustainable Design Methods and Tools. Sustainability. 2020 Oct 3;12(19):8174. doi:10.3390/su12198174
[6] ICAO. Best Practices and Standards in Aircraft End-of-Life and Recycling. 2019 [retrieved 2023 Oct]. Available from: https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg279-284.pdf
[7] Hallstedt SI, Isaksson O. Material criticality assessment in early phases of sustainable product development. Journal of Cleaner Production. 2017 Sep;161:40-52. doi:10.1016/j.jclepro.2017.05.085
[8] Al Handawi K, Andersson P, Panarotto M, Isaksson O, Kokkolaras M. Scalable set-based design optimization and remanufacturing for meeting changing requirements. Journal of Mechanical Design. 2021 Aug:143(2). Doi:10.1115/1.4047908
[9] United Nations (2015), The 2030 Agenda for Sustainable Development. United Nations Development Programme; 2015 [cited 2023 Oct].Available from: https://www.undp.org/
[10] Nakicenovic N, Messner D, Zimm C, Clarke G, Rockström J, Aguiar AP, Boza-Kiss B, Campagnolo L, Chabay I, Collste D, Comolli L. TWI2050-The World in 2050. The Digital Revolution and Sustainable Development: Opportunities and Challenges. Report prepared by The World in 2050 initiative. 2019.
[11] European Environment Agency, De Schoenmakere M, Gillabel J, Circular by design: Products in the circular economy, Publications Office of the European Union; 2017 Jan. Available from: https://www.eea.europa.eu/publications/circular-by-design. doi:10.2800/860754
[12] Watz M, Hallstedt SI. Profile model for management of sustainability integration in engineering design requirements. Journal of Cleaner Production. 2020 Feb;247:119155. doi:10.1016/j.jclepro.2019.119155
[13] Watz M, Hallstedt SI. Towards sustainable product development – Insights from testing and evaluating a profile model for management of sustainability integration into design requirements. Journal of Cleaner Production. 2022 Apr;346:131000. doi:10.1016/j.jclepro.2022.131000
[14] Villamil C, Schulte J, Hallstedt S. Sustainability risk and portfolio management—A strategic scenario method for sustainable product development. Bus Strat Env. 2022 Mar;31(3):1042-57. doi: 10.1002/bse.2934
[15] Schulte J, Knuts S. Sustainability impact and effects analysis - A risk management tool for sustainable product development. Sustainable Production and Consumption. 2022 Mar;30:737-51. doi:10.1016/j.spc.2022.01.004
[16] Clean aviation, Programme overview and structure [Internet]. Clean Aviation joint Undertaking; 2021 [cited 2023 Oct]. Available from: https://www.clean-aviation.eu/programme-overview-and-structure
[17] UK department of transport. Decarbonising Transport, A Better, Greener Britain. 2021. Available from:https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1009448/decarbonising-transport-a-better-greener-britain.pdf
[18] EU Commission. Communication from the commission – The European Green Deal. 2019 dec 11. Available from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
[19] I. Hallstedt S, Isaksson O, Nylander JW, Andersson P, Knuts S. Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from GKN Aerospace Engine System. Des Sci. 2023;9: doi: 10.1017/dsj.2023.22
[20] Maxwell J A, Qualitative Research Design - An interactive Approach, Third Edition, Sage publications, 2013
[21] IAEG, Introduction to IAEG [Internet]. International Aerospace Environmental Group; 2023 [Cited 2023 Oct]; Available from: https://www.iaeg.com/binaries/content/assets/iaeg/2023/iaeg_intro_09_2023.pdf
[22] ICAO, Environmental protection [Internet]. International Civil Aviation Organization; 2023 [Cited 2023 Oct]; available from: https://www.icao.int/environmental-protection/Pages/default.aspx
[23] Federal Aviation Administration, FAA´s website [Internet]. United States Department of Transportation; [Cited Oct 2023]. Available from: https://www.faa.gov/
[24] ACARE. ACARE goals [Internet]. Advisory Council for Aviation Research and Innovation in Europe; 2022 [Cited 2023 Oct]; Available from: https://www.acare4europe.org/acare-goals/
[25] European Environment Agency, European Union Aviation Safety Agency, European aviation environmental report 2022. Publications Office of the European Union; 2023. doi:10.2822/04357
[26] Van der Sman E S, Peerlings B, Kos J, Lieshout R, Boonekamp T. Destination 2050. Royal Netherlands Aerospace Center and SEO Amsterdam Economics. 2020. Available from: https://reports.nlr.nl/server/api/core/bitstreams/c9002b7e-224f-420c-b6da-ab6aecd48ea2/content
[27] Innovair. NRIA Flyg 2020, Our results up to now and the way forward. The Swedish Aeronautic Research and Innovation Agenda. 2020. Available from: https://innovair.org/wp-content/uploads/2020/04/nriaflyg2020-eng.pdf