Design Science

Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from GKN Aerospace Engine System

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Abstract

A radical shift in technology is necessary to enable future air transport solutions. Sustainability targets for aeroengine manufacturing mean more than reducing CO_2 and NO_X. The future will open up possibilities and bring new challenges when introducing hybrid- and electrical propulsion technologies using new materials, technology solutions and new business models. This article reports on findings from a longitudinal study and many years of collaboration between researchers and industry experts, where a first-tier aeroengine manufacturer transforms their product development capabilities to enable sustainable product development. The article highlights some activities undertaken and identifies critical challenges and opportunities remaining for a manufacturer of next-generation aeroengine solutions. It is argued that the challenge for aeroengine manufacturers to develop new-generation propulsive technologies will require a systemic change in the undertaking of design and development. The opportunities of sustainable technologies are evident yet require: (1) means to tighter integrate business and technology development, (2) the ability to quantify and assess sustainability impacts of different concept solutions, and (3) means to utilise natural resources, alloys and materials for a circular and life-cycle optimised solution.

Keywords: Sustainable product development, Capabilities, Design method, New technologies, Aerospace, Sustainable design

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1. Introduction

Although the geological definitions are still being formalised, it is widely accepted that we have lived since the mid-20th century in the Anthropocene era, where humans have a decisive influence on the state, dynamics and future of the earth system. This influence results in the long-term, or even irreversible, change of conditions on our planet. Industrial activities and the resulting products are central in human activities that impact our world, and following a brief introduction to sustainable development, the focus of this article will be on how aerospace

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manufacturing industry can adapt their product development practices to develop more sustainable solutions. Particular focus is on aeroengine component manufacturing within which the case company is predominately active.

1.1. Sustainable development and industrial challenges

Overall, the general awareness of sustainability challenges increases as the consequences are becoming imminent as well as incentives and initiatives to adapt and mitigate are continuously strengthened. The United Nations has been a global actor in raising awareness and establishing global-reaching agendas. In 1972, at the United Nations Conference on the Environment in Stockholm, the fundaments for producer responsibility were accepted, and when the concept of sustainable development was published by the World Commission on Environment and Development in 1987 (Brundtland 1987), this became a reference for collective action to address the unsustainable development. The Brundtland notion of sustainable development, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", is still widely used. Elkington & Rowlands (1999) further clarified the concept of "sustainability" and described the approach as the triple bottom line (TBL), which is based on the thought of the simultaneous pursuit of economic prosperity, environmental quality and social equity. Further development and discussion of the dependency of these three systems are explained as nested interdependent systems, meaning that the economic system is part of and dependent on the social system, which in turn, is part of and dependent on the ecological system (Gibson 2006; Pryn, Cornet & Salling 2015). Another difficulty with sustainable development is knowing and acting on long-term consequences in relation to short-term effects. Despite the many advancements made by humans and society over the last decades, the overall rate of change into a sustainable society is not sufficiently high. In the ecological dimension, global warming is one outstanding threat. The 1.5° target, that is, not exceeding the 1.5° increase compared to the pre-industrial levels to avoid worst-case scenarios, from the 2015 United Nations Climate Change Conference, COP 21, has wide acceptance. Yet the window to act is short, and actions need to be substantial. In 2022, (World Meteorological Association (WMO) 2022) another warm record year was reported, and the world temperature has increased by over 1° already. The ecological dimension of sustainability embraces much more than global warming, and when the planetary boundaries were presented (Rockström *et al.* 2009) they presented measurable boundaries for what our planet can withstand. In 2015, several of these tipping points had already been reached (Steffen *et al.* 2015), and will have irreversible consequences. The actions necessary to succeed in reaching a sustainable society are urgent and require radical and disruptive changes.

At present, the implementation of UN's 2030 sustainable development goals (SDGs) (Nakicenovic *et al.* 2019) are systematically being implemented in regional and national systems into education, legislation, taxation and development that all have an impact on the products, systems, solutions and infrastructure that are needed. Figure 1 illustrates how product development is affected by this change. For product development, it is instrumental to have an understanding of all necessary conditions and interventions that have an impact on the products and solutions that are needed, and how these can be designed. Sustainable development

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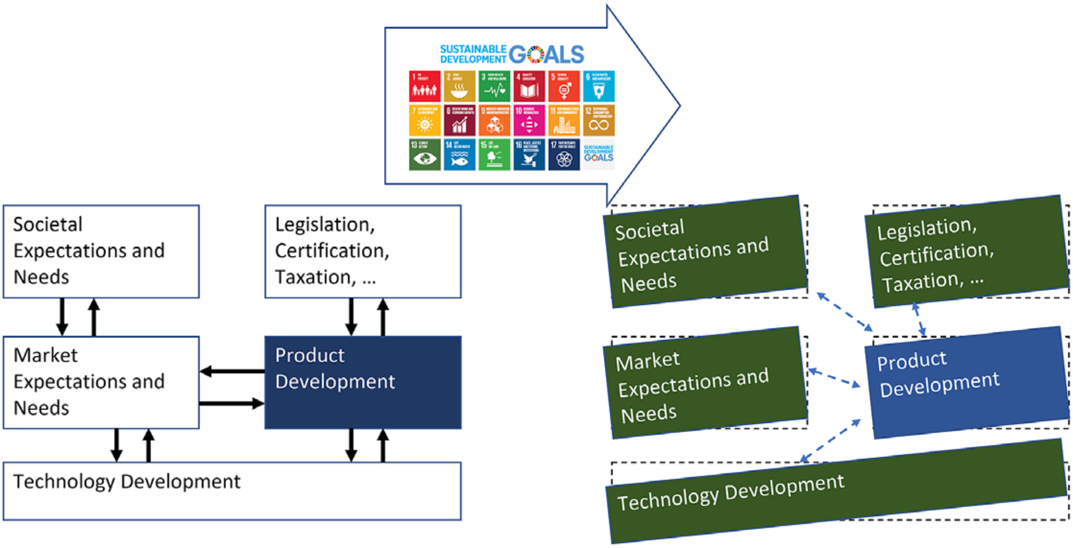

Figure 1. As conditions change, product development has to master new needs and utilise new technologies for new business models.

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 is consequently critical to include already in the early phases of product development.

The industrial challenges are significant. Established manufacturers need to develop new products that are provided in new business models, integrate new technologies from new domains, and adapt to changes in the market and customer behaviour, in addition to changes in regulatory and financial settings.

In a company, integrating sustainability aspects into product development is a complex task. This means: (i) developing solutions that benefit from new technologies, that is, new to the company and the market with a high sustainability potential; (ii) developing business models and solutions that cover the product life cycle, that is, from material acquisition to end of life, and its value chain, that is, the stakeholders and actors in the product life cycle and, (iii) managing and mitigating the risk associated with new technologies and new business models.

1.2. Sustainability challenges for aeroengine manufacturers

The aviation industry is estimated to be responsible for approximately 3.5% of the contribution to global greenhouse effects (Lee *et al.* 2021). Over a period of several decades, the aero manufacturers have increased the efficiency that reduced emissions per km by 80% from 1960 to the present. From 1960 to 2018, the growth in air traffic grew from 109 to 8,269 billion km yr^{-1}, and CO_2 emissions increased by a factor of 6.8 to 1,034 Tg CO_2 yr^{-1} (Lee *et al.* 2021). This increase should also be seen

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together with the three-fold growth in population and the role of air transport for globalisation and economic development.

At present, the IATA, representing the member airline companies, have committed their targets to reach a net-zero strategy for 2050 (IATA 2021). By 2050, the airline business expects that their part of the 1.5°C target will be met to 65% by the use of sustainable aviation fuels (SAFs); 13% by new technologies, electric and hydrogen; 3% by infrastructure and operational efficiencies; and 13% by offsets and carbon capture. For aerospace manufacturers, SAF has gained the most attention for long-range air transport as it provides equal energy density to currently used jet fuels. Sustainable production of SAF in large quantities remains a challenge. For short- and medium-range air transport hydrogen and various hybrid-electric propulsion solutions with lower energy density (than Kerosene and SAF) are being developed. These require a significant shift in aircraft and engine architecture as well as changes in interfaces to air transport infrastructure. Pure electric air transport is expected to have a small market share for small- and short-range transport due to the limitations in current, and foreseeable, energy density of batteries. For a review of alternative pathways to reach net-zero targets in avionics, see, for example, Vardon *et al.* (2022).

In Europe, the agenda for how to meet the aggressive net-zero 2050 visions (Clean Aviation 2021, p. 12) states that "Transforming aviation towards climate neutrality will require an integrated approach spanning technology providers and innovators, manufacturers and operators, public sector authorities and travellers", and "Transforming from the current, entirely fossil-based kerosene fuel-powered system to such a future aviation system with multiple energy carriers and architectures constitutes a massive and systemic challenge". Besides the dominant focus on dramatically reducing the contribution to GHGs, the business is also taking actions to meet the expected increase in legislation when it comes to chemical substances and materials.

The strategic research and innovation for aerospace in Europe are expected to require disruptive technologies in many different areas such as aircraft configurations, engines, infrastructure, materials, digitalisation and IT systems (Clean Aviation 2021). In the United Kingdom, the Jet Zero Strategy has recently been published as a similar strategy for the UK industry in order to decarbonise aviation until 2050 through rapid technology development (Department for Transport 2022). In addition to the 2050 visions, it will require targeting the near-total use of recycled materials and the ability to remanufacture, repair and recycle products and materials using circular economy methodologies. Lately, following the COVID-19 pandemic effect, it has become evident that society's sustainability challenges are not limited to only climate impact. The COVID-19 pandemic affected the aerospace industry with a dramatic decrease in flight hours due to flight delays, supply delivery issues, and loss of competences amongst aviation businesses, which then showed clearly the industry's sensitivity to such societal changes. To understand better the vulnerability to social conditions that influence market development, material prices and transport, there is a need for social sustainability considerations. In general, this includes a better understanding of how to avoid structural obstacles for people to meet their needs, and concretely to the aerospace industry it means, for example, to avoid conflict minerals and how to create a conscious and ethical supply chain.

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1.3. Purpose and aim

The purpose of this article is to argue for a transformation to sustainable product development (SPD) and analyse compiled research results based on over 10 years of experience of an aeroengine manufacturer. The article presents different key example areas affected by sustainability transition, that is, technology and materials, business transition towards sustainability, and, disruptive technologies and product realisation, undertaken at GKN Aerospace Engine System (GKN AES).

The aims are: (i) to address critical challenges and opportunities awaiting not only the company but likely also other manufacturers in the aerospace industry, and (ii) to contribute to practice in how to transform product development capabilities to enable SPD and identify how disciplines are mutually dependent. In addition, this research investigates the research question: What are the key factors for successful implementation of sustainability research in the product innovation process? This inquiry demonstrates the importance of long-term collaboration between industry and academia.

The next part of the article, Section 2, clarifies the concept of capability and includes a proposed definition of SPD capability. In Section 3, the method is presented, and Section 4 describes three different examples of key areas affected by sustainability transformation at the company. In Section 5, the main activities and contributions to a sustainability transition from collaboration projects between academia and practice are presented, and Section 6 present wider expectations of sustainability transformation. A concluding discussion and proposed answers to the research questions are then found in Section 7.

2. Sustainable product development capabilities

In the challenge to provide sustainable solutions, it is expected that product-developing companies need to simultaneously address new types of needs and integrate new types 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, SPD capabilities.

The capability notion is used in several contexts. Capability maturity was described in the software field in the 1980s through the capability maturity model (CMM; Humphrey 1988) with the purpose to assess the ability- and quality level of an implementation process of a software project. Maturity models, in general, aim to identify and prioritise challenges, and can be used as a benchmark for comparison, and in this sense support the understanding of making improvements. With this model, a better understanding of an organisation’s ability to produce required outcomes, based on its behaviours, practices and processes, can be achieved (Mettler 2011). Capabilities have further been described as “*complex bundles of skills and accumulated knowledge, exercised through organizational processes, that enable firms to coordinate activities and make use of their assets*” (Day 1994). Further, Day (1994) means that capabilities are the mechanisms and processes by which new competences are developed, and that makes it possible for wished activities to be carried out.

In a more recent study about prioritising resources and capabilities along the supply chain for circular plastic packaging by Stumpf, Schöggl & Baumgartner (2023), several types of capabilities including different aspects of human capital

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resources and organisational capital resources, central to a circular economy transition, are presented. Examples are operational capabilities, strategic capabilities, network capabilities, business analytics capability and ecodesign capabilities. Each specific capability has a certain definition. For example, in Galván, Casman & Fisher (2022), "innovation capability" is defined as a function of foundation skills, professional competencies and hypothesised innovation skills, that is, define the opportunity, discover the ideas, develop designs and demonstrate feasibility. In Morita & Machuca (2018), product development capability is described as three key areas to include in product development, that is, supplier involvement, customer involvement and manufacturing involvement, in addition to a cross-functional front-end loading in new product development.

The importance in building product development capabilities is evident from, for example, Saranga *et al.* (2018) and Wallin, Parida & Isaksson (2015), which means that product development leads to competitive advantage and value-added performance. Further on the authors state that in order to develop product development capabilities in-house research and development (R&D) is necessary. In-house education and training is also key activity to increase the capability for SPD. SPD is here defined as when a strategic sustainability perspective is integrated and implemented into the early phases of the product innovation process, including life-cycle thinking (Hallstedt & Isaksson 2017). To have a strategic sustainability perspective, a framework for strategic sustainable development (FSSD) can be applied (Broman & Robèrt 2017). This FSSD builds on backcasting from overarching socio-ecological principles for sustainability, which define the boundary conditions. According to Schulte & Hallstedt (2017), the main building blocks for SPD capabilities are support tools and methods, routines and practices and commitment and shared understanding of sustainability and SPD. In Table 1, definitions of capabilities are summarised. In this study, we define SPD capability 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 SPD tools developed are one of the key elements to bridge the gaps and challenges identified for integration of sustainability into the early phases of technology and product development (Hallstedt, Thompson & Lindahl 2013), and thereby a key element to build SPD capabilities. One of the main challenges is related to the breadth and complexity of sustainability (Broman *et al.* 2017), which leads to a risk of suboptimisation and long-term sustainability consequences (Byggeth Sophie *et al.* 2007). The second challenge is the limitation of time and of data availability in the early design stages to analyse sustainability in a rigorous manner (Ullman 1992), without compromising the completeness of sustainability or the product life cycle (Schöggl, Baumgartner & Hofer 2017). The third challenge is that there is difficulty in assessing and communicating sustainability to designers and engineers. This may be mainly due to the problem of showing numbers and 'hard facts' related to the value generated by sustainability-oriented decisions (Hallstedt, Bertoni & Isaksson 2015). These challenges indicate the need for methods and tools that ideally meet the following characteristics: cover a complete sustainability life cycle perspective and value chain, support in avoiding suboptimisation and rebound effects, can be applied in early phases, manage trade-offs, measure sustainability and, relate to risk and value creation. In other words,

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Table 1. A summary of capability explanations

Term	Explanation	References
Capability	The ability to do something. The physical or mental power or skill needed to do something. The ability to control people and events.	Cambridge Dictionary 2023
Capability maturity	The level of ability and quality of an implementation process. The level of ability to produce required outcomes.	Humphrey 1988; Mettler 2011
Capabilities	Complex bundles of skills and accumulated knowledge, exercised through organisational processes that enable firms to coordinate activities and make use of their assets.	Day 1994
Innovation capability	A function of foundation skills, professional competencies and innovation skills.	Galván *et al.* 2022
Product development capability	Consists of: supplier involvement in product development, customer involvement in product development, manufacturing involvement in product development and cross-functional front-end loading practice.	Morita & Machuca 2018
Sustainable product development capability	Consists of: support tools and methods, routines and practices and commitment and shared understanding of sustainability and sustainable product development.	Schulte & Hallstedt 2017

methods and tools, already in the early design stage, should highlight how a sustainable design choice can create value for customers and other stakeholders. A more sustainable design choice can result in resource-efficient solutions throughout the product life cycle, and may generate market success in both the short term and in the long term. However, even though more than 600 tools related to SPD have been developed (Schäfer and Löwer, 2021), companies are struggling with implementation and the uptake in the industry remains low (Peace *et al.* 2018). In many cases, the sustainability implementation is challenging, due to the low usability of existing tools (Schäfer and Löwer, 2021). Also, many tools lack a strategic perspective, that is, the requiring of system thinking, long-term and backcasting views, to consider the time spectrum in the planning process, the interaction of the complete system and the three dimensions of sustainability: environmental, social and economic (Villamil and Hallstedt, 2020).

To enable design teams to be more innovative, support tools are developed to be used to organise and perform an application of a method or guideline (Gericke *et al.* 2020). Gericke *et al.* (2020) further mean that academia, therefore, needs to learn from industrial practice of methods and tools to understand what methods that need to be refined, or what new methods are needed, to complement the existing ecosystem of engineering design methods at the companies. Thus, the support methods and tools developed from sustainable design research should be adapted to users to increase accessibility and usability, but in addition to supporting incremental changes, also improve the capacity for radical and revolutionary socio-ecological solutions (Bhamra & Hernandez 2021).

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3. Method

This article is based on a longitudinal case study (Åhlström and Karlsson, 2010) with a focus on one company, GKN AES, and its sustainability journey that the researchers and the R&D company team have followed and been part of for over 10 years.

The GKN Aerospace Engine System is an aeroengine component manufacturer that services approximately 90% of the world's aircraft and engine manufacturers on 100.000 flights every day. The technologies are used in large passenger planes, single-aisle aircraft, business jets and fighter aircrafts. The GKN Aerospace Engine System is one of three GKN Aerospace divisions, alongside aero structures and special products. The Engine System has approximately 4,000 employees worldwide whereof 2,000 at the headquarters in Sweden (15.000 in GKN Aerospace).

R&D is a large part of their business. The company works on a long-term basis with universities and research institutes and the company has around 50 PhD students in various research projects around Sweden. The aviation industry faces major challenges in the future, not least environmentally, where their lightweight technologies contribute to reduced fuel consumption and thus lower emissions. The technologies they develop are often linked to advanced manufacturing technology and can reduce the weight of engine structures by 15–30%. The company finds itself within a conservative industry due to its regulations and long-term development processes, and it is, furthermore, a relatively large company. This context makes it difficult for an easy transformation of changes. However, slow but systematic changes have been made and documented during the years.

This article shows an overview of the sustainability journey in retrospect and some step-by-step progression of how academic results within the field of sustainability in design have been implemented in practice. Several different research projects with the company have been compiled into a table (see Table 2) and sorted by time periods including the purpose of the project, funders and main academic contributions. The research projects were formed towards certain focus topics, relevant for the SPD area, and with the aim to contribute to increased capabilities in companies – to develop value-created sustainable life-cycle solutions and support in the transformation towards sustainable design.

The company R&D team collected and summarised the main activities and contributions at the company from the research projects, while the research team collected the main academic contribution at the same period of time. This compiled data constitutes the base for an analysis to argue for a transformation to SPD.

Three different examples of key areas affected by sustainability transformation at the company, that is, (i) technology and materials, (ii) business transition towards sustainability, and (iii) disruptive technologies and product realisation are analysed and discussed to address critical challenges and opportunities, and, to contribute to practice in how to transform product development capabilities to enable SPD and identify how disciplines are mutually dependent.

In addition, this work demonstrates the importance of long-term university–industry collaboration. Even if this sustainability journey was not a planned process, learnings from implementing research in general and sustainability research in particular into product development were found. Key factors are

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Table 2. From a 10-year period of collaboration, new support tools for sustainable product development have been developed

Time period	Main activities at the company/main contribution at the company	Main academic contribution
Until 2006	Product strategy to develop lightweight products to meet global CO_2 challenges, and developing capabilities for product-service systems development, strategic priority to systematically collaborate with academia.	Developing design and manufacturing technologies for reduced product weight (Runnemalm, Tersing & Isaksson 2009). Systematised strategic university collaboration (Wallin *et al.* 2014; Isaksson 2016). Models for PSS development (Isaksson, Larsson & Rönnbäck 2009; Wallin *et al.* 2015).
2006–2009	Investigated the current level of sustainability integration in the product innovation process. / An understanding of current challenges and possibilities for a strategic sustainability perspective in their product development innovation process.	An approach to assessing sustainability integration in strategic decision systems (Hallstedt *et al.* 2010). Key elements for implementing a strategic sustainability perspective in the product innovation process (Hallstedt *et al.* 2013). Capability development for product-service systems development (Wallin *et al.* 2015).
2009–2011	Application of a new SPD method including a strategic sustainability assessment and simplified life-cycle assessment. / A major change of a design decision, based on the findings from the SPD method, regarding a manufacturing process.	Assessing sustainability and value of manufacturing processes: a case in the aerospace industry (Hallstedt *et al.* 2015).
2010–2013	Workshop activities with actors in the value chain to identify future challenges in the life cycle. Material criticality assessment (MCA) method was developed from participation action research. / The MCA method was implemented in the company's technology readiness assessment method to support material selection in early design stages.	MCA in early sustainable product development (Hallstedt & Isaksson 2017).
2011–2013	Investigations of current measures to integrate sustainability in the product innovation process. Training sessions at the company. / A sustainability design space to give guidance on the most important sustainability criteria identified for the company, to be integrated in the technology readiness assessment method.	Sustainability criteria and sustainability compliance index for decision support in product development (Hallstedt 2017).

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Table 2. Continued

Time period	Main activities at the company/main contribution at the company	Main academic contribution
2013–2019	In co-production mode developed a user-friendly support method for sustainable product-service system innovations. / A first prototype of a model-based decision support for value and sustainability assessments was integrated with the company's engineering models.	Model-based decision support for value and sustainability assessment: applying machine learning (Isaksson *et al.* 2015), (Bertoni *et al.* 2020).
2015–2020	In close collaboration between academia and practitioners, including workshops, activities and case studies, evaluate support tools for sustainability integration in the early phases of the product innovation process. / Concrete support tools available to apply and integrate on different levels in the company to add value and avoid potential business risks.	Company risk management and sustainability (Schulte & Hallstedt 2018a). Sustainability product portfolio (Villamil & Hallstedt 2021). Sustainability in product requirements (Watz & Hallstedt 2020).
2018–2022	Close collaboration and co-production, including workshops activities and action research, for how to create a base for developing a digitalised implementation package. / A methodology and interconnected methods and tools to systematically integrate and implement sustainability in the product development process.	Digitalisation, sustainability and servitisation – the need of future product development capabilities (Hallstedt, Isaksson & Öhrwall Rönnbäck 2020). Support tool for sustainability risk management in concept development (Schulte & Knuts 2022).

identified and discussed if applicable also in short-term collaborations for a faster implementation journey.

4. Key areas affected by sustainability transformation

It should be evident that areas affected by sustainability transformation cannot readily be delimited. In addition, as a part of the complexity, they are intertwined. In the following sections, we discuss three areas of significance, on three different levels of granularity. In Section 4.1, the technology is placed in focus, and since GKN Aerospace is a manufacturer of advanced structural aeroengine structures, the focus is on advanced materials and advanced manufacturing processes. In Section 4.2, the focus is on the business models, partially enabled by the technologies discussed in Section 4.1 but focusing also on the design of life-cycle solutions. Finally, in Section 4.3, the view is on how to bring novel technologies into products and production processes and the section addresses ways to deal with new uncertainties and risks.

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4.1. Example: AM technology and critical materials

Gas turbines have been developed to utilise higher temperature and pressure to realise higher thermodynamic efficiency, something that has been possible through materials development, cooling designs and changes to the gas turbine engine as such. As product weight penalises fuel efficiency, seeking lightweight materials is a parallel track to enable a lower fuel burn. In aerospace, benefitting from advancement in material technologies, material selection has been a prime focus since the beginning of flight, seeking ever lighter and more durable materials. Over the last decades, the always-present focus on improving structural and thermal performance to a low weight has also been complemented by a growing attention to the availability and life-cycle cost of materials (ACARE 2012; Lloyd *et al.* 2012a). The combination of utilising higher temperature and lightweight materials comes with some challenges, such as material criticality. The scarcity of material elements is one obvious aspect of criticality, but there is also a social dimension to their criticality. The developed nations have been increasingly dependent upon imported materials from less stable supplying regions; some nations' policies have the potential to disrupt the operations of global markets; there is a clear recognition of the combined social and environmental consequences from extracting some raw elements; and, there is a trend of concentrated production sites for some elements creating supply monopolies (Moss *et al.* 2011; European Commission 2014). There is an increased importance for industry to understand when these materials are defined as critical and how materials can be assessed regarding their criticality (Glöser *et al.* 2015). In 2011, the aerospace industry formed the International Aerospace Environmental Group (IAEG 2016) as a means to jointly address and promote sustainability standards and agreements in the business. Accordingly, several recently published articles deal with the availability and criticality of materials (Speirs, Houari & Gross 2013; Sonnemann *et al.* 2015). Various terms, definitions and assessment methods in the field of material criticality are summarised in the review article by Sonnemann *et al.* (2015). A more recent approach is presented in a work conducted at GKN AES together with researchers (Hallstedt & Isaksson 2017). In this work, a material is defined as critical if a company becomes dependent on a material with availability limitations, and/or initiates activities that cause socio-ecological sustainability consequences in the supply chain, that is, raw material extraction and the pre-production phase. If the desired material composition contains any material that may become critical, there is not only a business risk for the manufacturer but also a risk for increased socio-ecological consequences upstreams at suppliers. Limited material availability will increase the material price and a high environmental impact will potentially cause stricter legislation. There are negative consequences of being dependent on such materials and this is a business risk that will threaten profitability, described as "environmental business risk" by Lloyd *et al.* (2012).

In the last few years, the growth of additive manufacturing (AM) has been exponential in the aerospace industry. One of the reasons is that AM technologies possibly will be part of the solution to two large challenges that the manufacturing industry is facing, namely (1) reducing fuel consumption and (2) reducing material waste (OECD 2017). These challenges are not only about the reduction of costs but also about sustainability improvements. High expectations are set on these new technologies, but they also have sustainability challenges (Tang, Mak & Zhao 2016)

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There are many benefits with the AM technology, such as freedom of design, customised design, high shape complexity (Ford & Despeisse 2016), improved and stronger structures with fewer materials (Griffiths *et al.* 2016), a wide range of materials used for low volumes (Thompson *et al.* 2016), adaptable design in a short period of time (Paris *et al.* 2016) and reduced weight (OECD 2017). Various types of AM technologies have been developed over the past decades, for example, powder bed (PB), that is, powder is spread out and a welding source melts the desired powder before another layer is spread, and direct energy deposition (DED) also known as metal deposition (MD), that is, powder or wire is fed into the welding source and melted into the desired shape. Both PB and DED/MD can use different welding technologies and the AM technology is named thereafter. Electric beam melting (EBM) is a PB technology using electric beam welding, and laser powder bed fusion (LPBF) or selective laser melting (SLM) is a PB technology using laser welding.

Depending on the requirements of the product, one AM technology might be more suitable than another to manufacture a specific product due to, for example, material, shape, function and so forth. Sometimes certain AM technologies might not even be possible to use, because of technical limitations, or material requirements. In a study conducted at GKN AES together with researchers, a sustainability assessment of some selected AM technologies identified some issues to solve regarding value-chain management, concept design, optimised material usage and social sustainability (Villamil *et al.* 2018).

4.2. Example: Business transition towards sustainability

Several collaboration projects in the European aerospace industry, for example, the EU-funded collaboration project Clean Sky 1 (2008–2016) and its successor Clean Sky 2 (2014–2020) have delivered technologies that reduce CO_2, NO_X and noise (Atkinson, Pfeiffer & Doerffer 2017; Clean Sky 2 2021). This progression has resulted in high expectations on the aerospace industry, hence the Clean Sky 3 targets call for a more disruptive, integrated and multidisciplinary approach. Therefore, while the reduction of CO_2 and greenhouse gases is still in focus, the aerospace industry is expected to contribute also to the other SDGs.

One challenge is that aircraft and aircraft engines are costly and technologically advanced to design, develop and produce, and so the partners collaborating in the business need to work well together. Technologies are often introduced on component and subsystem levels, yet have their anticipated effect on a system level, for example, blade aerothermal efficiency that impacts fuel consumption. Also the design of static components influences the system-level performance (Samuelsson *et al.* 2015). The interest in providing functionality, performance and aircraft availability as already impacted the aeroengine business logic, with the well-known “total care” and “power by the hour” concepts by Rolls Royce (Harrison 2006).

Design methods that can include how to best provide safe, reliable and environmentally efficient solutions also for component and subsystems providers, for example, through repair and remanufacturing strategies, have raised interests to include these aspects in the decision process (Lawand *et al.* 2020). In line with strategies and plans towards a more circular economy (European Commission 2020), new manufacturing technologies are needed which at the same time can create new business opportunities in the aerospace industry.

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With MD technologies, another AM technology, material is added onto finished (or used) products where needed, either to repair damages or to add functionality. This gives the opportunity for a greater life-cycle perspective where the manufacturer not only sells a finished product but also repairs, re-remanufactures and upgrades these products, using the same technologies. As MD technologies can be used for both manufacturing and repair, the same technology can be used in various stages of a product's life cycle, giving the manufacturing technology a greater role in the business of the product. One case at GKN AES is a product where the life expectancy of an already produced part was discovered to be too short. Rather than scrapping numerous components, the MD technology made it possible to just add material on already produced parts which successfully increased life expectancy. This is just one example of how new manufacturing technologies pave the way for a circular economy, new business opportunities and drastic reduction of waste material.

4.3. Example: Disruptive technologies and production realisation

For delivering new disruptive technologies, there is on the one hand a conflict with producing new technologies with a higher degree of uncertainty, and the aerospace business focus on flight safety which is conservative when handling risk. A recent example is the concept of zero defect in the aerospace business (Riggs 2018). This zero defect concept is product-related to the need for robust design and robust manufacturing where high-performing processes and clear definitions have to be chosen according to aerospace standards for the application and implementation of risk analysis, for example, AS13004, AS13100 and AS9145. High-performing standard processes, that is, processes that are under statistical control, as well as a product definition that handle the manufacturing and service needs, have to be regarded. In a classical sense, this is achieved by following a process and product for a long time, where corrections and removal of failure causes are continuously performed. A multidisciplinary design approach is used, where objectives are evaluated by contributions from several disciplines, for example, sustainability, finance, performance and manufacturing. When these objectives are traded against each other in a design risk analysis more conscious decisions can be made, in which also robustness is included (Schulte & Knuts 2022).

Generally, risk management is much related to the planning and handling of uncertainty. The challenge for all organisations today is how to develop new technologies with low uncertainties. At GKN AES, a technology maturity process is applied for technology- and concept development projects, and at each technology readiness level (TRL1–TRL6), the projects are reviewed and assessed against certain criteria. In the TRL assessments, checklists contain, for example, sustainability compliance and sustainability performance criteria. As the maturity increases the uncertainty is lowered, and at TRL 6, the technology is ready for industrialisation.

The systemic nature of a full sustainability perspective further requires decision support to take multiple disciplinary factors and perspectives into account simultaneously. Doing so in the early phases of design and development, therefore, require multidisciplinary modelling and simulation support, often in combination with automation technologies to generate necessary information. GKN AES has for

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decades worked on design automation, generative design and multidisciplinary decision support (Sandberg *et al.* 2017; Al Handawi *et al.* 2021).

Finally, the ability to capture and formulate the value of sustainable solutions has been a bottleneck. Historically, investments in sustainability measures have been seen as a non-value-adding necessity, and consequently a cost. There is now a clear customer value in sustainable solutions as well as a cost-saving perspective to invest in sustainable solutions for manufacturers. The ability to develop a solution with a clear value focus is another asset that GKN AES has worked on for the last 15 years.

5. Experiences of GKN AES's sustainable product development journey

The sections below present the main activities and contributions from collaboration projects between academia and practice, showing an interdependency to make progression in the field. The objective for these projects was to contribute to increased capabilities to develop value-created sustainable life-cycle solutions and create support in the transformation towards sustainable design.

5.1. Systematic collaboration for sustainable product development

Companies may have various obstacles in developing sustainable product design and production systems, such as unclear communication and priority from management, difficulties in easily identifying the most important sustainability aspects, weighting of sustainability aspects in relation to other design parameters to provide optimal value and so forth The R&D team at GKN AES has therefore over a 10-year period systematically collaborated with academic researchers in the field of SPD with the purpose to develop relevant tools for different organisational levels, that is, strategic, tactical and operational levels, and needs in the company.

In Table 2, the main activities and contributions at the company from different time periods of projects are presented, together with some main academic contributions and new tools.

One important factor for building approaches, methods and decision support tools through academic and industrial collaboration is to simultaneously address both strategic, tactical and operational levels in the organisation (Wallin *et al.* 2014). At the strategic level, the company goals and strategies are formulated. The SPD tools relevant on this level are for those that take management decisions, plan the strategic direction of the company, decide about overall company and product goals, and do long-term strategic planning. Examples of tools developed for this level have the purpose to identify short- and long-term sustainability criteria (e.g., Hallstedt 2017), and evaluate and assess the portfolio from a value and risk perspective (e.g., Villamil, Schulte & Hallstedt 2022).

At the tactical level, the targets for the concepts are decided. The processes for how to improve in order to integrate and implement sustainability in the innovation process are decided and managed at this level in the company. The SPD tools relevant on this level are for the people who have the responsibility to update the innovation- and development process, integrate new aspects and provide design teams with support and directions in concept development, assessment, evaluation

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and selection in the decision-making process. Examples of tools developed for this level have the purpose: to give guidance of sustainability integration in the requirement process (Watz & Hallstedt, 2020), and to define and manage "what to do when", based on sustainability risks and performance (Schulte & Hallstedt 2018a; Schulte & Knuts 2022).

On the operational level, the concept of solution development, evaluation and assessments take place to meet the targets and goals decided on the strategic level and that meet the expectations of different stakeholders. The SPD tools relevant on this level are for those who do the development, the assessment, the evaluation and the selection of concepts, which means teams that take decisions in the day-to-day engineering environment. Examples of tools developed for this level have the purpose to identify, define, model and evaluate design concepts and refinements in the sustainability design space (e.g., Bertoni *et al.* 2020; Kwok, Schulte & Hallstedt 2020).

5.2. Development phases in the sustainability journey at GKN AES

At the start of the sustainability journey at GKN AES, while focusing on contributing to CO_2 reduction through low-weight products, the wider sustainability work was reactive and concentrated to a small group that worked mainly on handling chemicals in production due to new legislation of customer requests (Hallstedt & Nylander 2019). As the work continued it became more preventive focusing on the whole product life cycle, with the aim to improve corporate image and reduce costs, which lead to a greater awareness of short- and long-term perspectives. Later, the work became proactive to avoid potential future problems and the awareness of the sustainability effects from early design choices grew. In 2017, GKN AES got a sustainability reward from one of their most important customers, Pratt & Whitney, for their work with sustainability. This was an important stepping stone, where the company received evidence that sustainability is a customer value that needs attention. This set the company into a new phase, the systematic phase. The company started working continuously with sustainability development, incorporating it in the corporate culture to ensure that it is not dependent on specific individuals. The work is not only focused on avoiding future problems but to ensure future business success.

The current phase, the visionary phase, reveals a backcasting perspective on the sustainability work, which is much needed for the immense task of becoming net zero. As sustainability has received more attention in society; it has also received more attention from the company. The long-term goal of becoming a "net-zero greenhouse-gas-emissions-business" before 2050 has led to investments in, for example, disruptive technologies such as electric and hydrogen engines, renewable energy sources and life-cycle assessment capabilities. The current vision of the company is to become "the most trusted and sustainable partner in the sky", which is supported if SPD is implemented fully on all organisational levels.

The focus has changed from specific problem solving to general problem solving. The driver for more SPD has changed from external drivers, such as customer requirements and legislations, to internal business drivers to provide increased customer value in the form of more sustainable manufacturing/technology solutions. The awareness has changed from a specific group to a general awareness across disciplines and from a short-term perspective to a long-term perspective (see Table 3). The sustainability responsibilities have changed from

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Table 3. The sustainability journey at GKN Aerospace Engine System

	Reactive phase	Preventive phase	Proactive phase	Systematic phase	Visionary phase
Year	2006–2009	2009–2013	2013–2017	2017–2020	From 2020
Focus	Chemicals	Product life cycle	Critical materials	Continuous sustainable development	Sustainability vision and disruptive innovations
Driver	Legislation customer request	Corporate image reduction of cost	To avoid potential future problems	Future business success	Business success
Awareness at GKN AES	Awareness of sustainability within a certain group.	Awareness of short- and long-term perspectives.	Awareness of the effect of our choices in early design phases.	General sustainability awareness across disciplines (culture).	Sustainability is critical for business.
Skills	Able to take responsibility for all chemicals in the production.	Able to make simplified sustainability assessment of product life cycles.	Apply new support tools to guide decisions that will have large effects on the solution's sustainability profile.	Develop a systematic approach to implement relevant tools and methods for SPD.	Continuously refine, develop and advance the implementation of SPD with a backcasting perspective.

specific responsibilities to general responsibilities, independent of the individual ones.

In retrospect, it is possible to distinguish a number of development phases that the company has gone through during this period of time. This collaboration period between academia and industry has led to increased awareness among a few people at the company which in turn has permeated the entire company and become business critical. The projects have not only contributed to increased awareness at the company but also increased skills and capability for SPD.

6. Wider expectations on sustainability transformation

The industry-negotiated strategies in Europe (Clean Aviation 2021) and the UK (Department for Transport 2022) outline measures necessary to meet the 2050 greenhouse-gas-emission targets. However, this is not enough for a sustainability transformation, the aerospace manufacturing industry will also need to meet other goals expressed in the European Union's Green Deal (European Commission 2019). One such area is resource use, where circular economy solutions and legislative measures are central. A fundamental challenge, however, is how to succeed with radical and disruptive changes while maintaining the high safety standards of today, because aviation safety has practically limited the possibility of introducing too radical solutions in the business in the past.

Following the description of three key areas affected by sustainability transformation, recommendations are proposed on directions for transforming product development capabilities to enable SPD for the aerospace industry.

6.1. Technology and materials

The evolutionary development of increasingly advanced and high-performance materials has brought advanced materials that are difficult to manufacture, remanufacture and repair. Two major changes are seen. One is the shift in business models (see Section 6.2) and the other one is the shift in system architecture for aircraft propulsion (see Section 6.3) driven by decarbonisation targets. Materials and manufacturing technologies that enable repair, remanufacture and even reuse increase in importance since such measures address the value of materials in circular solutions. Circular solutions need to be designable and possible to certify for aerospace applications. As an example, AM can be used to improve structural integrity of already produced parts (Al Handawi *et al.* 2021) as a repair and remanufacturing strategy. The ability to change the design after its certification is however limited and should be included already in the design and certification phase. Other solutions, such as life extensions using sensors for condition monitoring can be difficult to certify due to high safety standards. The shift in focus from performance to sustainability impact implies that the historic priority on more efficient products as drivers for development is complemented with more strategic sustainable development.

Recent research at GKN AES provides examples of designing and optimising re-manufacturable design solutions supporting circular business models (Al Handawi *et al.* 2021) that make use of AM technologies for repair and remanufacture. To further promote materials development, circular business

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models for "end of life", for example, disassembly, repair, remanufacturing and reuse are becoming increasingly important.

6.2. Business transformation towards sustainability

Since the business value of providing sustainable solutions has radically increased, it is necessary to understand the link between technologies, processes and business models. The aerospace propulsion business has already established life-cycle-oriented business models, for example, total care and product-service systems development capabilities. As such, aerospace engine manufacturers have already experience with life cycle business models. Circular solutions need to be formed in the design phases of development (European Environmental Agency 2017). The material content for every component in service needs to be known down to the level of alloy content and their origin need to be traceable. This also opens up business opportunities, since there will be an increased value of material resources due to raw material availability limitations (Hallstedt & Isaksson 2017). Consequently, several authors have identified the potential for circular economy in aerospace (Gialos *et al.* 2018; Dias *et al.* 2022).

Product development relies on the ability to understand needs and evaluate the impact of alternative solutions early. To design sustainable solutions, criteria for sustainable design need to be possible to formulate, to capture and to use for decision-making. It is, however, 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. Challenges that remain in the near future for a business transformation towards sustainability are:

(i) Base business models on increased life-cycle responsibility of manufacturers and suppliers in the value chain.
(ii) Develop criteria for sustainable design and guidance for sustainability performance.
(iii) Strengthen the ability to manage and trace sustainability data in early design phases.
(iv) Establish digital sustainability implementation platforms to enable a focused strategic, tactical and operational support for SPD.

6.3. Disruptive technologies and product realisation

Radical technological changes are underway on both the system level (new propulsion systems) and on the component and materials level (see Section 6.1), which increases the need to account for new factors in development. In order to successfully integrate innovative solutions at the subsystem and technology level with new system architectures, an ability to innovate across system levels in the value chain is needed and includes new suppliers in the design integration effort.

A number of factors are highlighted here:

(i) The necessity to integrate new technologies into new system-level architectures.

This requires an increased ability to co-design systems and subsystem-level solutions through the supply chain. Already today, the design of subsystems and components, typically done by tier-one partners and the system-level design are tightly coupled. Loads, constraints and interfaces are defined in whole engine

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models (WEMs) that are based on the component design and behaviour, that is, coupled system. Such iterations are time- and resource-consuming iterations already, and which need to explore an even greater variety of architecture and technology.

(ii) Explore, design and evaluate new design solutions.

Novel designs, using new technology, require typically physical testing to reduce risk. Such tests are eventually conducted in large-scale demonstration programs of new system architecture, normally led by OEMs and integrators, together with partners in the value chain who contribute with novel technologies. To maximise learning, the test to failure strategy can be used to find limits and margins for the solutions, for example, Petroski (2018) yet the latest decades of development have been to minimise the use and cost of physical testing in favour of virtual testing and simulations. Virtual testing relies on the fact that underlying behaviour is well understood, which may not be the case for novel technologies. Strategies to make increased use of combined digital and physical data, such as Digital Twins, need to be used also during development (Panarotto, Isaksson & Vial 2023).

(iii) Design robust and resilient multidisciplinary solutions.

By including the multidisciplinary view, including technical functionality, manufacturing, material, maintenance and other critical criteria including sustainability aspects, the chances to make changes and future upgrades are significantly improved. Sustainable solutions need also to be better at handling uncertainties of the future, that is, be resilient. Robust design methods need to be extended to include uncertainties and margins related to sustainable solutions and variability.

(iv) Ability to identify and manage risk.

Introducing new technologies in new architectures, and also solutions that include alternative life-cycle strategies, increases risk. It becomes more important to work closely on a system level, which requires partnership between OEM and supplier, and the need of identifying risks and controlling risks, by mitigation and communication of the risks in terms of criticality. The ranking scales used in the risk analysis have to be further developed to handle the sustainability risks, for example, reputational risk, regulatory risk, litigations risk, as well of the perspective that should be long term instead of short term. The long-term perspective is necessary when questioning technical concepts on the architectural level. These aspects of sustainability risk management have been developed further by Schulte (2021) and a sustainability risk management tool is described in Schulte & Knuts (2022). The failure mode and effects analysis is one established method in industry to deal with risk. To be proactive to include sustainability risks already during design, a combination with multidisciplinary optimisation techniques is required.

(v) Ability to qualify and certify new solutions.

Proactive and close collaboration with regulation authorities, for example, EASA and FAA, is expected already in design phases to qualify and certify new design solutions. An example is provided by Dordlofva (2020) who suggests that improved qualification strategies for metal AM are needed to benefit from its potential. It can be argued that the need to develop new strategies and principles for certification of new technologies will require close collaboration also with certification authorities.

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6.4. Recommendations

Based on remaining challenges in the near future, recommendations are proposed on directions for business transformation towards sustainability and transforming product development capabilities to enable SPD for the aerospace industry:

(i) A business model development that builds on retaining the value of materials in use, that is, circular economy, and presumes the increasing of responsibility of the manufacturers and their suppliers from both legislation development and market expectations.

(ii) Strengthen the ability to direct product development by developing criteria for sustainability that offer both the search for new solutions and evaluation of sustainability performance of emerging and existing products.

(iii) Develop the ability to ensure traceability of sustainability governing data already from the design phases. This is driven by the increased value of resources through product life, and that legislative actions are foreseen in this direction in clarifying this value.

(iv) Establish digital sustainability platforms that allow the gathering of the multiple aspects of sustainability in a focused way. Especially the strategic, tactical and operational levels need a coordinated approach, which can support a coordinated transformation in an organisation.

(v) The ability to identify and manage risk already in design needs to be strengthened. As solutions become more complex, for example, building on life-cycle activities such as repair and remanufacture, there are new risk factors that need to be covered.

(vi) Develop and educate for a deeper understanding of sustainability amongst decision makers on all levels, from engineers to senior management and company boards.

For companies that are in a reactive phase and want to move on to a more mature sustainability phase and towards sustainability transformation, the recommendation is to assess the organisation's current capabilities in relation to key elements for the successful implementation of sustainability in the product innovation process, see, for example, Schulte & Hallstedt (2018b). Based on this assessment, a systematic improvement plan and a roadmap can be developed, with step-by-step measures needed to make progress towards increased SPD capabilities. To transform product development capabilities to enable SPD, it is also recommended to create a common view of an ideal sustainable solution for the company from a life cycle perspective. This step is described in Schulte & Hallstedt (2018c).

7. Concluding discussion

Aerospace manufacturers need not only to deal with radical changes in architecture and technology to meet net zero and decarbonisation of air transport, but they also need to develop skills and strategies for the wider implications of sustainability that address resources and social sustainability.

This article has presented how a manufacturing company, in this case, GKN AES, has addressed the sustainability transformation challenge and how thorough collaborative research initiatives with universities have worked to concurrently improve design and development capabilities. Universities can provide new

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knowledge and demonstrate new abilities, whereas the company needs to systematically drive the necessary change, over time, internally.

The described long-term transformation journey towards SPD is a process of change that is still ongoing at the company and which has been partly initiated by various challenges in several areas, such as new requirements for new technologies and materials; changing business models; and, adaptation to disruptive technologies with new risk management. However, a journey of change towards sustainable development needs to constantly handle the upcoming sustainability challenges in order for a company to become successful also in the future. From this longitudinal study, one can draw the conclusions that the main benefits of a transformation to SPD can be summarised as follows:

- increased ability to build knowledge in the area of sustainability;
- generally an increased awareness and common vision and understanding of the area at the company;
- ability to use new types of decision support methods and tools; and, also,
- preparing product development teams to become better equipped for upcoming challenges and take the lead in the development towards more sustainable solutions.

These capabilities in SPD are necessary as there are more challenges to come, such as the need to simultaneously welcome radical technology shifts without comprising flight safety and business risk. Sustainability requires a more holistic and systemic approach, where impact and consequence on a system level links to details in design and production. The life-cycle integration into design and development needs to be even more pronounced, and integrated into design and evaluation support. Making use of data from experiments, tests and in service, possibly using machine learning and data analytics to reduce risk, will be key to better include sustainability during design. The opportunities of sustainable technologies are evident, yet require (1) the means to tighter integrate business and technology development, (2) the ability to quantify and assess the impact of solutions from defined sustainability criteria, and (3) develop new means to utilise natural resources, alloys and materials for a circular and life cycle optimised solution. For companies not yet applying SPD practices, a systematic improvement plan, with step-by-step measures needed to make progress towards increased SPD capabilities is recommended as a first step. Also to create a common view of an ideal sustainable solution for the company from a life cycle perspective is recommended, with the purpose to clarify the current sustainability challenges and gaps to be addressed.

It is impossible to translate the benefits with an SPD capability into a precise quantitative metric that reflects the business value. But there are concrete examples, showing that GKN AES has got appreciation from both customers and within the GKN group, due to proactive work and the sharing of competence and concrete science-based decision support tools with other GKN sites. Manufacturing companies that want to follow the GKN AES's example should be prepared for the fact that there are different areas that are affected by a transformation to SPD at a company, which can produce a number of different consequences in product development. Table 4 summarises a number of transformation trends, which include several disciplines that need to increase awareness but also increase skills and capability for SPD. Companies that are prepared for these trends in a

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Table 4. Give an overview of some trends in sustainable transformation that affect product development at a company, with a number of different consequences

Trends in a sustainable transformation	Consequence in product development
Business transformation	Circular economy calls for development of optimised resource-efficient life-cycle solutions within the value chain.
Technology transformation	New technologies demand multiple domain contributions to integrate during design.
Market transformation	Shifting needs and preferences on markets and by customers require secure material resources and risk management due to, for example, scarcity and availability issues.
Climate transformation	A demand for a fast and update product portfolio including sustainable solutions that are novel and disruptive.

sustainable transformation are assumingly more likely to be the companies that will lead the market in the future.

The challenge facing the transportation industry in general and aerospace in particular will require a significant shift in products and technologies. Realising such challenges requires equally a shift in thinking, acting and the way of ensuring 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.

The transformation of a company's SPD capability requires a shift in several dimensions. The nature of sustainability as a design problem is highly multidisciplinary, and so the engineering and decision support tools need to be continuously developed and adapted, together with a change management and competence transition strategy that needs to be in place. In companies the philosophy, strategy and business rationale change over time, and therefore, a consistent sustainable development methodology is needed. From studying the SPD progression at GKN AES, it is now possible to propose a generic methodology with integrated tools and methods for the different organisational levels which can increase the ability to integrate and implement a strategic sustainability perspective in the product development process. In retrospect, we have also been able to learn and understand what challenges it entails from a user perspective to apply academic tools. The tools developed in the projects have often involved several other companies to ensure generalisability and scalability. However, few companies have been involved for such a long and continuous period as GKN AES. In collaboration with academia, GKN AES has selected some of the tools and adapted these to their own processes and toolbox. This selection, adaptation, and application work at GKN AES provides a basis for conducting a validation study and exploring the impact of the tools, which often requires more time than can be accommodated within a PhD- or a post-doc study. These long-term collaboration

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periods are therefore needed and show an interdependency to make progression in the field.

The sustainability implementation journey at GKN AES began over 10 years ago, and demonstrates the importance of long-term university–industry collaboration. Even if this sustainability journey was not a planned process, learnings from the implementing of research in general and sustainability research in particular into product development can be found. Key factors, described below, are identified as applicable also in short-term collaborations for a faster implementation journey.

Common understanding and openness. The more the product design teams participated and engaged in the activities and surveys, the more was the learning and usefulness of the research outcome for them, which was seen already in the preventive phase. The company also allowed an openness which meant that the researchers could spend as much time as needed at the company doing interviews, workshops, collecting data and so forth, and the researchers, therefore, were able to get a good understanding of the industrial situation and challenges. Specifically for sustainability research implementation was the importance of the continuous interactions, exercises, and regular presentations of the research results at the company that gave a good understanding in the product design team of what sustainability means, of the products' sustainability impact, of sustainability improvement potentials and of the current research being conducted. Based on this understanding, it became an incentive at GKN AES to include sustainability in early decisions regarding technology and product development, which according to, for example, Chiu & Chu (2012) can provide opportunities for enhancing product competitiveness.

Customisation and adaptability of tools and methods. Apart from previous research findings related to meeting the desired characteristics of support tools (Ahmad *et al.* 2018), a customisation of the support tools derived from the research to the company's specific needs is a key factor. This customisation process which took place in the proactive phase at the company should be led by the industrial partner to make it fit the current processes and tools at the same time as it is supported by the researcher to secure that the core of the support tool is not lost. This step-by-step process for tool delivery from research to practice, so-called scaffolding, is important for sustainability research implementation as it helps individuals at the company to feel confident, which leads to motivation for a change that is needed to include sustainability in a design project (Gould 2018).

Receiver in industry and in-kind contribution. To implement sustainability research in product development, companies need to have a receiver that can actively participate in the research project. It is important to have at least one person disposing of time and having responsibility in the company, a person who also has the interest, the knowledge, the ability to receive and implement the research results, and get it into the system for complete implementation. For GKN AES, the major influence on the transformation from preventative to systematic phase was this person as the understanding of where and how to implement each tool or method can be difficult for an external person.

Long-term and continuous collaboration. Sustainability might require large organisational changes on strategic, tactic and operational levels, and thus, it is a long-term journey. Continuous collaboration creates trust between people and it is important that the industry is involved from the beginning in the creation of the

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research questions, throughout the research and until the collection of results. For successful research implementation, it is important that the academic and industrial partners share the expectations of the outcome of the research. This became obvious in the research projects conducted with GKN AES, see Table 2, as the expectations were thoroughly discussed before each project.

Parallel projects regarding sustainability create a positive atmosphere to sustainability, supporting capability development, and offering a win–win situation for the projects. For example, a method development project can support the implementation of new sustainable technologies. A synergy effect occurs when the technology projects can provide concrete sustainability targets, which the management understands and can thereby justify company investments in sustainability initiatives (Alblas, Peters & Wortmann 2014).

Nomenclature

AM	additive manufacturing
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration
GKN	GKN Aerospace
GKN AES	GKN Aerospace Engines System
MD	metal deposition
MDO	multidisciplinary design optimisation
SDGs	sustainable development goals (UN 2030)
SPD	sustainable product development
WEM	whole engine model

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