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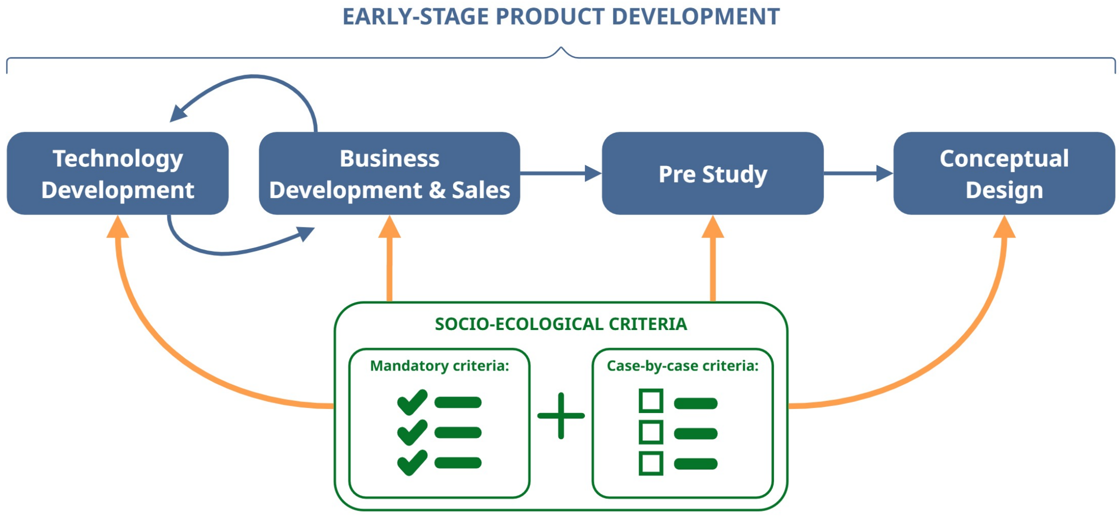

Integrating Socio-Ecological Criteria into Early-Stage Product Development

In Collaboration with GKN Aerospace

Master's thesis in Product Development

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Abstract

Integrating socio-ecological criteria into early-stage product development remains challenging due to limited data availability and uncertainty. This thesis aims to address this issue at GKN Aerospace by developing a prioritised list of socio-ecological criteria and an accompanying integration framework for practical application in the early stages of product development. The purpose is to support trade-off scenarios and embed socio-ecological aspects into the design process.

Through a semi-systematic literature review, an initial list of 263 criteria was collected and funnelled down to 41 through aggregation and guided filtering with sustainability experts. In parallel, interviews were conducted with practitioners at GKN Aerospace to identify gaps and integration opportunities in the company's current product development processes. An additional literature review identified criteria prioritisation methods, from which expert opinion and the DEMATEL method were adapted to evaluate criteria importance and interdependencies.

Through the prioritisation and mapping of company processes, 16 primary and 25 case-by-case criteria were proposed for integration into product requirements and concept selection matrices. The framework and criteria were validated through interviews with practitioners and life-cycle-focused academic research.

The validation confirmed the importance of prioritising criteria that impact the use phase, to which over 90% of the product-related emissions can currently be attributed. In addition, there is an opportunity to ensure more robust compliance with sustainability-related regulations by embedding them into product requirements. Further research should focus on developing measurable metrics and assessment methods for each criterion to support their practical implementation in the design process.

Keywords: Sustainable Product Development, Socio-Ecological Criteria, Early-Stage Product Development, Aerospace Industry, Concept Selection, Product Requirements.

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Eygló Anna Arnardóttir & Selin Oguz, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CO_2	Carbon Dioxide
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DNSH	Do No Significant Harm
EU	European Union
FSSD	Framework for Strategic Sustainable Development
GHG	Greenhouse Gas
GKNA	GKN Aerospace
LCA	Life Cycle Assessment
LCSA	Life Cycle Sustainability Assessment
MCDA	Multi-Criteria Decision Analysis
NO_x	Nitrogen Oxides
REACH	Registration, Evaluation, Authorisation & Restriction of Chemicals
S-LCA	Social Life Cycle Assessment
TBL	Tripple Bottom Line

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Introduction

1.1 Project Background

The 2025 UN Emissions Gap Report highlights the improvements that have been made in terms of renewable energy transition, expanded climate policy, and reduction of global warming projections since the adoption of the Paris Agreement in 2016 [1]. This indicates that accelerated climate action is possible and effective with global commitment. However, current warming projections remain well above the Paris Agreement, and global greenhouse gas (GHG) emissions continue to increase each year, requiring significant systematic action, particularly within fossil fuel-reliant industries [1].

There is a growing interest in sustainable product development and a need to assess and measure sustainability performance, as well as handle different associated trade-offs. In the early stages of the product design process, the sustainability profile for a product's life cycle is set, after which only incremental changes in the product architecture can be made. To deliver products that are sustainable, the requirement is not only to consider the socio-ecological impacts but to maintain them as integral product requirements [2]. Sustainability is composed of ecological, social and economic dimensions. Socio-ecological criteria, therefore, fall under sustainability criteria with a focus on social and ecological aspects. This is particularly relevant in manufacturing within the aerospace industry, where a radical shift in how organisations work towards achieving sustainability is needed to meet targets for reducing carbon dioxide (CO_2) and nitrogen oxides (NO_x) emissions [3].

In 2022, the aviation industry, in particular departing flights, accounted for roughly 4% of the total combined EU and EFTA GHG emissions [4]. This includes CO_2 and non-CO_2 emissions (e.g. NO_x, PM and SO_x). In addition, the aerospace industry contributes to social issues such as noise pollution from flights, impacting the affected individuals' mental and physical health [5]. To address such sustainability challenges, GKN Aerospace (GKNA) has a long-term collaboration with academia, developing methods and tools to increase sustainability consideration in various phases of the product development process [3]. This project is a part of this ongoing research on sustainable product development, focusing on the early design phases.

It is, however, challenging to address socio-ecological criteria early in the design process, as this often requires substantial knowledge and data that are missing in the early development stages [6]. To bridge the knowledge gap, it is necessary to rely on qualitative data and employ a systematic approach to ensure early socio-ecological considerations despite the associated challenges [6].

This project builds upon ongoing collaborative research on sustainable product development between GKNA and academia through the development and prioritisation of socio-ecological design criteria for use in early-stage product development. For GKNA, this project provides a systematic approach for identifying and prioritising socio-ecological criteria relevant to the aerospace industry to support early-stage decision-making.

1.2 Company Background

GKN Aerospace is a global technology leader in the aerospace industry with their Engine Systems division headquartered in Trollhättan, Sweden, where high-precision products such as engine components are developed, manufactured, and maintained. GKNA supplies commercial and military aircraft engines, with technology and products present in more than 100,000 flights per day around the world [7].

GKNA believes that technology is the key driver of innovation in the aerospace industry, from additive manufacturing to future propulsion systems, including product design, manufacturing processes, and sustainability. Through collaboration with research partners and academia, the company supports thesis and PhD students in research projects. Several studies have been conducted on efforts to embed sustainability in the early stages of product development. The company targets several strategic sustainability goals, such as 1) reaching net-zero GHG emissions across the value chain by 2050, 2) reducing absolute Scope 1 and 2 GHG emissions by 50% in 2030, and 3) upholding its commitment of "being the most trusted and sustainable partner in the sky" [8].

The general product development process at GKNA can be seen in Figure 1.1. The official product development begins with "Pre Study", at which stage products are already defined to a large extent, with fixed requirements and constraints. Products are conceptualised in the "Business Development" stage before the official product development process, where initial negotiations with customers on product deliverables take place. Before the start of product development, a product can also enter several iterations of technology development, where aspects of the product can be developed and demonstrated. In this study, early-stage product development was therefore expanded to include stages of "Technology Development", "Business Development", "Pre Study" and "Conceptual Design" in the GKNA development process, as presented in Figure 1.1.

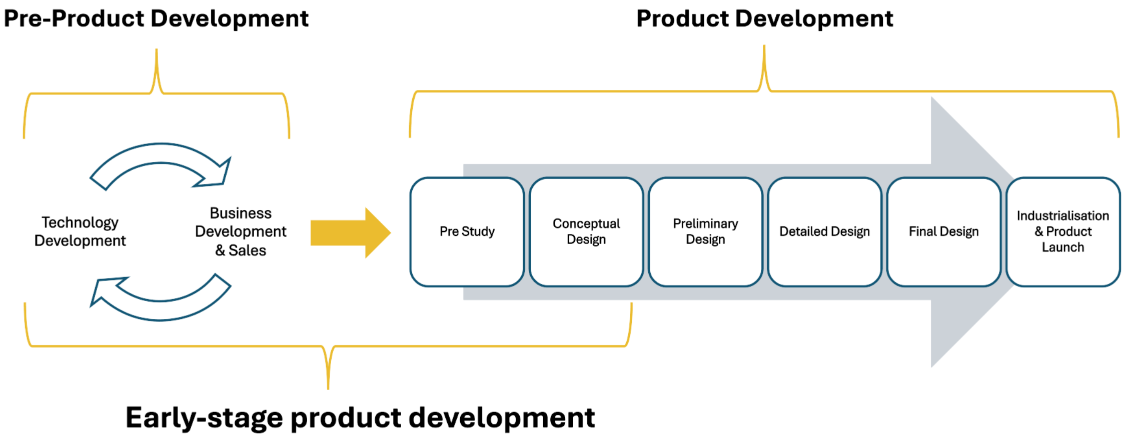

Figure 1.1: The early stages of development within the GKN Aerospace process.

1.3 Purpose

The purpose of this project is to enhance sustainability integration into early-stage product development at GKNA. Due to a high degree of uncertainty and limited data availability, it is often difficult to evaluate and incorporate sustainability considerations into decision-making. Therefore, creating a need for practical approaches that enable sustainability aspects to be systematically incorporated in product development processes. The project aims to address this by identifying and implementing science-based socio-ecological design criteria into early-stage product development.

In a broader context, the purpose is to explore how socio-ecological criteria can be systematically embedded in early-stage product development. This is particularly challenging in a highly regulated industry such as the aerospace industry, where the design space is largely predefined by certification and performance requirements, even in the early product development phases [9]. A rigid design space leads to an increase in different trade-offs that must be considered during the design process. Inclusion of socio-ecological criteria and sustainability requirements increases the likelihood of conflicting criteria and complex trade-offs [10]. If such trade-off scenarios are identified in the early product development stages, associated risks can potentially be avoided. Trade-off management is therefore a critical component of the project and should accompany the proposed design criteria.

The broader purpose of this thesis is to contribute to ongoing research in sustainable product development by documenting methods for integrating socio-ecological criteria into existing product development processes. The identified methods may apply to other aerospace companies or potentially to other industries and research in sustainable product development.

1.4 Objectives and Research Questions

The following research questions have been developed to guide this project:

1. What socio-ecological criteria are the most critical to consider during the early product development stages within the aerospace industry?
2. How should the criteria be prioritised to support decision-making and navigating trade-off situations in the product development process?
3. How can the identified criteria be systematically integrated into the design and decision-making processes of GKN Aerospace?

The objective of the thesis is to identify, define, and prioritise the most relevant socio-ecological sustainability criteria for early-stage product development within the aerospace industry. In addition, prioritise the identified socio-ecological criteria to support decision-making and trade-off management. Another objective is to propose a developed framework to support socio-ecological integration while ensuring alignment with company needs, goals, and practical implementation.

1.5 Scope and Limitations

The main focus of the project is on the early stages of product development, including product planning and conceptual design phases, which in GKNA's processes translates to technology development, business development & sales, pre study and conceptual design as seen in Figure 1.1.

The project is limited to the civil sector of the aerospace industry due to restricted access to data for defence and space-related applications. Additional limitations are related to the affiliated company. GKNA is a relatively large organisation, which typically implies more rigid structures and slower implementation of change; therefore, implementation or execution of the developed tools or methods was not considered and excluded. Preliminary validation was instead conducted through literature, interviews, and focus groups. In addition, sensitive data of specific company products are entirely excluded from the project, which limits the extent to which the methods or tools can be validated on example cases.

Since the affiliated branch of the company is located in Sweden, the project is subject to geographical limitations. Although GKNA is a global company with international suppliers and customers, some locational bias needs to be considered, as interviews are conducted with engineers and managers located in Sweden. Additionally, only EU laws and regulations are explored within this context, since including US and other worldwide regulations is not reasonable within the time frame of the project.

2

Theoretical Background

2.1 Sustainability and Sustainable Development

Sustainability is defined by the Brundtland Commission of the United Nations as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" [11]. Although Brundtland's definition of sustainable development is widely accepted and used as guiding institutional principles to address modern challenges, scholars have argued the need to shift in how it is understood and implemented, as it is conceptually broad [12].

Sustainability should not solely be viewed as rigid and technical, but rather include perspectives of economic, ecological, ethical, and political. In addition, it requires the inclusion of multiple disciplines, as sustainability is not solely an engineering or environmental problem, but it also involves social and political dimensions [12].

In an engineering context, sustainability comprises three dimensions: ecological, social, and economic, all of which need to be balanced and considered in parallel when adopting a systematic perspective in product development [13, p. 115].

2.1.1 Sustainable Product Development

Product development is defined by Ulrich et al. [14] as "the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product". Beyond this description, product development is a cross-functional and interdisciplinary activity requiring contributions of a company's marketing, design and manufacturing functions [14].

Product development determines most of the technical architecture and impact of a product's lifecycle; therefore, sustainability must be strategically embedded early within the product development process. Product development and manufacturing companies play a central role in the sustainability transition as they provide the impact of goods such as products, technology, and services, while also having a negative effect by consumption of natural resources and energy [15]. In the early stages, most products' lifecycle impacts are determined [16], however, it is difficult and challenging to assess product sustainability performance due to high uncertainty, lack of data, and time constraints [17]. Researchers have highlighted the importance of companies integrating quantitative sustainability metrics into early decision-making; otherwise, there is a risk of down-prioritisation and environmental degradation [18].

Sustainable product development can be defined as an organisation's capability to strategically make sustainable decisions in product development to systematically integrate the early phases of the product innovation process [3]. The capabilities, also referred to as sustainable product development capabilities, are required to address new needs and integrate technologies into functioning solutions. Studies argue the importance of building product development capabilities, as it leads to competitive advantage and value-added performance [3]. According to Hallstedt [19], the key blocks for these capabilities include tools and organisational culture such as routines, practices, and shared understanding of sustainability and sustainable product development.

In sustainable development, the Triple Bottom Line (TBL) framework covers the dimensions profit, people, and planet. The framework can be used to conceptualise the integration of social, economic, and environmental aspects for assessing the long-term impacts of business decisions [20]. Furthermore, society depends on the economy, and the economy depends on the global ecosystem.

In the early stages of product development, a product's socio-ecological impacts throughout its lifecycle are already set, making it important to introduce a socio-ecological perspective early [19]. Thus, the early stages of product development must be given particular attention.

According to Hallstedt [19], if sustainability aspects are included in a product's requirement list, it would be easier to avoid costs and reduce environmental impact, and drive for innovation with sustainability as the core. However, it is difficult to reach more sustainable solutions, for instance, due to the breadth and complexity of sustainability, as well as practical limitations such as time constraints and limited data availability in early product development innovation. In industrial conceptual product development, limited data availability further constrains analyses in sustainability, highlighting the need for creating approaches with a socio-ecological perspective.

2.1.2 Sustainability Challenges in the Aerospace Industry

Within the aerospace industry, manufacturers have to shift the focus from a purely performance- and technology-driven view to developing skills and strategies to have a more holistic view to meet sustainability goals that address resources [3]. The aerospace industry is undergoing a sustainability transformation, challenging and requiring manufacturers to adapt their product development practices to develop more sustainable solutions and opportunities.

However, it is complex to integrate sustainability aspects into product development, as it requires companies to 1) develop solutions that benefit from new technologies with high sustainability potential, 2) develop business models and solutions that include the lifecycle of a product, from material acquisition to end-of-life and value chain, and 3) manage and mitigate the risks associated with the shift towards new technologies and business models [3].

The aviation industry is estimated to be responsible for approximately 4% of observed human-induced global warming [21], [22]. By far the largest contributor to this impact is the use phase, as up to 94% of the total lifecycle emissions of CO_2 and NO_x in freight and passenger aviation transport is due to tailpipe emissions from direct fuel combustion [23], [24]. In comparison, the raw material extraction and aircraft manufacturing are much less impactful, by many estimates contributing to less than 1% of an aircraft's lifecycle GHG emissions [25], [26], [27]. Despite this, the manufacturing phase is highly important as it can influence and improve some of the factors that affect an aircraft's operating emissions, mainly aircraft weight and engine efficiency.

Since 1960, aero manufacturers have contributed to an increased efficiency, leading to the reduction of emissions per km by 80% [28]. The growth in air traffic from 1960 to 2018 has, on the other hand, increased dramatically, growing by roughly two orders of magnitude by 2018, resulting in an increase in CO_2 emissions [28]. Several socioeconomic shifts have contributed to this growth, mainly global population growth, the role of air transport for development in globalisation and economic growth, leading to increasing total emissions [3].

2.2 Early-Stage Product Development & Decision-Making

The generic product development process displayed in Figure 2.1, as described in "Product Design and Development" by [14], is composed of product planning, concept development, system-level design, detailed design, testing and refining, and production and ramp-up.

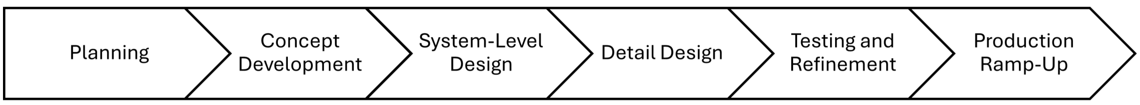

Figure 2.1: The Generic Product Development Process.

Other standard textbooks on product development and engineering design, such as "The Mechanical Design Process" by [29] and "Engineering Design - A Systematic Approach" by [30], present similar broad design stages, including planning, conceptual design, detailed design, prototyping, testing and production. These phases are often presented linearly, but with the clarification that the product development process is iterative in practice, involving several loops.

Within this process, the product planning and concept development phases are often referred to as the "early stage" or the "Fuzzy Front End", a term first popularised by [31]. The "Fuzzy Front End" encompasses early product innovation activities, characterised by a high degree of freedom and low cost of change, leading to the resulting product specification from which a more systematic development can commence [32]. The main activities are (1) opportunity identification, (2) opportunity analysis, (3) idea generation & enrichment, (4) idea selection, and (5) concept definition, which mirror various activities in the product planning and concept development phases proposed by [14] and [30].

This definition of early-stage product development is supported by a more recent review of management practices for sustainable product development by [33], where a systematic review of 312 studies revealed 61 key management practices for sustainable product development. These were classified by context of application, including stages of the product development process and support processes such as programme management and strategic planning. The results indicate that most sustainable product development practices are implemented during the early stages, namely the product planning and conceptual design phases.

2.2.1 The Product Planning Phase

Table 2.1 displays the product planning steps outlined by the textbook "Product Design and Development" by Ulrich et al. [14]. The product development perspective by Ulrich et al. [14] outlines a broad product planning phase that begins with opportunity identification. Following the identification of new potential projects, the project portfolio is evaluated and prioritised. This activity describes some typical tasks in portfolio management, which is described as a support process to product development by Vilochani et al. [33]. The third activity involves resource and time allocation for projects, which leans towards program management, another product development support process according to Vilochani et al. [33]. The output of the product planning phase is a mission statement, including business goals, primary market, stakeholders, as well as assumptions and constraints of the project.

The product development perspective places an emphasis on business development in the early stages, while highlighting that these processes are not linear despite being presented as such and often require multiple iterations between activities in practice. The planning phase of product development can vary in interpretation and execution, but generally involves opportunity identification for product ideas, market, technology, and company analysis, prioritisation of products and further analysis of the selected product. The product planning phase is broad and open-ended, with its scope varying depending on the degree of novelty of each product.

Table 2.1: Product Planning Activities

Activity	"Product Design and Development" [14, ch. 4]
1	**Identify opportunities:** - From customers and trends - Mine opportunities - Screen opportunities

Table 2.1 (continued)

Activity	**"Product Design and Development" [14, ch. 4]**
2	**Evaluate and prioritise projects:** - Competitive strategy - Market analysis - Technological analysis - Balancing the portfolio
3	**Allocate resources and plan timing for projects**
4	**Complete pre-project planning:** - Outline benefit proposition, key business goals, assumptions and constraints, budgeting and staffing - Output is a mission statement

2.2.2 The Concept Development Phase

The phase that follows the planning phase in the product development process is referred to as the "Concept Development" phase by Ulrich et al. [14]. The suggested activities in this phase are presented in Table 2.2. The concept development phase, as described by Ulrich et al. [14], begins with identifying customer needs in activity 1, from which a target specification is then established in activity 2. As the target specifications are established before the team is fully aware of the constraints of the product technology, these specifications need to be refined after the development and selection of a product concept in activity 6. Activities 3, 4 and 5 outline the generation, selection and testing of product concepts. Several iterations of these three activities can take place before the development team is satisfied with the degree to which the product concepts meet the target specification. Finally, in activity 7, a development plan of the concept is specified, including a development schedule and resource allocation.

The concept development phase involves the fundamental steps of establishing initial requirements/specifications, generating product concepts and evaluating them. Similar to the planning stage discussed in Section 2.2.1, the product development perspective by Ulrich et al. [14] includes project management and engineering design activities.

Table 2.2: Concept Development Activities

Activity	**"Product Design and Development" [14, ch. 7]**
1	**Identify customer needs**
2	**Establish target specifications:** - Translating customer needs into technical requirements
3	**Generate product concepts:** - Problem understanding - Problem decomposition into subproblems - External search - Internal brainstorming - Systematic exploration
4	**Select product concepts:** - Decision matrices

Table 2.2 (continued)

Activity	**"Product Design and Development" [14, ch. 7]**
5	**Test product concepts:** - Verify that customer needs have been met - Assess the market potential - Identify shortcomings
6	**Set final specifications:** - Revise earlier target specifications after a concept has been selected and tested
7	**Project planning:** - Detailed development schedule, strategy to minimise development time, identify resources, etc.

2.2.3 Design Criteria, Requirements and Metrics

As discussed in Sections 2.2.1 and 2.2.2, the identification of product requirements/specifications is a fundamental step in early-stage product development. The product specification definition is an iterative and ongoing activity as concept development progresses and more information about the product limitations emerges. Ulrich et al. [14, p. 97] defines a specification as a combination of a metric and a value. Metrics should ideally reflect the degree to which the product satisfies the customer needs, and ideally comply with the following criteria Ulrich et al. [14, pp. 99–102]:

- Metrics should be complete: ideally, each customer need corresponds to each metric. In practise, several metrics are often necessary to reflect a single customer need.
- Metrics should be dependent variables: specifications need to indicate what the products need to do/fulfil, not how the specification will be achieved. For example, the mass of the product can be a metric but not the material.
- Metrics should be practical: the development team should be able to directly observe or analyse the products in terms of the metrics.

A metric needs to be measurable with a value, but a value can take on several forms, e.g. a particular number, a range, an inequality or even a binary pass/fail or yes/no. Ulrich et al. [14, p. 99] proposes the use of the Quality Function Deployment (QFD) method to translate customer needs into requirements/metrics. This method is also mentioned in the sustainable product development context as a tool used for integrating sustainability criteria into product requirements [34]. In some cases, a customer need cannot easily be translated into a metric and needs to be left as is in the target specifications. In these cases, a unit "subj." can be used and a qualitative scale of e.g. 1-5 can be introduced as a value.

The engineering design book by Pahl and Beitz [30, pp. 145–157] has a slightly looser definition of what they call a "Requirements List (Design Specification)", namely, a consumer and market-driven collection of demands and wishes that should evolve as the complexity of the product increases. Demands are requirements that must be met for the solution to be acceptable/viable, while wishes can range in importance and should be taken into consideration when possible. The requirements list should include both explicit and implicit demands/wishes. The explicit requirements include the expected product properties that are defined directly by the customer, whereas the implicit requirements are market and customer expectations/wishes that are not explicitly stated.

The term "criteria" is mostly mentioned by [14] and [30] in terms of "evaluation criteria" or "selection criteria" in the concept selection within the concept development phase. According to Ulrich et al. [14, pp. 150–165], selection criteria by which concepts are evaluated are adapted from customer and other stakeholder needs. Selection criteria are compiled in decision matrices, some of which require weighing of the criteria to facilitate a more informationally complex concept scoring.

Similarly, Pahl and Beitz [30, pp. 192–194] suggests that the evaluation criteria be derived from the requirements list as well as general technical and economic characteristics so that the areas of function, working principles, embodiment, safety, ergonomics, production, quality control, assembly, transport, operation, maintenance, recycling and cost are covered. When translating the requirements list into selection criteria, the probability that the concepts satisfy the demands should be considered first and foremost, as should the degree to which they exceed the minimum requirements and the extent to which they can satisfy the wishes. In this way, the initial requirements from product planning and the selection criteria in the concept generation stage are linked and coordinated.

In sustainable product development, the term "criteria" is also used to refer to integrating sustainability criteria into design requirements [2]. The general term "criteria" can therefore be thought of both as selection criteria in the concept development phase, as well as aspects that go into the initial requirements specification in the product planning phase.

2.2.4 Product Development in the Aerospace Industry

The general product development process as described in Sections 2.2, 2.2.1 and 2.2.2 is largely theoretical and needs to be adapted to each industry and company in practise. The aerospace industry has several product development challenges, including significantly long lead times, which lead to forecasting challenges and high levels of uncertainty regarding market assumptions, technology development, regulations and other external factors [35]. In addition, aerospace products are designed for extensive lifecycles, typically over 20 years for commercial aircraft [36]. This reality makes it challenging to apply the traditional product development method of designing products based on a fixed set of requirements [35].

Another set of challenges arises from the complex systems and systems of systems (SoS) that aerospace products are a part of, which add layers of complexity to requirement specification and associated trade-off situations since a broader set of stakeholder needs must be considered [35]. With these challenges in mind, [35] outlines a product development approach tailored for SoS. In contrast to traditional product development processes, where emphasis is almost exclusively placed on customer needs, [35] highlights the importance of considering geopolitics, regulations, business case, technological threats and time frame in addition to customer needs when exploring needs and boundary conditions of a product. [35] also places a large emphasis on systematic design space and capability exploration through scenario analysis, and the breakdown of SoS into constituent systems and subsystems with their own sets of individual requirements.

The *V-model* is a widely used process model that breaks down and simplifies the complex systems-of-systems within the aerospace industry [37]. It begins with the development of the overall aircraft at the highest level, followed by the development of the various systems within the aircraft. This can be broken down further into subsystem-level design and eventually individual component development within each subsystem. Within each of these development levels, the following four general steps known as the RFPL steps are performed: (1) requirements are set, (2) the required functions are identified to meet the specified requirements, (3) the logical system architecture is defined which describes the structure of the system through its interacting elements, (4) the physical system architecture is developed with the physical implementation of the system and the distribution of its components [37]. At every step, the developed systems are also monitored through verification and validation to ensure that they meet the requirements and stakeholder needs [37].

In order to manage the extensive lifecycles and complexity within the aerospace industry while maintaining the quality of the systems and products involved, the stage-gate model is used [38]. The stage-gate process breaks down long development projects into distinct stages with assessment gates following each stage, where necessary decisions are made on the continuation of the project. The role of the gates is to evaluate the work that has been done at each stage and to determine whether the project can "Go", move on to the next stage, having met all of the requirements. The gate reviewers can also decide to "Kill" or exterminate the project if the progress has not been sufficient and the continuation of the project poses too great a risk. The project can also be placed on "Hold" or "Recycle", if certain adjustments need to be made in order for the project to move on to the next stage [38]. Any delays from the stage-gate process pose economic risks due to extended lead times. In the aerospace industry, this poses an added risk as a contract is typically signed between the participating companies before product development begins, and delays due to gate decisions can lead to penalties as stipulated in the contracts [38].

The aerospace industry deals with unique challenges relating to elongated product time frames and extensive complexity, which require adaptations to the traditional product development process to tackle. The necessary adaptations include added layers of development, including system, subsystem and component level development with embedded performance reviews, as well as consideration of a broader set of stakeholders and external factors in the early stages of product development.

2.3 Socio-Ecological Criteria

As defined in Section 2.1, sustainability is composed of ecological, social and economic dimensions. Socio-ecological criteria therefore fall under sustainability criteria, with a focus on social and ecological aspects. The term "socio-ecological criteria" is often used interchangeably with the term "sustainability criteria" in sustainable product development literature [19], [2]. Sustainability criteria can be used for decision-support tools in early product development to introduce a sustainability perspective [19].

The Product Social Impact Life Cycle Assessment (PSILCA) database provides a comprehensive overview of social sustainability and is available in the open-source Life Cycle Assessment (LCA) software, OpenLCA [39]. The PSICLA database classifies indicators by stakeholder groups, including workers, local communities, society, value chain actors, children and consumers [39]. Under each category, there are subcategories with outlined indicators; for example, workers include the subcategories of child labour, forced labour, fair salary, working time, and discrimination. [39]. Indicators are widely used in sustainability research, in particular in relation to LCAs, and can be expressed quantitatively or qualitatively, similarly to metrics as defined in Section 2.2.3 [19]. In sustainable product development, Hallstedt [19] has defined a criterion as a "target" or "level" of a sustainability aspect (e.g. no hazardous chemicals used). An example of social criteria in line with the PSICLA guidelines could be no child labour used. A single criterion can therefore be measured through several indicators.

Other, more industry-focused literature provides a different classification of social sustainability. In a paper aimed at managers, industry leaders, and policy leaders within the energy sector, Afshari et al. [40] categorises social sustainability indicators into four categories: (1) human rights and social life, (2) occupational indicators, (3) business-related indicators, and (4) legal, political, and government-related indicators. Another paper by Richter et al. [41] addresses the challenge for companies of assessing and reporting on social sustainability by compiling three catalogues of criteria, each addressing a group of stakeholders. The stakeholder groups are "workers, suppliers, other cooperation partners, customers, competitors", and "local community" [41].

While social criteria primarily address direct impact on human well-being and rights, ecological criteria focus on planetary impacts, such as the Earth's ecosystems, natural resources and climate change. The widely cited article by [42] proposed planetary boundaries, which are fundamental for the maintenance of the safe operating space for humanity within Earth's biophysical subsystems. The boundaries are (1) climate change, (2) rate of biodiversity loss, (3) biochemical flows, (4) stratospheric ozone depletion, (5) ocean acidification, (6) global freshwater use, (7) change in land use, (8) atmospheric aerosol loading, (9) chemical pollution, the first three of which have already been crossed [42]. The breach of the proposed thresholds of these boundaries could lead to irreversible and abrupt environmental change and threaten continued human development [42].

2.4 Criteria Prioritisation and Weighing Approaches

In the early stages of development projects, some important requirements may not be elicited and analysed enough due to tight deadlines and budgets. Prioritisation of requirements is not only a way to solve conflicts and balance trade-offs, but a way for customers and stakeholders to be a part of the discussion and rating of them [43]. As described in Section 2.2.3, requirements can be divided into demands and wishes, which form the basis for prioritisation of requirements. When comparing socio-ecological, economic, and technical criteria, they rarely perform equally or are equally critical, making it necessary to prioritise.

When all possible criteria and characteristics are considered, designers have a large number of possible design concepts which must be reduced early [44]. Although the concept reduction must be done early, it is important to be careful not to eliminate principles that may seem weak on their own, because their combination with other principles can create a valuable advantage in a bigger system structure. The evaluation of the concepts, which may include criteria such as technical, safety, environmental and economic, is compared to determine the value of a solution. To support decision-making when assessing the value of a solution, evaluation criteria are typically derived from the requirement list, which ensures that no critical criteria are missed or ignored. Since design concepts are not equally good solutions or perform equally in each criterion, it is necessary to prioritise criteria during concept comparison, selection, and evaluation.

Recent studies suggest that for designers to consider and integrate sustainability in the early-stage design, where design freedom is high, there is a need for methods and tools that support making better-informed decisions, elicit, and evaluate sustainability trade-offs against other aspects [10]. New concepts must satisfy at least the operational performance, manufacturability, and sustainability domains [10]. Criteria often conflict with each other, resulting in difficult trade-off scenarios [10]. Support tools can prevent risks as early as in the conceptual design stage. There exists a knowledge gap and a need for understanding trading off and evaluating sustainability against other metrics, which requires abstracting sustainability into quantitative formats [10]

Another approach used during concept selection is the Pugh concept selection matrix, also referred to as concept screening, with the purpose of comparing concepts, reducing concepts quickly, and improving them. The selection matrix is prepared by listing evaluation criteria vertically (rows) and concepts horizontally (columns) [14]. While this concept selection method is effective, as it provides a practical tool to compare concepts and includes teamwork, it does not provide support when multiple criteria are conflicting and cannot be compared directly.

Multi-Criteria Decision Analysis (MCDA) is an approach for assessing sustainability and encompasses a variety of specific methods [45]. These methods are flexible and act as a bridge, ensuring transparency between multiple stakeholders. Sustainability assessments are complex, requiring structured, transparent, and reliable decisions and trade-offs. These challenges can be addressed by MCDA both at micro and macro levels; multiple criteria can be considered at the product level for supporting decision-making in comparing alternatives [45]. This is relevant and important at the early stages in product development where socio-ecological, economic, and technical criteria must be considered and balanced for decision-making in design under conditions where uncertainty is high. Different MCDA approaches can be applicable to evaluation and assessment for examining various sustainability trade-offs.

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) is an MCDA method which is used to construct direct and indirect interrelations between identified socio-ecological criteria and to determine their influences and importance [46]. The method calculates an average matrix by involving expert knowledge and evaluation to get an understanding of how criteria influence each other. It is conducted on a predefined scale of 0 to 4, ranging from no influence to very strong influence. An initial direct influence matrix is then calculated by normalising the average matrix where the diagonal elements are equal to zero. The direct influence matrix is transformed into a total matrix capturing direct and indirect effects.

2.5 Sustainability Integration

Sustainability integration frameworks can be embedded into an organisation's business strategy to support sustainability-related approaches and goals, including ways to measure, manage, and report its impacts. Sustainability is usually complex, requiring structured frameworks that can support systematic decision-making. During early-stage product development, where uncertainty is high and the lack of data is limited or unavailable, frameworks can help in guiding decision-making, structuring criteria and ways of prioritising them, and handling trade-offs of conflicting aspects.

2.5.1 Existing Sustainability Frameworks and Methods

Framework for Strategic Sustainable Development (FSSD) provides a systematic step-by-step approach to guide organisations toward sustainability. By identifying the current situation and defining a future sustainable vision, the approach is working backwards; create solutions and identify actions to fill the gap between the current situation and the future vision. Sustainability Compliance Index (SCI) is a qualitative matrix-based measurement tool used to support assessment with levels of design guidelines for decision-making during the development and selection of new concept ideas. The Sustainability Fingerprint is another qualitative measurement tool designed for early stages to support designers in decision-making during concept selection to compare solutions and identify hotspots and opportunities for improvement.

Assessing and measuring sustainability in product development can be done through methods such as LCA, which is an environmental method that covers the full lifecycle of a product to identify its environmental impacts. Another method is Social Life Cycle Assessment (S-LCA), focusing on social impacts such as communities and workers. Although it is usually harder to quantify and has limitations with data availability, it is still used as a complementary method for LCA. Ecodesign is a more design-focused approach to integrating sustainability into development by making design choices to reduce environmental impacts.

Framework for Strategic Sustainable Development (FSSD)

The transition to a sustainable society is very complex, requiring collaboration across disciplines and sectors. A response to this problem has been the development and result of the FSSD - a systematic approach supporting organisations in understanding sustainability challenges, strategic planning, and decision-making toward sustainability practices [47]. The development of this framework has been a 25-year collaboration between scientists and practitioners, where the result is an iterative and continuous process through development and testing. An important aspect of the framework is that its purpose is not to replace or exclude other existing supporting methods and frameworks for sustainable development, but instead to see how they relate and can support strategic sustainable development.

One key advantage of the framework is that it provides a systematic step-by-step approach to guide organisations toward sustainability. It consists of the following four steps: (1) clarifying the current situation and sustainability challenge, (2) analysing it in relation to a defined sustainable vision, (3) creating solutions to fill the gap between the current situation and future vision, and (4) prioritising the solutions into a strategic plan [47]. The FSSD framework builds on backcasting from socio-ecological sustainability principles, which define the boundary conditions for sustainable development [3]. The framework provides a complete picture of sustainability by explicitly defining socio-ecological aspects and sustainability principles, intended to guide organisational decision-making toward sustainability [19].

Sustainability Compliance Index (SCI)

SCI is a qualitative, matrix-based, measurement tool used to support assessment with levels of design guidelines to guide decision-making during development and selection of new concept ideas [19]. Each criterion is divided into the SCI levels 0, 1, 3, 6, and 9 to score sustainability, where 9 is the excellent level. SCI can also be used for concept comparison or selection in the early-stage design from a sustainability perspective, and the identified levels can give guidance in decision-making and moving towards future development or improvement of socio-ecological criteria [19].

Sustainability Fingerprint

Sustainability Fingerprint is another qualitative sustainability measurement tool designed to be used in the early stages by the development team. By identifying company-specific sustainability criteria and deriving the sustainability performance of potential products and technologies, the tool enables and supports designers in decision-making to compare and select alternative design solutions while identifying hotspots and improvement opportunities [6].

Life Cycle Assessment (LCA) and Ecodesign

LCA is a systematic and standardised assessment method used to evaluate the total environmental impact of a product or process. An LCA covers all stages of a product's lifecycle from cradle-to-grave, including raw material extraction and acquisition, manufacturing, distribution, use and maintenance of products, and end-of-life (recovery and disposal of used products and waste) [48].

The application of LCA can support decision-making in product development at the product level and identify environmental hotspots of a product or process within an organisational level or across the supply chain [49]. Studies in European industry show that LCA is used internally to identify hotspots in products and systems [49]. For instance, in large Danish companies, the use of LCA revealed unexpected new environmental aspects of products, which led to, in 79% of the cases, the establishment of new priorities for environmental efforts. Often resulting in measures such as saving or substituting materials in products and processes [49].

Several studies ([50], [51], [52]) outline the importance of using LCA results of previous products to develop design criteria and requirements for new products, since LCAs are widely considered the most objective and available tool for environmental evaluation. Other sources of ecological criteria include legal frameworks and sustainability standards [53].

Ecodesign is a systematic approach widely used by organisations in their products and services to reduce their environmental impacts throughout their lifecycle [54]. LCA is often used to assess and evaluate these impacts. Ecodesign aims to include environmental requirements into the product development process and is similar to other concepts such as Design for the Environment (DfE), Life Cycle Engineering (LCE), and sustainable product design [55]. Addressing environmental aspects in the early-stage product development is beneficial for achieving the greatest environmental opportunities [55].

The ISO 14006:2020 standard provides a guideline for organisations to incorporate ecodesign by considering environmental aspects in design and development [56]. The aim is to integrate lifecycle thinking into Environmental Management Systems (EMS) processes to reduce negative environmental impact, addressing the organisation's growing recognition of considering environmental aspects [56]. Organisations should integrate ecodesign into design and development due to the increasing environmental concerns, such as climate change and depletion of resources [56]. Beyond the environmental concerns, ecodesign also allows for business opportunities related to resource efficiency, such as strategies to enable lower carbon use, and circular economy, such as product reuse and repair.

Social Life Cycle Assessment (S-LCA)

S-LCA is a method to assess and evaluate the social and socio-economic impacts of a product's or service's lifecycle, from raw material extraction to end-of-life [57]. It provides a systematic framework that allows for qualitative and quantitative data to support decision-making on the impacts with the purpose of improving an organisation's social performance [57]. Similar to LCA, it has a lifecycle perspective, but differs in its inclusion of more social aspects in the phases: (1) goal and scope, (2) Social Life Cycle Inventory (S-LCI), (3) Social Life Cycle Impact Assessment (S-LCIA) and (4) interpretation.

Application of S-LCA can be embedded in an organisational process to support decision-making involving various stakeholders, identifying social hotspots along the lifecycle or value chain and manage the potential risks, and provide materiality assessment in a consistent way [57]. In the context of product development, S-LCA can provide valuable insights into social impacts that are linked to materials, supply chains, and production processes, supporting more sustainable product development.

2.5.2 Framework Design

To design a framework, it is crucial to understand the context behind frameworks and what makes effective frameworks. Partelow [58] compiles various definitions of the term "framework" with the general idea that frameworks are positioning tools within scientific fields that compile a set of conceptual objects and the relationships among them on the one hand, and as bridging tools that enable connections between levels of knowledge on the other.

A concept related to frameworks is "design tool", an instrument (physical, digital or conceptual/abstract/methodological) that supports the generation, organisation, and manipulation of resources (material or immaterial) to perform tasks and to support the decision-making process throughout the phases of the design process [59]. A design tool must go through the process stages of (1) data input, (2) information processing by the tool, (3) a tangible result/output, translated into a specific format from which the development is in a better position to make more accurate decisions [60]. Several barriers often hinder the implementation of sustainability-related design tools, including a lack of alignment of the tools to product design culture, knowledge of sustainability and tool application, time and resources, perceived benefits of the tool, and alignment of the tool with project requirements [60]. Vicente and Camocho [60] therefore outlines five key eligibility criteria for the successful design of sustainability tools:

1. Facilitate the integration of principles, strategies and criteria of sustainability in a systematic way into the design process.
2. Focus on one or more phases of the design process to improve the circularity and sustainability performance of the solution under development.
3. Must go through 3 main steps: input, processing, output.
4. Must be aligned with the needs of designers, available resources and project objectives.

5. Must allow to be used autonomously by designers, without recourse to non-designer specialists.

To design effective frameworks and tools, meta-frameworks and criteria are needed to integrate insights from previous research into the design process and avoid common pitfalls. The development of a framework/tool can therefore be approached similarly to a product development project.

2.6 Sustainability Regulations and Compliance in Aerospace

The development and design of an aircraft is complex and regulated by law since the system is safety-critical [61]. Regulatory documentation is stringent, and organisations must demonstrate compliance with regulatory requirements set by authorities such as the European Aviation Safety Agency (EASA) [61]. As requirements become embedded in engineering practices, they function as constraints shaping design decisions.

2.6.1 Aviation Emissions and Fuel Regulations

According to [62], the aviation industry has one of the fastest-growing impacts of GHG emissions. The European Union (EU) has acted to address these emissions by developing measures with global reach. For instance, the EU Emissions Trading System (ETS) requires all airlines operating in Europe, European and non-European alike, to monitor, report, and verify all environmental emissions and account for them financially [62].

The EU-ETS initiative to reduce emissions by adding additional costs requires the aviation industry to take responsibility for its emission contribution by either reducing the emissions or purchasing allowances [63]. This creates incentives for "abatement efforts" which represent investments determined to reduce emissions, such as the purchase of more fuel-efficient planes and operational optimisation [63]. Although manufacturing companies may not be responsible for the emissions generated during flight, the relevance of EU-ETS can be linked to the emissions produced during their production of products and processes.

2.6.2 Material and Manufacturing Regulations

The European Union's Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC) No 1907/2006 is a framework governing the production and use of chemicals and the risks posed to protect the environment and human health [64]. REACH affects a wide range of companies across many sectors and requires companies to comply with the regulation by identifying and managing the risks of the substances they manufacture and market in the EU [64].

In the aviation industry, an authorisation risk management process is in place covering chemical Substances of Very High Concern (SVHC), including carcinogens, mutagens, and toxic to reproduction [65]. REACH poses challenges to the aviation industry. For instance, the industry is already a complex supply chain involving many stakeholders, making coordination difficult. Achieving compliance is also difficult due to the low volume of specialised aviation chemicals [65]. Aircraft are expected to have a high operational longevity, requiring that materials, components, and systems meet safety standards throughout their lifecycle, making it difficult to redesign and use alternative substances frequently, as all changes require approval.

In early-stage product development, REACH can create uncertainty due to slow compliance and authorisation processes colliding with the aviation industry's complex systems and strict certification requirements, creating trade-offs between airworthiness and sustainability.

2.6.3 EU Taxonomy Regulation

In addition to regulatory frameworks, the core of the EU action plan is the Taxonomy Regulation (EU) 2020/852, which is a classification system and transparency tool to identify criteria for economic activities aligned with the European Green Deal objectives, such as the net-zero goal for 2050 [66].

For this regulation, the following shall be environmental objectives: (1) climate change mitigation; (2) climate change adaptation; (3) the sustainable use and protection of water and marine resources; (4) the transition to a circular economy; (5) pollution prevention and control; (6) the protection and restoration of biodiversity and ecosystems [66]. To contribute to sustainability, an economic activity must contribute to at least one listed objective while not significantly harming any of the others, following the "Do No Significant Harm" (DNSH) principle.

By covering broader environmental aspects other than climate, this initiative helps companies establish a common dictionary or language for economic activities considered environmentally sustainable in a detailed list. This enables upscaling of sustainable investments, creating security for investors and protecting them from greenwashing, simultaneously helping companies become more climate-friendly [66]. The European Commission created a detailed list with definitions of technical screening criteria (TSC) for each environmental objective set by the European Commission to ensure companies and investors use a unified system that complies with legal acts [66].

3

Methodology

3.1 Overall Thesis Methodology

This project does not involve the development of a typical product development product, but rather a process in the form of a set of design criteria and an accompanying framework of implementation. Despite this, the methodology of Ulrich et al. [14] was employed, and the generic product development process outlined in Section 2.2 was used as a guiding tool. With that in mind, the prioritised set of criteria and the accompanying implementation framework become products which could be developed through the product development process. Due to time constraints and the scope of the thesis, the project is limited to the stages of product planning and concept development. Figure 3.1 provides an overview of the development process used in this project. The overall methodology of the project is also influenced by the FSSD framework, outlined in Section 2.5.1. The first steps of the framework, including empirical examination to build upon existing knowledge, followed by iterative validation through practitioner feedback, were directly implemented in the methods.

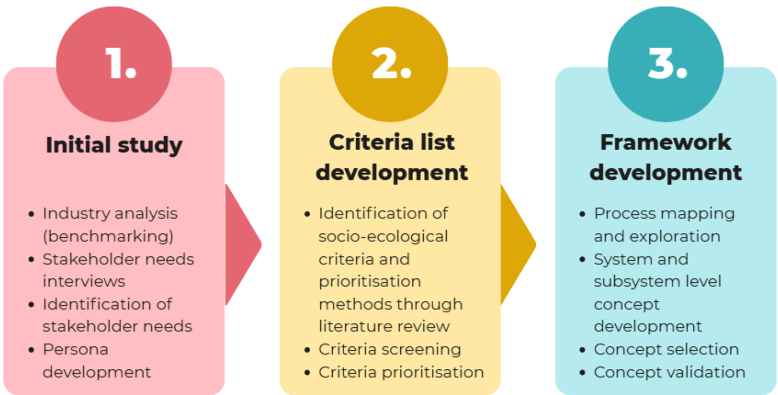

Figure 3.1: The overall process of the thesis.

Section 3.2 outlines industry benchmarking that was performed early in the thesis. Section 3.3 outlines how the stakeholder needs study was performed. Sections 3.4 and 3.5 cover the methods used to develop and prioritise a list of socio-ecological criteria, respectively. Lastly, Sections 3.6 and 3.7 outline the methodology for the final part of the thesis involving the development and validation of the framework, respectively.

3.2 Industry Sustainability Benchmarking

Competitive benchmarking is described by Ulrich et al. [14] as a multi-purpose tool which can be used to identify product development opportunities in the planning phase, as a supporting tool in the concept generation phase and as a source of benchmark metrics in concept evaluation and selection. In this project, industry benchmarking was conducted early in the development process to identify which socio-ecological aspects are already operationalised in the aerospace manufacturing industry and to identify areas where integration remains limited. A further purpose of the benchmarking was to explore broad opportunities for improvement regarding the company's consideration of socio-ecological aspects that could subsequently be addressed through the proposed framework. Therefore, the competitive benchmarking serves a dual purpose: to broaden the understanding of GKNA's sustainability integration in relation to its competitors and customers and to identify gaps and opportunities that could later be translated into stakeholder needs and inform the development of the socio-ecological criteria list and the implementation framework.

At first, a list of companies in the aerospace manufacturing industry was compiled. The benchmarking was conducted as described in Chapter 6 of Ulrich et al. [14], where each competitor is assessed against a common set of benchmarking criteria. The data was collected from the most recent publicly available sustainability report of each company. The companies assessed are GE Aerospace, SKF, MTU Aero Engines and Safran. These companies were selected since they are all manufacturers of aircraft components with production sites in Europe, similar to GKNA. In addition, these companies have substantial public sustainability reporting, which could be analysed and benchmarked with GKNA's sustainability report. The following sustainability reports were used for this analysis:

- GKNA: Melrose Industries PLC Sustainability Report 2024 [67]
- GE Aerospace: 2025 Sustainability Report [68]
- SKF: Annual Sustainability Report 2024 [69]
- MTU Aero Engines: ESG Factbook 2024/25 [70]
- Safran: 2024 Universal Registration Document [71]

The same method of evaluation was used for GKNA for consistency. No internal information about GKNA was used in the competitor benchmarking to prevent biases in the results.

The benchmarking criteria were broken down into social and ecological aspects. Social sustainability aspects were categorised by the stakeholder groups of "own workers" and "supply chain workers" to specifically include the supply chain workers, which can be overlooked due to the difficulty of assessment. The ecological criteria could be more concrete since ecological evaluation is more quantifiable and is therefore typically more mature at companies with greater consideration. The ecological benchmarking criteria are: (1) Does the company assess and report its alignment with the EU Taxonomy framework? (2) Does the company assess emissions across its value chain (Scope 1–3 GHG emissions)? and (3) Does the company address hazardous substances and material compliance (e.g. REACH, SVHC, SIN)?

This set of benchmarking criteria was chosen to get an idea of the maturity of each company in terms of considering various socio-ecological aspects. The criteria do not assess how sustainable each company is, but rather to what degree the company is aware of different sustainability-related aspects. This assessment is broad and exploratory due to the limited information presented in the sustainability reports, but it can indicate the degree of the company's awareness and transparency of its socio-ecological impacts.

3.3 Stakeholder Needs Study

At the start of the development process, a stakeholder needs study was conducted in order to design a solution that is compatible with its various stakeholders. First, key stakeholder groups within the company were identified, and interviews were conducted with several practitioners from each group to identify potential needs and opportunities. This process is outlined in detail in Section 3.3.1. In addition, a competitor analysis was performed through benchmarking to gain insights into how GKNA compares with its customers and competitors in terms of socio-ecological aspects. The benchmarking methodology is explained in Section 3.2. The result of the stakeholder needs study is the identification of stakeholder needs for the list of socio-ecological criteria on the one hand and the implementation framework on the other. The method is outlined in Section 3.3.2.

3.3.1 Stakeholder Needs Analysis - Interviews

The stakeholder needs analysis was designed to capture and explore explicit needs as well as implicit and latent needs. Implicit and latent needs may not be directly linked to stakeholders, but are still important since they influence decision-making. Emphasis was placed on understanding current ways of working and existing tools at the company, understanding how sustainability-related considerations are perceived and identifying current gaps in sustainability integration in the early-stage product development.

13 interviews with practitioners from various departments were conducted, including departments such as technology development, business development, and product development. All interviews were 30 minutes and divided into a set of 12-15 questions, including background, role-specific topics, organisational aspects, and challenges. Wrap-up questions were asked to gather recommendations on whom to contact.

3.3.2 Extracting stakeholder needs for criteria list and framework

Based on the data and general insights from the stakeholder needs study, including the initial interviews, several stakeholder needs were identified for the criteria list as well as the implementation framework. The needs were identified with the methods outlined by Ulrich et al. [14] in mind. The book describes the following process for identifying customer needs:

1. Gather raw data from customers.
2. Interpret the raw data in terms of customer needs.
3. Organise the needs into a hierarchy of primary, secondary and if necessary, tertiary needs.
4. Establish the relative importance of the needs.
5. Reflect on the results and the process.

Instead of "customer needs", this project required a broader range of stakeholder input, including various stakeholder groups within the company, such as the engineers and managers working with the criteria, as well as the team responsible for furthering sustainability initiatives within the company. Otherwise, the same general method outlined above was used, starting with the gathering of data through the stakeholder needs study, followed by the interpretation of the data in terms of customer needs. In this step, some needs were explicitly stated by the interviewees and could be easily identified. Other, more implicit or latent needs were more difficult to identify and required a more thorough analysis of the interviews and current company processes. After identifying the stakeholder needs for the criteria list on the one hand and the integration framework on the other, the needs were presented in a list with relative importance scoring for each stakeholder need.

3.3.3 Stakeholder Persona Development

Personas were developed according to three stakeholder groups- (1) sustainability experts, (2) engineers, and (3) managers- from the stakeholder needs analysis, based on patterns identified during interviews. Sustainability experts were chosen due to their level of knowledge and perspective on socio-ecological aspects; engineers were consulted for practicality and product-level perspective, whereas managers were chosen due to their broader organisational systemic perspective. Rather than representing specific individuals, the purpose of the personas was to reflect generalised profiles that group stakeholders with similar roles and responsibilities. They represent key actors in early-stage product development and framework needs, supporting the development of the framework and criteria prioritisation. Furthermore, the personas were used as a support tool to better understand how different stakeholder groups interact with and consider sustainability in early-stage product development.

3.4 Developing a List of Socio-ecological Criteria

The following section outlines the methods used to develop a list of socio-ecological design criteria. Initially, a semi-systematic literature review was conducted to gather a large number of potential criteria as described in Section 3.4.1. The list was then aggregated by reducing redundancies into a more manageable size, as further explained in Section 3.4.2. The list was then reviewed and expanded to cover both social and ecological dimensions. This expansion step is outlined in Section 3.4.3. The resulting criteria were then presented to sustainability experts for screening as described in section 3.4.4. Lastly, the list was refined as described in Section 3.4.5. The prioritisation and scoring of the resulting criteria list is explained in Section 3.5.

3.4.1 Literature Review: Criteria collection

To collect an initial list of socio-ecological criteria, a search was conducted using the search database Scopus on the 12th March 2026, with the following keywords in the title or abstract: "(social OR ecological OR sustainability OR environmental) AND (criteria OR requirement OR indicator) AND ("product development" OR "early design" OR "conceptual design" OR "early stage")". The search was further filtered to only include review papers or articles in English within the subject area of engineering and ranging between the years 2020 and 2026. This search yielded 642 results. The titles of the resulting papers were scanned for potential relevance. Papers concerning industries that were deemed too distinct from the aviation industry, such as the culinary, medical and construction industries, were excluded. Industries or broad topics such as product development, eco design, manufacturing, the automotive industry and material science were not excluded. This resulted in 105 papers that were selected to be examined further.

Each of the 105 papers was examined for socio-ecological design criteria. Papers were excluded if they contained no specific criteria, or contained too specific or too broad a set of criteria. Criteria were considered too specific if they had been developed directly for a particular product unrelated to the aerospace industry. This happened most frequently with broad product development research papers. As an example, one paper explored the design of traditional kitchen cookware through various sustainable design methods. The resulting set of criteria was deemed too specific. Examples of criteria that were deemed too broad include "environmental performance", "social performance", and "sustainable materials". This resulted in the collection of 263 criteria from 23 remaining papers. In some cases, additional papers were cited with further expansion of the criteria. These additional criteria were also collected.

3.4.2 Aggregating Initial Criteria List

The initial raw list of criteria from the literature review contained many repetitions and redundancies. This list was aggregated by combining criteria that were interpreted as having the same or very related definitions. Similar criteria were grouped together so that redundant criteria could be identified and removed. As an example, criteria such as "easy recyclability", "scrap recyclability" and "recyclability" were combined into a single criterion, "ease of recycling".

3.4.3 Expansion of Initial Criteria List

After aggregation, the criteria list was examined and expanded. The Scopus literature review yielded ecological criteria. To combat this, the social sustainability papers ([40], [41]) discussed in Section 2.3 were scanned, and missing criteria were added. The broad criterion of GHG emissions was expanded to specify each lifecycle phase, including raw material extraction, manufacturing, use, maintenance and end of life. This was done to separate the use phase emissions from other lifecycle emissions, since the use phase emissions are attributed to the majority of the lifecycle emissions.

3.4.4 Expert Screening of Criteria

After aggregation of the initial raw list of criteria, the list was validated and screened through a focus group with sustainability experts at GKNA. The purpose of this step was to ensure that the list of criteria was relevant and applicable to the company and to condense the list before moving forward to the next step of prioritisation. The participants were chosen due to their combined knowledge and experience with sustainable product development research as well as the processes, products and goals of the company. In the focus group, the list of criteria was first presented and then filtered based on discussion and eventual agreement on whether the criteria were: (a) redundant/repetitive, (b) not relevant to GKNA, (c) not relevant to early-stage product development, and (d) not applicable due to other reasons, which were clarified and documented. The resulting condensed list of criteria was used as the input into the prioritisation outlined in Section 3.5.

3.4.5 Refine and classify criteria

Before the framework design phase of the project, the list of criteria was refined and classified. First, the criteria list was examined, and some redundancies were aggregated. For each of the remaining criteria, a more detailed description was added, often from a supporting framework for complex criteria that are difficult to interpret. A possible metric/assessment method was also added to further clarify the potential use of the criteria in the context of product requirements or concept selection criteria.

The criteria were then classified by lifecycle phase based on the LCA framework as discussed in Section 2.5.1. The lifecycle phase of use and maintenance was broken down into two separate phases, since GKNA is typically directly responsible for the maintenance of the products but not the use phase. The lifecycle phases by which the criteria are classified are therefore the following: (1) raw material extraction, (2) manufacturing, (3) distribution, (4) use, (5) maintenance, (6) end of life.

The criteria were assigned to the lifecycle phases where they have the highest potential socio-ecological impact. Most of the criteria affect all lifecycle stages to some extent, but only the main direct impact stages were highlighted. As an example, the criterion of optimised product weight was assigned to the use phase only, despite potentially impacting the raw material extraction phase, since lighter products could lead to less material extracted from the earth. This lifecycle phase classification provides context for the criteria, as well as assisting in the validation of the final criteria based on literature, allowing comparison with LCA studies.

3.5 Prioritising criteria

The following section covers the method used to prioritise the developed list of socio-ecological design criteria. A combination of qualitative and quantitative methods was applied. Relevant prioritisation methods and approaches were identified and analysed through a structured literature review, focusing on methods suitable for early-stage design. Stakeholder validation and insights were captured during focus group sessions, where criteria were scored based on factors relevant to each stakeholder group. Finally, a simplified DEMATEL method was applied to gain expert judgement from the sustainability experts and to understand criteria relationships and interdependencies.

3.5.1 Literature Review: Prioritisation Methods

Prioritisation methods for criteria were explored through a structured literature review using the databases ScienceDirect and Scopus. The search process was iterative, starting with identifying key dimensions: (1) sustainability context; (2) criteria; (3) prioritisation; (4) decision-making methods. The search was filtered based on title, abstract, keywords and limited to publications in English within the fields of engineering and environmental science. Keywords were continuously refined to balance relevance. Initial searches were a combination of keywords such as "social", "ecological", "criteria", "requirement", and "prioritisation", resulting in a large number of publications. For instance, an example keyword combination was: (sustainability OR environmental) AND (criteria OR requirement) AND (aviation OR aircraft) AND (prioritization OR weighting).

To improve relevance and narrow the search, additional keywords- such as "early-stage", "conceptual design", "product development", "criteria prioritisation and weighing"- were introduced. An example keyword combination was: ("socio-ecological" OR sustainability OR environmental OR social) AND (criteria OR requirements) AND ("product development" OR "engineering design" OR "concept development") AND (prioritization OR weighting OR ranking) AND ("early stage" OR "conceptual design"). This reduced the number of results and improved the alignment with the scope of the project. However, including keywords such as "aviation" or "aircraft" resulted in very limited findings. This indicates and highlights a lack of prioritisation regarding socio-ecological criteria in early-stage product development, particularly within the aerospace industry.

Key keywords were further combined, and the identified sources were screened and evaluated based on the following criteria: (a) prioritisation method mentioned; (b) relevance; (c) aerospace specific; (d) early-stage specific; (e) potential usefulness for framework development. This structured screening process enabled the identification of relevant methods and frameworks that could potentially be used in focus groups, future framework development, and the validation of the framework.

3.5.2 Criteria Scoring Through Focus Groups

Criteria scoring in focus groups was conducted with the stakeholder groups sustainability experts, engineers and managers to refine the defined list of criteria and validate it based on the identified stakeholder needs. The purpose of the focus groups was to identify gaps, e.g. knowledge, data availability, identify important and relevant criteria, feasibility, and potential future actions for the company to implement the list of criteria. The agenda of the sessions was: (1) introduction of the project and definition of socio-ecological criteria; (2) present the list of criteria; (3) score based on different aspects; (4) discussions and insights.

The scoring of the criteria for the focus groups was conducted using the logic of the concept selection methodology by [14]. Decision matrices were used to evaluate and compare concepts against criteria that were derived from customer and stakeholder needs. The purpose of using decision matrices in a group-based environment was not only to systematically score and compare alternatives but to facilitate discussion, transparency, alignment, and agreement among participants.

Due to time constraints, the initial plan for the focus groups was refined after the first session with each stakeholder group. With the sustainability experts, the criteria filtering and scoring were divided into two sessions each, totalling four sessions. Since engineers and managers only had to score the criteria, fewer sessions were required. Two sessions were held with the engineers, while the managers held one session.

The stakeholder groups evaluated the criteria using a Likert scale of 1-5, where 5 was the highest score and 1 was the lowest score. This scoring approach was selected due to the large number of criteria evaluated, requiring a simple method to effectively differentiate between them. Each stakeholder group had a different focus: sustainability experts prioritised social and ecological impact, engineers focused on technical feasibility and relevance to products and early-stage product development, and managers prioritised strategic alignment. Similarly, they all scored the criteria based on the following perspective:

(a) Ease of implementation - How easy is it to measure and assess?

- **Score 5:** Very easy to implement: the necessary data to assess products based on the criteria are readily available, all necessary assessment tools and methods are known and practised within GKNA.
- **Score 3:** Moderately easy to implement: The criteria are relatively simple to assess, but some assessment tools or data are missing/ difficult to collect. Implementation would require some tool development, data collection, training, etc.
- **Score 1:** Very difficult to implement: large systematic/process changes would be needed within the company in order to assess products based on the criteria. Critical assessment tools, data, training, etc., are missing.

Focus Group 1: Sustainability Experts

The criteria were also scored based on: (b) potential ecological impact; (c) potential social impact, defined by:

(b) Potential ecological impact - How much potential ecological impact can the criteria have when implemented within product development at GKNA?

- **Score 5:** Very high potential impact: systematic implementation of the criteria will result in a significant reduction of the environmental footprint of GKNA products.
- **Score 3:** Moderate potential impact: systematic implementation of the criteria will result in a moderate reduction of the environmental footprint of GKNA products.
- **Score 1:** Minimal impact: systematic implementation of the criteria will not result in any reduction of the environmental footprint of GKNA products.

(c) Potential social impact - How much potential social impact can the criteria have when implemented within product development at GKNA?

- **Score 5:** Very high potential impact: systematic implementation of the criteria will result in a significant reduction of the social footprint of GKNA products.
- **Score 3:** Moderate potential impact: systematic implementation of the criteria will result in a moderate reduction of the social footprint of GKNA products.
- **Score 1:** Minimal impact: systematic implementation of the criteria will not result in any reduction of the social footprint of GKNA products.

Focus Group 2: Engineers

The criteria were also scored based on: (b) relevancy to GKNA's products; (c) relevancy to early-stage product development, defined by:

(b) Relevance to GKNA products - How relevant/applicable are the criteria to GKNA products?

- **Score 5:** Highly relevant: the criterion directly impacts GKNA products and can be used to evaluate them.
- **Score 3:** Moderately relevant: the criterion impacts GKNA products to some degree, but it may be indirect.
- **Score 1:** Not relevant: the criterion does not impact GKNA products in any meaningful way.

(c) Relevance to Early-Stage Product Development - How relevant/applicable is the criterion to early-stage product development?

- **Score 5:** Highly relevant: the criterion is directly applicable in early-stage PD decisions and strongly influences the conceptual design stage or earlier.
- **Score 3:** Moderately relevant: the criterion is partially applicable in early-stage PD decisions with some but limited influence on the conceptual design stage or earlier (may be highly relevant later).
- **Score 1:** Not relevant: the criterion is not applicable in early-stage PD decisions in the conceptual design stage or earlier (may be relevant later).

Focus Group 3: Managers

The criteria were also scored based on: (b) strategic alignment, defined by:

(b) Strategic alignment - How well aligned is the criterion with customer and stakeholder needs, overall goals and priorities of GKNA?

- **Score 5:** Very high alignment: the criterion is directly aligned with customer and stakeholder needs as well as the overall goals and strategy of GKNA moving forward.
- **Score 3:** Moderate alignment: the criterion is somewhat (maybe indirectly) aligned with customer and stakeholder needs as well as the overall goals and strategy of GKNA moving forward.
- **Score 1:** Minimal/no alignment: the criterion has limited or no alignment with customer and stakeholder needs, as well as the overall goals and strategy of GKNA moving forward.

3.5.3 Criteria Scoring Through the DEMATEL Method

After focus group scoring with sustainability experts, several high-performing criteria were selected to identify their relationships and interdependencies by applying a method inspired by DEMATEL. Unlike other scoring methods, DEMATEL allows for identifying which criteria act as drivers and those that are influenced by others.

During the session with three sustainability experts, the method involved a table of definitions and a visual board to display the selected criteria. A traditional DEMATEL method requires experts to score pairwise influences directly within a matrix; however, the approach used in this session was simplified due to time constraints and to reduce complexity. During a 15-20 minute individual session, the experts drew coloured arrows to map relationships and influences between criteria. Following this, all results were displayed where experts discussed their findings and final scores were refined. The following scoring scale in Table 3.1 shows the structure of the scoring:

Table 3.1: DEMATEL Exercise Scoring

Arrow	Meaning	Influence	Scoring
→	Green arrow	Very strong influence	4
→	Blue arrow	Strong influence	3
→	Yellow arrow	Medium influence	2
→	Red arrow	Weak influence	1
–	No arrow	No influence	0

The results from the DEMATEL exercise were used by converting the influences between each criterion by replacing the coloured arrows with scores 0-4 in a matrix. These results were then aggregated into an average direct-relation matrix (A). A was normalised to obtain the initial direct influence matrix (D) by using the maximum row sum of the matrix which the factor was calculated as: $s = \frac{1}{\max_i \sum_{j=1}^{n} a_{ij}}$, where

a_{ij} represents the influence of criteria i on criteria j. The matrix was calculated by using $D = sA$ to ensure all values remain within the interval $[0, 1)$.

Next, the total relation matrix (T), which captures both direct and indirect relationships among criteria, was calculated using $T = D(I - D)^{-1}$, where I is the identity matrix. Finally, from this matrix, the sum of rows (D), representing the total influence dispatched by a criterion to other criteria, and the sum of columns (R), indicating the total influence received by a criterion from others, were calculated.

The indicators $D+R$ and $D-R$ were calculated to analyse the relationships further. $D+R$ represents the overall importance of a criterion within the system, and $D-R$ identifies whether a criterion belongs to the causal group or the effect group. For instance, if $D - R > 0$, the criterion is considered a causal factor, and if $D - R < 0$, it is considered an effect factor. The results were used to construct a cause-effect diagram by plotting $D + R$ on the horizontal axis and $D - R$ on the vertical axis. This visualises and identifies the most influential drivers and the criteria primarily affected by others. The results of the DEMATEL were subsequently used to support the further selection of criteria for the framework development.

3.6 Framework Development

The development of the framework was performed based on the framework needs, the results from the criteria scoring and a company process mapping described in Section 3.6.1. The framework concept development consisted of initial system-level concept development and a subsequent subsystem-level concept development outlined in Section 3.6.2.

3.6.1 Company Process Mapping

To develop concepts for the framework, it was important to understand the current integration of the criteria into the company processes. This was done by systematically reviewing current sustainable product development tools, the company's product development process, including design reviews, as well as the business and technology development processes. In addition, higher-level processes, including the lifecycle gates and product development planning, were analysed. These process maps were scanned for any mention of the criteria through the descriptions, attached documents and templates. The level of integration of each criterion was scored according to Table 3.2. If the criterion was not found in any of the company processes or attached documents, it was classified as "not integrated" and given a score of 1. A criterion was classified as "voluntary" if it appeared as an example or suggestion in a supporting tool, but with no requirement to consider it. A voluntary criterion was assigned a score of 2 if it was mentioned in a few (1 or 2) stages, or a score of 3 if it was mentioned frequently across many different stages. If a criterion was mentioned as a requirement or a concept selection criterion, it was labelled as "mandatory" and assigned an integration score of 4 if present in a few of the stages or a score of 5 if it was consistently mentioned throughout the company processes.

Table 3.2: Level of Integration Classification

Level of integration	Description	Score
Not integrated	No mention of the criteria was not found in any of the company processes viewed	1
Voluntary: across limited stages	The criteria is mentioned in some stages as an example or suggestion	2
Voluntary: across many stages	The criteria is mentioned across many stages as an example or suggestion	3
Mandatory: across limited stages	The criteria is mentioned as a requirement in some stages	4
Mandatory: fully embedded	The criteria is consistently mentioned as a requirement throughout the processes	5

3.6.2 Framework Concept Development

The framework was developed with stakeholder needs in mind through system and subsystem concept development. At the system level, concepts regarding the overall nature of criteria integration were generated through brainstorming sessions. In the system-level brainstorming, the following guiding questions were addressed:

1. How pre-defined should the scoring of the criteria be in the framework?
2. How specific should the framework be to each development stage (from technology development to conceptual design)?

The first question determines whether the framework should provide an already scored list of criteria or if it should instead provide tools by which the criteria can be prioritised for each product. The second question considers the extent to which the framework should be tailored specifically to each development stage, e.g. whether the same or different sets of criteria should be integrated into each stage. After generating system-level concepts, a concept selection was performed using a Pugh decision matrix, Pugh [72], based on the outlined framework needs.

On the subsystem level, the framework was developed in further detail for each specific development stage, from technology development to conceptual design. The subsystem level dealt with the following questions:

1. Which specific criteria should be proposed in the framework?
2. Where in the process of each development stage should the criteria be integrated?

To tackle the first question, the refined criteria list and the results from the criteria scoring were analysed, and different criteria combinations were brainstormed. The second question was explored by analysing the results of the company process mapping described in Section 3.6.1. The subsystem development depended entirely on the results from the system-level concept, as the specific criteria depend on the extent to which they need to be scored/prioritised. The two development stages were therefore performed consecutively.

3.7 Validation Approach

Validation of the criteria and framework was carried out to assess their feasibility, alignment with sustainable product development and strategic sustainability. According to Marwedel [73], validation is the process of checking whether or not a certain design or partial design is appropriate for its purpose, meets all constraints and will perform as expected. In this project, an initial validation of the framework concept was conducted through practitioner interviews and a review of academic research on the development of sustainable product development tools and frameworks. The purpose of the validation interviews is to assess whether the framework is feasible in practise and whether it meets the needs of its potential users. In addition, the framework was validated through academic literature to examine whether it aligns with the guidelines of established academic research. The criteria were validated through academic literature to examine whether the selected mandatory criteria and the criteria scoring results are consistent with lifecycle-focused academic research and whether the criteria meet the fundamental need of potential social or ecological impact on GKNA products.

3.7.1 Evaluation of Framework Through Case Study Interviews

The integration framework was evaluated through semi-structured interviews with practitioners from different backgrounds at GKNA. Engineers working in product development, managers involved in planning stages, and practitioners working in technology development were gathered. During the interviews, questions were asked about a recent product case the participants had worked on. The case did not have to concern a specific product; it could be discussed in general terms. The following questions were asked:

1. What type of product have you worked on?
2. In what stage of the product development, business development, or technology development were you part of?
3. How much information was known at that stage?

The integration framework concept was then presented, and the participants were asked whether the approach of including mandatory criteria and case-by-case criteria was feasible. The interviews continued with a discussion of where the criteria could be implemented, where they could be reviewed, and which tools could support this process. It was also discussed whether this proposed framework could act as a complement to or be a part of the existing processes in the future.

The mandatory criteria were presented and explained, including the reasoning for their selection, both due to regulations and the scoring focus groups. Each criterion was discussed in terms of whether it has already been implemented or if there is a potential for implementation, and at which stage. The case-by-case criteria were also presented, and similar questions were asked. The aim was to understand each participant's perspective and experience on the criteria, and whether any of them should instead act as mandatory criteria rather than case-by-case, and vice versa. This interview approach allowed participants to elaborate based on their industry experience and to reflect on perceived strengths and weaknesses, as well as real industry challenges related to the implementation of the proposed framework concept and future opportunities.

Interview notes were analysed, and similar feedback related to usability, organisational and process fit, ownership, and integration with existing processes was identified and grouped to identify recommendations for future work and improvement of the framework.

3.7.2 Validation of Criteria Through Academic Literature

In addition to focus groups and validation interviews, the proposed criteria were validated through academic literature through a lifecycle lens. The goal of the validation was to determine whether the selected mandatory criteria and the criteria scoring results comply with academic findings and whether there is an academic basis to prioritise some of the criteria over others. To explore this, several lifecycle assessments were studied, through which potential trade-off scenarios were identified and discussed. Some of the research papers addressed specific criteria directly. In papers where criteria were not mentioned directly, the results were extrapolated to the criteria through a lifecycle impact lens, relying on the classification of the criteria by the lifecycle phase of impact, discussed in Section 3.4.5.

3.7.3 Validation of Framework Through Academic Literature

In addition to the validation of the framework through case study interviews, the framework was also validated through academic research. The validation approach involved assessment of the framework against established criteria and design principles. The purpose of the assessment was to identify whether the method by which the framework was designed complies with existing literature. In addition, the outcome of the framework was validated with success criteria by Vicente and Camocho [60] discussed in Section 2.5.2.

4

Results

4.1 Industry Sustainability Benchmarking

A broad benchmarking was conducted through the assessment of public sustainability reports of aerospace manufacturing companies to explore opportunities for improvement in terms of GKNA's consideration of socio-ecological aspects. The companies assessed were GE Aerospace, SKF, MTU Aero Engines and Safran. The reports were benchmarked on the aspects of EU Taxonomy reporting, value chain emission reporting, ecological supply chain consideration, hazardous substances assessment and social stakeholder group considerations. The key findings are summarised below.

EU Taxonomy Framework Reporting:
SKF, MTU and Safran all report their alignment with the EU Taxonomy Regulation, further described in Section 2.6.3. Safran reports a turnover eligibility rate of 91%, but a 0% alignment rate due to the DNSH pollution classification criterion [71]. MTU reports 16% taxonomy-aligned revenues from the EU Taxonomy alignment criteria of activity 3.21 Manufacture of Aircraft [70]. SKF breaks down its alignment with each of the DNSH criteria, reporting some alignment and some opportunities for improvement, particularly within the climate change adaptation, biodiversity and pollution criteria [69]. As of the 2024 sustainability report, GKNA has not assessed its EU Taxonomy eligibility and alignment, but plans on conducting this assessment for the 2025 report [67]. There is no mention of the EU Taxonomy regulation in the GE Aerospace report [67].

Value Chain Emission Reporting:
All of the studied companies report their Scope 1, 2 and 3 emissions, but they vary in what they include in the Scope 3 analysis. Safran, MTU Aero Engines, SKF and GE Aerospace all include the emissions from the use of sold products in their estimated Scope 3 emissions. Of the studied companies, GKNA is the only company that did not report the emissions from sold products in the 2024 sustainability report.

Assessment of Hazardous Substances:
Mention of REACH regulations varies greatly between the companies. Safran mentions REACH substance obsolescence risk and specifies the tracking of 4,600 substances to identify [71]. The Safran report specifies that the exact quantity (mass of the substance in a product) is not communicated to the group by the suppliers concerned since the REACH regulation requires the identification of substances of very great

concern present in articles above the 0.1% threshold, but not their quantity. The MTU report mentions the use of REACH-compliant materials in its internal policy, but does not specify any methods to ensure compliance with the REACH regulations [70]. The SKF report specifies that the company ensures traceability of substances of concern until products are delivered to customers through REACH and RoHS certificates, with an additional hazardous substances policy covering traceability in the value chain [69]. Similarly, GE Aerospace reports actively monitoring and managing its operations to remain compliant with the Toxic Substances Control Act and the REACH regulations [68]. The GKNA report mentions REACH in the context of supplier service agreements, many of which contain requirements to comply with all environmental laws and regulations, including the REACH regulations [67]. The report does not mention substance tracking or other methods that ensure compliance with REACH regulations.

Social Stakeholder Group Considerations:
The assessment of social considerations was broken down into the stakeholder groups of (1) own workers and (2) supply chain workers. All of the companies studied report extensive assessments and audits of the company's own workers, in terms of health and safety, human rights, and overall well-being.

The way in which the companies deal with social aspects regarding value chain workers varies greatly. MTU Aero Engines conducts annual risk assessments of its direct suppliers on social issues, including forced and child labour. In addition, the report specifies that key suppliers must undergo an ESG assessment by external parties and that MTU reserves the right to conduct on-site audits to verify compliance with the company's code of conduct [70]. SKF also reports a risk-based approach to assessing its supply chain regarding human rights and labour practices, specifying that tier one and sometimes tier two and three suppliers are audited [69]. GE Aerospace emphasises rigorous in-person auditing to assess suppliers' compliance with social and environmental requirements before onboarding, particularly focusing on safety, environment and working conditions. In addition, GE Aerospace reports country-risk level classification every two to three years, assessing manufacturing and human rights risks, as well as ongoing compliance monitoring of supply chain actors using on-site or remote audits [68]. In contrast, Safran and GKNA do not mention supplier auditing, relying on risk assessments to assess supplier compliance with social and environmental aspects [67, 71].

This benchmarking report outlines to what degree different aerospace manufacturing companies have already integrated or considered several broad social and ecological aspects according to their publicly available sustainability reports. It highlights several improvement areas for GKNA, namely, the assessment of EU Taxonomy eligibility and alignment, estimation of product use phase emissions, monitoring and tracking of hazardous substances and assessment of supplier compliance with social and environmental aspects.

4.2 Stakeholder Needs Study

This section presents the results of the stakeholder needs study conducted at GKNA, including stakeholder needs interviews, identification of stakeholder needs, and persona development. The interviews include the main priorities and challenges of the stakeholder groups, while the personas describe their role in product development and relevance to the study.

4.2.1 Stakeholder Personas

Stakeholder interviews revealed different perspectives on integrating sustainability into early-stage product development. To synthesise these findings and support framework development, personas were developed to represent key stakeholder groups. These personas include sustainability experts, engineers, and managers, as presented in Table 4.1, which outlines the identified stakeholder groups, their roles in product development, and their relevance to the study.

Table 4.1: Stakeholder Personas Overview

Stakeholder Personas		
Stakeholder Group	**Role in Product Development**	**Relevance to the Study**
Sustainability Expert	Supports sustainability integration within PD processes by conducting assessments, ensuring compliance, refining organisational processes, and utilising support tools.	Provides expertise in socio-ecological criteria, sustainability assessment methods, and relevant regulations, supporting informed decision-making and sustainability integration.
Engineer	Develops and evaluates concepts and solutions within early-stage PD and technology development.	Acts as the primary user of the framework during concept development and concept selection.
Manager	Guides technology development and roadmaps, strategic decision-making, business development, and product planning.	Influences implementation, priorities, and strategic organisational alignment.

4.2.2 Stakeholder Needs Interviews

The interviews revealed several stakeholder needs regarding the integration of sustainability into early-stage product development. These include:

- Clearer sustainability requirements.
- Simplified and improved decision-making tools, methods, and processes.
- Traceability in information-sharing and ownership.
- Stronger cross-functional communication and organisational integration of sustainability considerations.

Table 4.2 summarises the main priorities and key challenges.

Table 4.2: Stakeholder Priorities and Challenges

Stakeholder Needs Study		
Stakeholder Group	**Main Priorities**	**Key Challenges**
Sustainability Expert	Early-stage sustainability awareness across teams/organisation, ensuring REACH compliance, increasing transparency and awareness in environmental assessments.	Lack of early-stage data, support tools, and information sharing IT tools and processes. Unclear ownership and poor traceability, uncertainty in underlying assumptions.
Engineer	Concept and solutions that meet lightweight designs, airworthiness, cost efficiency, performance, and manufacturability.	Lack of clear sustainability requirements, regulatory and supplier uncertainty, limited support tools, difficulty in balancing sustainability with other aspects (e.g. cost and performance).
Manager	Customer partnership and market competitiveness, sustainability targets, regulatory compliance and fuel efficiency.	Lack of clear and standardised sustainability measurements and assessments, sustainability metric uncertainty, and limited influence over engine-system decisions.

The lack of clear sustainability requirements was addressed by several stakeholders, as they are often viewed as vague and difficult to interpret, inconsistently communicated, or poorly integrated into the requirement specification and concept evaluations. Furthermore, engineers and managers highlighted that sustainability considerations usually rely on an individual's personal awareness or interest rather than systematic engineering standards or requirements.

Stakeholders expressed a need for simplified decision-making tools capable of supporting trade-offs and guiding sustainability considerations. Some participants were unfamiliar with existing tools such as the Environmental Sustainability Tool (EST) and Sustainability Impact Assessment (SIA) tools (outlined in Section 4.4.1), and others highlighted limitations of the tools with respect to consistency and practical influence on decision-making. Stakeholders emphasised the need to systematically integrate sustainability into lifecycle and commercial gates, concept selection matrices, and trade studies.

Lifecycle and supply chain impacts were highlighted as important factors that should be introduced earlier in the development stages. Key challenges include data availability, the lack of traceability, and insufficient lifecycle evaluations during pre study activities. These issues were highlighted with respect to compliance with REACH, critical materials, and tracking and managing long-term lifecycle emissions.

The practitioners emphasised the need for stronger organisational alignment on sustainability integration, arguing that sustainability must be driven by management rather than relying on individual practitioners and should be embedded into strategic priorities, lifecycle gates, planning, and requirements. Consistent and cross-functional communication between management, engineering, procurement, and sustainability teams should be improved for successful and consistent integration.

4.2.3 Stakeholder Needs for Criteria List

Table 4.3 summarises the stakeholder needs that were extracted from the interviews discussed in section 3.3.1. After identification, the stakeholder needs were assigned an importance score from 1-5 in order to highlight which needs are prioritised. The top needs, with a score of 5, deal with the practical "must-haves" for the criteria list.

The first need outlines the main purpose of the socio-ecological criteria, which is to improve the social or ecological impact of GKNA products. Similarly, as stated by the second need, since this criteria list is developed specifically for GKNA, all criteria need to be relevant to GKNA products within some context. The third "must have" need addresses the practicalities of implementing the criteria into product requirements or concept selection matrices. To assess product concepts, the criteria need to be measurable. The fifth need, requiring the criteria to be quantifiable, is extracted from the interviews with engineers at GKNA, highlighting the importance of having a quantified range of acceptance for product requirements. This need is ranked slightly less important than measurability, as not all criteria are suitable for a numeric scale. Some criteria could have a binary yes/no or go/no-go metric.

The stakeholder needs number 4 and 6 were extracted from sustainability experts interviews at GKNA. Need number four addresses the concern that sustainability-related regulations, in particular the REACH regulations, are lacking in official company product development-related processes. The sixth need outlines importance of considering both social and ecological aspects in the criteria list, as the sustainability experts expressed a lack of social consideration in the current processes and tools.

Stakeholder needs number 7, 8 and 9, with importance scores below 4, should be considered but should not be used to eliminate certain criteria. Need number 7, addressing the compatibility of criteria with the company's strategic goals, is practically important since it indicates how likely it is for the company to consider the criteria. However, this need is only given an importance score of 3 because the company's strategy is continuously developing and adapting to the market, technology and internal drivers. This stakeholder need should therefore not be used to eliminate any particular criterion. The eighth need is also given an importance score of 3 because whether a criterion applies to the early product development stages is highly dependent on the product and its technology readiness level.

The ease of implementation expressed by need number 9 has a low importance rating, as this need might limit the effectiveness of the criteria list. If criteria which are easy to implement due to, e.g. availability of data, are prioritised, this might contradict the first stakeholder need of potential socio-ecological impact. A criterion that is difficult to implement due to a lack of data or a lack of assessment tools can be viewed as an opportunity for improvement for the company rather than a reason for excluding the criterion altogether.

Table 4.3: Stakeholder Needs for the Criteria List

No.	Stakeholder need	Imp.
1	The implementation of the criteria has the potential to improve GKNA products in terms of social or ecological impact	5
2	The criteria are applicable to GKNA products	5
3	The criteria are measurable	5
4	The list of criteria addresses regulatory compliance	4
5	The criteria are quantifiable	4
6	The criteria list considers both social and ecological aspects	4
7	The criteria are compatible with GKNA's overall goals/strategy	3
8	The criteria apply to the early stages of product development	3
9	The criteria are easy to implement	2

4.3 Socio-Ecological Criteria List and Prioritisation Methods

Figure 4.1 presents an overview of the criteria list development, which resembles a typical concept development process with an initial expansion, followed by iterative reduction and expansion steps. The criteria were funnelled from the initial 263 criteria identified in the literature review down to 41 refined criteria. The results from the initial literature review and the added social criteria in the expansion stage can be viewed in Appendix A.

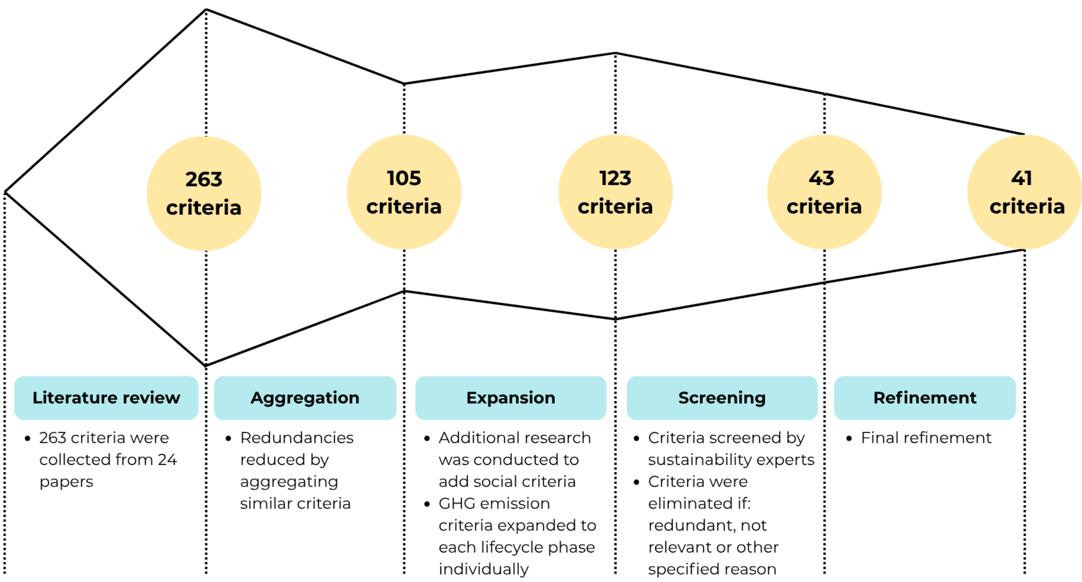

Figure 4.1: The criteria list development process.

Figure 4.2 illustrates the aggregation results of the criteria related to recycling. Criteria such as "easy recyclability", "scrap Recyclability", "recyclability", etc., were combined into a single criterion, "ease of recycling". Similarly, the criteria "recycled materials" and "share of recycled materials" were aggregated into "use of recycled materials". The remaining criteria highlighted in blue in Figure 4.2 are more systematic, focusing on overall practical recycling potential throughout a product's lifecycle. This set of criteria was therefore compiled into the term "material circularity capability", which captures the potential for materials to be kept in the market at the highest possible quality for multiple product lifecycles [74].

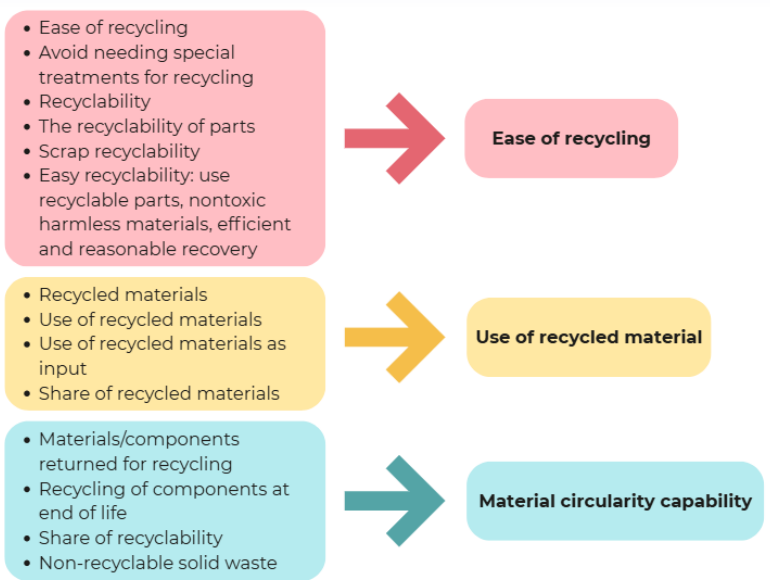

Figure 4.2: Aggregation of criteria related to recycling.

The screening results of the aggregated criteria list are presented in Appendix B. Sections 4.3.2 and 4.3.3 present the highest and lowest ranked criteria from the focus group scoring and the DEMATEL scoring, respectively. The full results from the criteria scoring can be viewed in Appendix C. After the criteria scoring, the list of criteria was refined, further defined and classified by the lifecycle phases of impact. The resultant refined list is presented in section 4.3.4.

4.3.1 Prioritisation and Scoring Methods Results

The literature review of prioritisation approaches identified several methods and frameworks for prioritising criteria. Relevant methods were identified and grouped into the following categories: (1) simple scoring-based methods, (2) MCDM methods, (3) relationship-based methods, and (4) advanced hybrid methods. The methods are presented below:

1. QESC model, P5 frameowrk, Rough-Grey analysis
2. AHP, TOPSIS, Fuzzy-TOPSIS, Best-Worst Method (BWM)
3. DEMATEL
4. Choquet Integral approaches, Fuzzy MCDM Frameworks

Each category was highlighted with its core idea, strengths, limitations, data requirements, uncertainty handling, early-stage and framework development fit. The review revealed that simple scoring-based methods are easy to use and require minimal data, making them suitable for early-stage product development. However, these methods assume that criteria are independent and rely on expert judgement, which may introduce bias. In contrast, relationship-based methods, such as DEMATEL, allow for the analysis of cause-and-effect relationships and interdependencies among criteria. Studies highlight the value of DEMATEL, as it can identify the most influential criteria and key drivers of the system, as well as reduce the complexity associated with large sets of criteria. Advanced hybrid methods allow for the capture of synergies and conflicts and can provide more robust prioritisation; however, they are mathematically complex and difficult to apply, requiring expertise.

The review highlighted a gap in the literature, where research addresses sustainability criteria, prioritisation methods, and aerospace applications individually, but not in an integrated manner. There is therefore a need for future research that integrates these aspects within early-stage product development in the aerospace industry.

Given the focus on early-stage product development, where data availability is limited, methods requiring large datasets were not selected. Therefore, expert-based scoring and evaluation were selected as the primary prioritisation method to assess the relevance of criteria to products, early-stage product development, socio-ecological impact, and ease of implementation. The DEMATEL method was selected as a complementary approach, as it analyses the influence of criteria and their interdependencies, providing insights that cannot be captured by simple scoring.

4.3.2 Socio-Ecological Criteria Scoring through Focus Groups

Scoring of socio-ecological criteria was conducted through focus groups with stakeholder groups, sustainability experts, engineers, and managers, who collectively scored the criteria. Each group used a scale of 1 to 5 (where 5 was the highest score and 1 was the lowest) to evaluate criteria based on evaluation factors such as ease of implementation and evaluation factors. The evaluation factors are based on the stakeholder needs outlined in Table 4.3, catering to the expertise of each stakeholder group. The comparison of the highest and lowest scored criteria for ease of implementation for all stakeholder groups can be seen in Table 4.7.

Stakeholder 1 - Sustainability Experts

The sustainability experts consisted of three practitioners associated with the company, with complementary expertise in sustainable product development, LCA, and sustainability strategy within the aerospace industry. Table 4.4 summarises the highest and lowest evaluated criteria based on potential ecological and social impact. These evaluation factors correspond to the first stakeholder need outlined in Table 4.3.

Table 4.4: Highest and lowest scored socio-ecological criteria from the sustainability expert focus group.

Criteria	**Ecological Impact**	**Social Impact**	**Total**
Highest scored criteria			
Weight	5	2	7
Use of conflict materials	2	5	7
Use phase GHG emissions	5	2	7
Product quality	2	5	7
Product safety (operational)	2	5	7
Product performance	4	3	7
Use of recycled material	4	3	7
Use of substances listed in REACH candidate list	3	4	7
Risk of being exposed to dangerous substances	3	4	7
Material utilisation	4	3	7
Raw material consumption	4	3	7
Repairability	4	3	7
Use of substances listed in SIN candidate list	3	4	7
Lowest scored criteria			
Ease of recycling	3	1	4
Qualified labour forces	1	3	4
Emissions from energy consumption	2	2	4
Energy consumption	2	2	4
Material circularity capability	3	1	4
Vertical range of manufacture	1	3	4
Job creation and skills development	1	3	4

The sustainability expert focus group prioritise criteria related to material, compliance, and product use phase, including weight, use phase GHG emissions and use of conflict materials. This indicates a focus on reducing environmental impact while ensuring compliance with sustainability-related regulations. Criteria, such as material circularity capability, job creation and skills development, and vertical range of manufacture, received lower scores, indicating less focus on organisational and manufacturing-related aspects.

Stakeholder 2 - Engineers

The engineer focus group consisted of three practitioners associated with the company, with complementary expertise in product development, engineering analysis, and aerospace component design. Table 4.5 summarises the highest and lowest evaluated criteria based on relevance to GKNA products and to early-stage product development. These evaluation factors correspond to the second and eighth stakeholder need presented in Table 4.3.

Table 4.5: Highest and lowest scored socio-ecological criteria from the engineering focus group.

Criteria	**Relevance to GKNA Products**	**Relevance to Early-Stage PD**	**Total**
Highest scored criteria			
Weight	5	5	10
Use phase GHG emissions	5	5	10
Product quality	5	5	10
Product safety (operational)	5	5	10
Product performance	5	5	10
Improved functionality	5	5	10
Durability (life)	5	5	10
Ease of serviceability	5	5	10
Material utilisation	5	5	10
Potential for dual use	5	5	10
Lowest scored criteria			
Water consumption	1	1	2
Carbon footprint - scope 1 and 2	1	1	2
Vertical range of manufacture	1	1	2
Emissions from energy consumption	1	1	2
Noise to the surroundings	1	1	2
Risk of corruption	1	1	2
Raw material extraction GHG emissions	1	1	2
Transportation	1	1	2
Upgradeability	1	1	2

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Table 4.5 – continued from previous page

Criteria	Relevance to GKNA Products	Relevance to Early-Stage PD	Total
Use of substances listed in SIN list	1	1	2
Qualified labour force	1	1	2
Situations where human rights are at risk	1	1	2
Freedom of association and collective bargaining	1	1	2

The engineers assigned the highest scores to criteria related to product performance and the use phase. Some social criteria, such as qualified labour force and situations where human rights are at risk, were scored the lowest. Overall, a relatively large number of criteria received low scores from the engineers in terms of relevance to GKNA products and early-stage product development. This indicates that engineers place emphasis on criteria that directly influence product performance and other operational outcomes, and view other criteria, including some labour-related criteria, as not directly relevant to product development.

Stakeholder 3 - Managers

The manager focus group consisted of three senior practitioners associated with the company, with complementary expertise in product development and strategy, materials and manufacturing processes, and industrial engineering and production systems within the aerospace sector. The following Table 4.6 summarises the highest and lowest evaluated criteria based on strategic alignment. This evaluation factor corresponds to the stakeholder need number 7 as presented in Table 4.3.

Table 4.6: Highest and lowest scored socio-ecological criteria from the managerial focus group.

Criteria	Strategic Alignment
Highest scored criteria	
Weight	5
Energy consumption	5
Water consumption	5
Product quality	5
Product safety (operational)	5
Product performance	5
Durability (life)	5
Use of substances listed in REACH candidate list	5
Employee health and safety	5
Qualified labour force	5
Risk of being exposed to dangerous substances	5
Labour rights violation risk	5

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Table 4.6 – continued from previous page

Criteria	Strategic Alignment
Supplier compliance with regulations	5
Risk of corruption	5
Lowest scored criteria	
Use of substances listed in SIN list	1
Vertical range of manufacture	2
Raw material consumption	2

Compared with the other stakeholder groups, the managers assigned the criteria higher overall scores. Product-related criteria such as quality, safety, and performance remained highly scored. Several criteria related to consumption, compliance, and employee-related factors such as energy consumption, water consumption, employee health and safety received the highest scores, showing strategic importance for governance, workforce, and ethical business practices.

Comparison of Stakeholder Ease of Implementation Results

During each stakeholder focus group, the criteria were scored based on ease of implementation, corresponding to stakeholder need number 9 as outlined in Table 4.3. Table 4.7 highlights criteria consensus and disagreement across the stakeholder groups. The following describes the colour coding:

- **Green highlight:** For the highest-scored criteria, all three stakeholder groups scored the criteria as 5 or 4, and for the lowest-scored criteria, all three stakeholder groups scored the criteria as 1 or 2.
- **Yellow highlight:** Two out of three stakeholder groups scored the criteria as 5 or 4 for the highest-scored criteria, or 1 or 2 for the lowest-scored criteria.
- **Not listed:** The stakeholder groups scored the criteria inconsistently.

The results show an agreement across all three stakeholder groups regarding product-related criteria, suggesting that these criteria are measurable and integrated into company processes. An interesting finding is the criteria use phase GHG emissions, which was scored highly by the sustainability experts and engineers, but not by the managers.

Several criteria received low scores across all stakeholder groups, including situations where human rights are at risk, raw material extraction GHG emissions, and freedom of association and collective bargaining. Most of the criteria received inconsistent scoring by the stakeholder groups, with either two stakeholder groups in agreement or none.

Table 4.7: Comparison of highest and lowest ease of implementation scored criteria across the three stakeholder groups.

Sustainability Experts	**Engineers**	**Managers**
	Highest scored criteria	
Weight	Weight	Weight
Product quality	Product quality	Product quality
Product safety	Product safety	Product safety
Product performance	Product performance	Product performance
Durability	Durability	Durability
Employee health and safety	Employee health and safety	Employee health and safety
Flexibility of supply chain	Flexibility of supply chain	Flexibility of supply chain
Carbon footprint - scope 1 and 2	Carbon footprint - scope 1 and 2	Carbon footprint - scope 1 and 2
Use phase GHG emissions	Use phase GHG emissions	
Ease of recycling		Ease of recycling
Qualified labour force		Qualified labour force
	Use of critical materials	Use of critical materials
	Energy consumption	Energy consumption
	Water consumption	Water consumption
	Use of substances listed in REACH candidate list	Use of substances listed in REACH candidate list
	Compliance with regulations	Compliance with regulations
	Vertical range of manufacture	Vertical range of manufacture
	Lowest scored criteria	
Upgradeability	Upgradeability	Upgradeability
Raw material extraction GHG emissions	Raw material extraction GHG emissions	Raw material extraction GHG emissions
Raw material consumption	Raw material consumption	Raw material consumption
Material utilisation	Material utilisation	Material utilisation
Freedom of association and collective bargaining	Freedom of association and collective bargaining	Freedom of association and collective bargaining
Material circularity capability	Material circularity capability	
	Use of recycled material	Use of recycled material
	Potential for dual use/secondary function	Potential for dual use/secondary function
Use of substances listed in SIN list	Use of substances listed in SIN list	
Situations where human rights are at risk	Situations where human rights are at risk	
Job creation / negative impact and skills development		Job creation / negative impact and skills development

4.3.3 Socio-Ecological Criteria Prioritisation through DEMATEL

A DEMATEL-inspired method was conducted through a focus group with sustainability experts to analyse the relationships and interdependencies between the prioritised socio-ecological criteria, which was intended to identify the influence of the criteria. Prior to the focus group, the criteria were narrowed down to 17 top-scoring criteria by selecting criteria with the following scores:

- Ecological impact + social impact of score ≥ 7
- Ecological impact + social impact + ease of implementation score ≥ 10
  - Result: 17 socio-ecological criteria

Each sustainability expert worked individually for 20 minutes, drawing arrows between criteria they believed influenced one another. Afterwards, the results were presented to the group, and similar patterns and differing opinions were discussed. These discussions took place while new arrows were drawn between criteria. The results of the session with drawings can be seen in Figure 4.3.

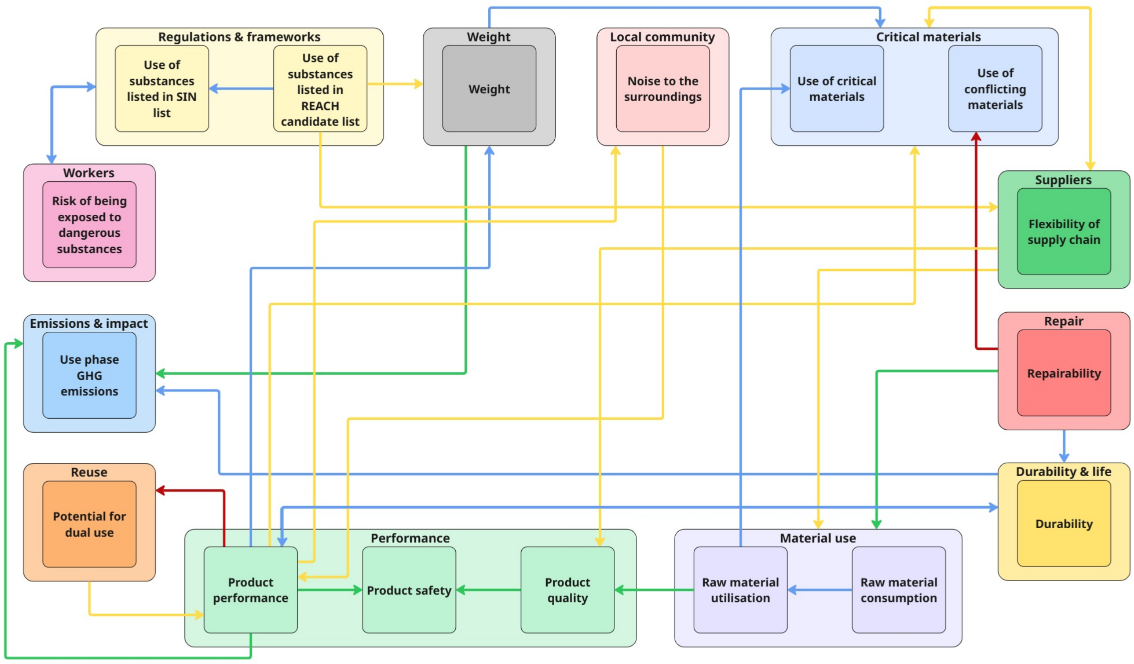

Figure 4.3: DEMATEL focus group results.

The results indicate that criteria such as product performance, repairability, and durability influence many criteria, suggesting that these are strong drivers of the system. In contrast, criteria such as use phase GHG emission, product safety, and product quality are primarily influenced by other criteria. To continue with the DEMATEL method, several matrices were developed. First, a direct influence matrix A was created with 17 criteria in the rows and columns, creating a 17x17 matrix. The assigned colours of the arrows were translated into scores ranging from 0 to 4. The scores in each row were then summed, and the highest row sum (17), corresponding to the criterion "product performance", was used as the normalisation factor s. The resulting matrix can be viewed in Appendix D.

Next, the matrix was transformed into a normalised direct-influence matrix, D, presented in Appendix E, where each criterion's score was calculated as: $D = A/17$. The total relation matrix represents the total influence of the criteria. The total relation matrix is presented in Appendix F. Based on the total relation matrix, a cause-effect matrix was created to calculate the following DEMATEL indicators:

- D = sum of rows: Total influence a criterion gives to others. Higher value $\rightarrow$ criterion influences many others.
- R = sum of columns: Total influence received from others. Higher value $\rightarrow$ criterion is strongly affected by others.
- $D + R$ = Measures overall importance in the system. Higher value $\rightarrow$ greater prominence.
- $D - R$ = Cause/Effect
- $D - R > 0$ = Criterion is a cause (driver): influences the system more than influences.
- $D - R < 0$ = Criteria is an effect: mostly influenced by others.

Table 4.8 presents the DEMATEL scoring of the criteria. The criteria are presented in order of highest prominence to highlight the most influential criteria.

Table 4.8: DEMATEL Cause-Effect Summary

Criteria	D	R	D+R	D-R	Group
Product performance	1.311	0.522	1.833	0.789	Cause
Flexibility of supply chain	0.601	0.576	1.178	0.025	Cause
Use of critical materials	0.188	0.963	1.151	-0.774	Effect
Use of substances listed in REACH candidate list	0.883	0.262	1.145	0.621	Cause
Raw material utilisation	0.500	0.639	1.139	-0.138	Effect
Weight	0.655	0.417	1.072	0.238	Cause
Repairability	1.070	0.000	1.070	1.070	Cause
Risk of being exposed to dangerous substances	0.557	0.485	1.042	0.073	Cause
Durability (life)	0.584	0.445	1.029	0.139	Cause
Use phase GHG emissions	0.000	0.947	0.947	-0.947	Effect
Use of conflict materials	0.188	0.673	0.862	-0.485	Effect
Product quality	0.235	0.571	0.806	-0.336	Effect
Use of substances listed in SIN candidate list	0.275	0.485	0.760	-0.210	Effect
Raw material consumption	0.265	0.235	0.500	0.029	Cause
Noise to the surroundings	0.272	0.179	0.451	0.093	Cause
Product safety	0.000	0.370	0.370	-0.370	Effect
Potential for dual use	0.272	0.090	0.361	0.182	Cause

The following Figure 4.4 represents the DEMATEL cause-effect diagram. The criteria with the strongest causal influence are repairability, product performance, and use of substances listed in the REACH candidate list, as they have the highest positive D-R value, therefore highlighted in bold. Criteria such as weight, risk of being exposed to dangerous substances, and durability also influence other criteria.

As seen in Table 4.8, product performance has the highest prominence and a strong positive D-R value, indicating that it is both highly influential and highly interconnected. Among the cause factors, repairability exhibits the highest D-R (1.070), indicating the strongest causal driver, followed by the Product performance and use of substances listed in the REACH candidate list, also indicating high prominence and strong causal influence. In contrast, criteria such as use of critical materials, use phase GHG emissions, product safety, and product quality are dependent criteria and do not act as drivers.

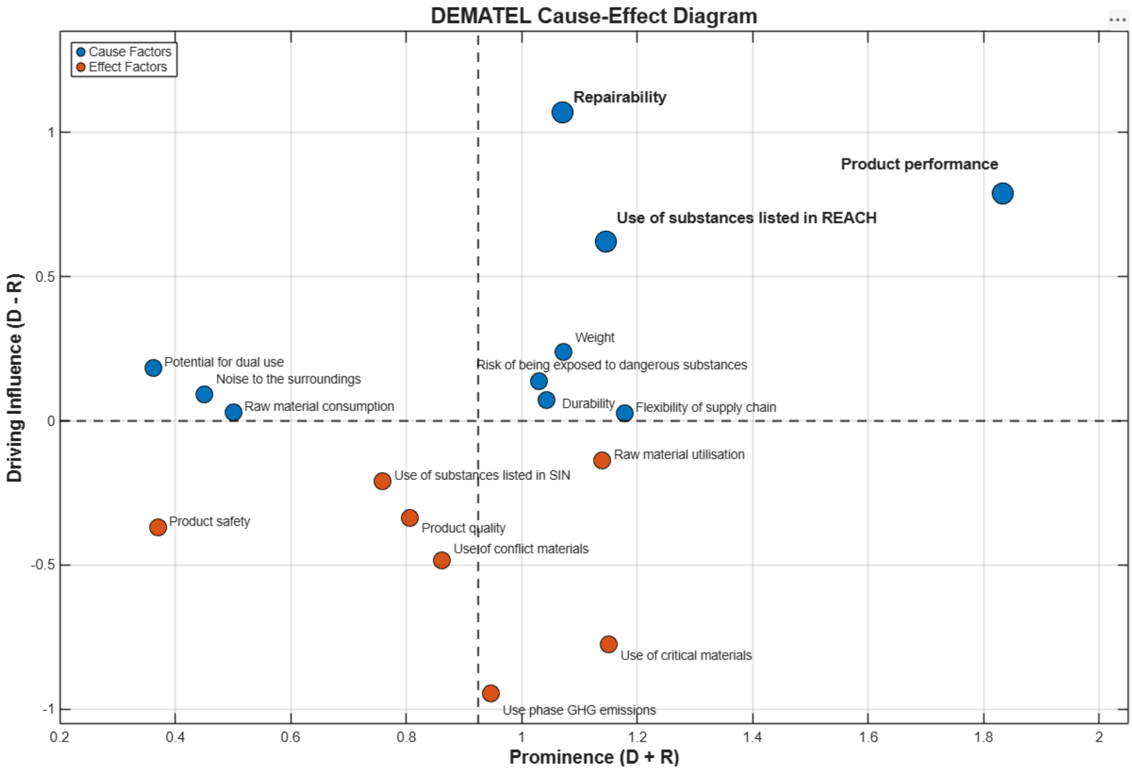

Figure 4.4: DEMATEL cause-effect diagram.

4.3.4 Refined List of Criteria

Before the framework design phase of the project, the list of criteria was refined and classified. The criterion of "compliance with regulations" was removed as it was deemed too overarching and broad. The criterion of "emissions from energy consumption" was also removed, since it is made redundant by the criteria of "raw material extraction GHG emissions", "carbon footprint - Scope 1 and 2", and "use phase GHG emissions" in the lifecycle stages of raw material acquisition, manufacturing and use, respectively. Table 4.9 presents the refined criteria list with more detailed descriptions, possible metrics or assessment methods, lifecycle phases of impact and their sources, either from the literature review, additional research or the focus groups.

Table 4.9: Refined List of Socio-Ecological Criteria

Socio-ecological criteria	Description	Possible metric/ assessment method	Lifecycle phase	Source
C1: Ease of recycling	Recyclability of materials involved in the product, amount of non recyclable waste, ease of disassembly (product complexity). [75]	Qualitative scoring	End of life	[6, 76–80]
C2: Material circularity capability	The potential of maintaining products, components and materials in closed loops through reuse, remanufacturing and recycling [81].	Qualitative scoring	End of life	[34, 45, 82–84]
C3: Use of recycled material	How much recycled material does the product contain?	% of recycled material mass of overall product mass	Raw material extraction	[6, 34, 85]
C4: Use of conflict minerals	Use of high-demand materials from regions suffering from armed conflicts or weak governance with systematic violations of international law [86].	Material criticality tool [87]	Raw material extraction	[87]
C5: Use of critical materials	Use of critical materials that pose high associated supply risks [88].	Material criticality tool [87]	Raw material extraction	[34, 83, 85]
C6: Weight	Optimised product weight	kg	Use	[34, 82, 83, 89]
C7: Material utilisation	How much of the total material purchased is used in the final product?	buy-to-fly ratio	Raw material extraction, End of life	[76]
C8: Raw material consumption	Amount of raw material consumed throughout the product's lifecycle.	kg	Raw material extraction	[19, 45]
C9: Energy consumption	The company controlled and material-related energy consumption associated with the product.	kWh	Raw material extraction, Manufacturing, Distribution, Maintenance	[77, 80, 90, 91]
C10: Water consumption	The company controlled and material-related water consumption associated with the product.	Volume	Raw material extraction, Manufacturing, Maintenance	[84]

Socio-ecological criteria	Description	Possible metric/ assessment method	Lifecycle phase	Source
C11: Carbon footprint scope 1 and 2	Emissions from company's own activities and from the production of purchased energy associated with the product [92].	$tCO_2eq.$	Manufacturing, Distribution, Maintenance	[6, 77]
C12: Overall toxic and hazardous emissions to air, water, soil	The risk of toxic and hazardous emissions to air, water and soil associated with the product.	Risk assessment	Entire lifecycle	[79, 84]
C13: Use phase GHG emissions	The use phase greenhouse gas emissions associated with the product.	$tCO_2eq.$	Use	[34, 84, 93]
C14: Raw material extraction GHG emissions	The emissions from raw material extraction associated with the product.	$tCO_2eq.$	Raw material extraction	[34, 84, 93]
C15: Transportation	Impact of transportation related to the product	$tCO_2eq.$.	Distribution	[6, 45, 76]
C16: Human toxicity: cancer and non cancer effects	The risk of human toxicity effects associated with the product.	Human toxicity potential [94]	Entire lifecycle	[45]
C17: Hazardous waste: avoid needing special measures for disposal	The potential hazardous waste generation associated with the product throughout its lifecycle.	Hazardous waste generation factor (HWGF) [95]	End of life	[6, 45]
C18: Potential for dual use/secondary function	Potential for product/ components/ materials to be reused or adapted for a secondary function.	Qualitative scoring	End of life	[84, 96]
C19: Product quality	The degree to which the product fulfils specified requirements [97] with additional aerospace specific safety, reliability and compliance requirements.	Qualitative assessment	Use	[91, 98]
C20: Product safety (operational)	The probability that the use of the product will result in illness, injury, death or negative consequences to people, property or equipment [99].	Qualitative assessment	Manufacturing, Use, Maintenance	[34, 79, 85, 90]
C21: Product performance	The ability of a product to fulfil its intended functions under specific conditions [100]	Multifaceted assessment depending on product	Use	[45, 91, 101]

Socio-ecological criteria	Description	Possible metric/ assessment method	Lifecycle phase	Source
C22: Improved functionality	Expansion in the range or improvement in the quality of the operations/functions that a product performs relative to its previous generations.	Qualitative/ performance assessment	Use	[84]
C23: Vertical range of manufacture	The extent to which the company occupies successive levels in the production hierarchy from raw materials to the final consumer [102].	Ratio of in-house/ external manufacturing	Manufacturing, Distribution, Maintenance	[84]
C24: Durability	The ability of the product to remain able to perform its required function under specified conditions of use and maintenance until a limiting state is reached [103].	Estimated no. of years	End of life	[45, 76, 91, 96, 101, 104]
C25: Serviceability	The degree of difficulty or ease with which a product can be restored to its operable state [105].	Maintenance time	Maintenance	[76, 91, 101]
C26: Repairability	The probability that a failed product will be repaired to its operational state within a given active repair time [105].	Repair time/energy consumption	End of life	[45]
C27: Upgradeability	The potential and fitness of a product to be effectively and efficiently modernised during the usage and/or remanufacturing stage [106]	Qualitative assessment	End of life	[76]
C28: Use of substances listed in REACH candidate list	The amount (kg) of substances listed in the REACH candidate list involved in the entire lifecycle of the product [107].	w/w percentage	Entire lifecycle	[34, 83]
C29: Use of substances listed in SIN list	The amount (kg) of substances listed in the SIN list involved in the entire lifecycle of the product [108].	w/w percentage	Entire lifecycle	[34, 83]

Socio-ecological criteria	Description	Possible metric/ assessment method	Lifecycle phase	Source
C30: Employee health and safety	The prevention of occupational risks, protection of safety and health, elimination of risk and accident factors, informing and training of workers related to the product [109].	Risk assessment	Manufacturing, Distribution, Maintenance	[6, 34, 45, 83, 84, 90, 91, 101]
C31: Qualified labour force	The availability of a workforce with the required skills and knowledge to develop the product.	Competency assessment	Manufacturing, Distribution, Maintenance	[84]
C32: Risk of being exposed to dangerous substances	The risk of people being exposed to dangerous substances associated with the product throughout its lifecycle.	Risk assessment	Entire lifecycle	[34, 83]
C33: Situations where human rights are at risk	Situations during the lifecycle of the product where human rights are at risk.	Risk assessment	Entire lifecycle	[101]
C34: Freedom of association and collective bargaining	Freedom of association and collective bargaining of internal and supply chain workers related to the product.	Trade union density assessment [110]	Entire lifecycle	[41]
C35: Labour abuse	Infringement of labour laws, such as failure to pay minimum wage.	Risk assessment	Entire lifecycle	[41, 90]
C36: Flexibility of supply chain	The number of available suppliers for the components/materials required for the product (multi-sourcing).	No. of possible suppliers	Raw material extraction, Manufacturing, Maintenance	Focus group
C37: Supplier compliance with regulations	Supplier compliance with all applicable multi-jurisdictional regulations [111].	Supplier auditing	Raw material extraction	[40]
C38: Job creation/loss and skills development	The potential job creation or job loss associated with the product.	No. of jobs created / No. of jobs lost	Manufacturing, Maintenance	[101]
C39: Noise to the surroundings	Noise pollution associated with the product affecting workers and affected communities.	Standards [112], [113]	Manufacturing, Use, Maintenance	[34, 83]

Socio-ecological criteria	Description	Possible metric/ assessment method	Lifecycle phase	Source
C40: Due diligence	Continuous process to help enterprises identify risks relating to human rights, labour rights and the environment [114].	Qualitative assessment of customers and suppliers	Entire lifecycle	[101]
C41: Risk of corruption	Country risk of corruption.	Risk assessment	Entire lifecycle	[101]

4.3.5 Criteria List Evaluation

To evaluate the success of the socio-ecological criteria list presented in Table 4.9, it can be assessed based on the stakeholder needs (SN) outlined in Table 4.3. The criteria were assessed on stakeholder needs number 1, 2, 7, 8 and 9 through the focus group scoring sessions presented in Section 4.3.2. The other stakeholder needs are less complex and can be assessed without expert input.

SN1: Potential social or ecological impact
The results of the lowest-scoring criteria in terms of ecological and social impact presented in Table 4.4 show that nearly all of the criteria have a score of 3 or above in either potential social or ecological impact. This indicates that the sustainability experts believe that the implementation of the criteria has at least a moderate potential to reduce the environmental or social footprint of GKNA products. Only two criteria were scored below 3 in both the social and ecological criteria: "emissions from energy consumption" and "energy consumption". In the focus group, these criteria were viewed as company-controlled energy consumption, excluding the use phase, which led to the lower scoring.

In the refined list of criteria, "emissions from energy consumption" was removed and aggregated with "carbon footprint Scope 1 and 2" due to their overlap and low scores. Energy consumption (C9) was kept but expanded to include the material-related energy consumption. Now the criterion includes all upstream energy consumption related to the product. This criterion was not, however, extended to the use phase, since its inclusion would overshadow and preclude consideration of the upstream lifecycle phases due to the overwhelming magnitude of fuel consumption associated with an airborne product over its lifecycle. According to the sustainability expert scoring, all criteria in the refined criteria list have at least a potential moderate impact on the social or ecological footprint of GKNA products.

SN2 & SN8: Applicability to GKNA products & early-stage PD
The criteria were evaluated based on the second and eighth stakeholder needs through a focus group scoring by engineers. As displayed in Table 4.5, several of the criteria were given a score of 1 in terms of how applicable they are to the GKNA product and early-stage product development. This includes criteria that were scored highly on potential socio-ecological impact, such as noise to the

surroundings (C39). During the focus group, it was observed that the participants conducted the scoring based on the current product development practises at the company. It was also observed that the participants view product development as primarily a means to fulfil a product's functional requirements, excluding business development and management-related aspects. This resulted in the low scoring of, e.g. the criteria qualified labour force (C31). Lastly, some criteria, including use of substances listed in the SIN list (C29), were scored low, mostly due to the participants' lack of familiarity with the criteria. In order to keep the potential for change and improvement in the current processes open, it was therefore decided not to exclude any criteria based exclusively on the scoring of the engineer stakeholder group.

SN3 & SN5: Criteria are measurable and quantifiable
In Table 4.9, a possible metric or assessment method is proposed for each of the criteria. These metrics/assessment methods are only preliminary examples, but they indicate that each of the criteria can in some ways be measured, often with existing frameworks and assessment tools. Therefore, the list of criteria meets SN3. Not all of the criteria can, on the other hand, be quantified numerically. Some of the criteria may need to be assessed through risk assessments with qualitative "high", "medium" or "low" risk metrics. SN5 can therefore not be met for all of the proposed criteria, but this alone should not exclude the criteria, as more research is required to determine the degree to which these criteria can be practically applied in product development at the company.

SN4: Criteria list addresses regulatory compliance
The criteria list addresses regulatory compliance through several criteria, including use of substances listed in REACH candidate list (C28), human toxicity, cancer and non-cancer effects (C16), situations where human rights are at risk (C33), labour abuse (C35), risk of being exposed to dangerous substances (C32) and supplier compliance with regulations (C37). Therefore, SN4 is, to some extent, met by the criteria list, although further development of the criteria is required to effectively measure and integrate them into the company processes.

SN6: Criteria list considers both social and ecological aspects
To assess the degree to which the criteria list considers both social and ecological aspects, the sustainability expert scoring results were examined. The sum of the ecological impact scoring of all criteria outlined in Table 4.9 is 111, while the sum of the social impact scoring is 125. This indicates that the list is somewhat balanced between social and ecological impact and does not noticeably neglect, e.g. ecologically leaning criteria over social criteria.

SN7: Compatibility with GKNA's goals/strategy
The compatibility of the criteria with the company's overall goals and strategy was assessed through a focus group of practitioners in managerial or strategy-related roles. As shown in Table 4.6, only three criteria scored below 3 in strategic alignment: use of substances in the SIN list (C29), raw material consumption (C8), and vertical

range of manufacture (C23). These criteria were not, however, eliminated based on the strategic alignment scoring, especially since the first two criteria were scored highly by the sustainability experts, with a score of 4 in either potential social or ecological impact. 30 of the 41 criteria on the refined criteria list received a score of 4 or 5 in strategic alignment, indicating that the list is mostly in line with the company's goals.

SN9: Ease of implementation
The criteria were assessed for ease of implementation in each focus group, with the results presented in Table 4.7. Only five criteria were consistently scored low (1 or 2) by all three stakeholder groups. The groups showed consensus on only 8 criteria that were considered easy to implement, with scores of 4 or 5. Due to the inconsistency of the results, it cannot be concluded to what extent the list of criteria is easy or difficult to implement. Instead, the scoring can indicate which criteria are broadly considered easy to implement with the required assessment tools and data already available at the company.

4.4 Framework Design

The integration framework was developed in two stages. First, broad system-level concepts were generated to determine the level of detail the framework should provide, the results of which are presented in Section 4.4.4. This was followed by a more detailed sub-system level development in Section 4.4.5 based on the company's process mapping, where the specific processes and criteria were defined. Current SPD tools at GKNA and the mapping of the current criteria integration are outlined in Sections 4.4.1 and 4.4.2, respectively.

4.4.1 Current Company SPD Tools

GKNA has implemented two main sustainability tools: the Sustainability Impact Assessment (SIA) tool and the Environmental Sustainability Tool (EST). The SIA is used as guidance for sustainability assessment of products in the stages of technology development, pre study, conceptual design and onwards. The tool guides the user through several steps, including assessing alternative solutions by specific socio-ecological criteria, estimating a product's use phase emissions, the material criticality, and an overall sustainability impact assessment of a product. The SIA tool is mandatory to use in technology development and aligns its steps with the technology readiness level (TRL) of a product. It is also mandatory for the first time in the conceptual design stage within the product development process, as well as in the lifecycle gates and design reviews after conceptual design. When the use of the tool is mandatory, it is not mandatory to meet specific criteria or thresholds within it. Rather, as specified in the tool, its purpose is to raise awareness of the sustainability impacts of products through their design and development processes.

The EST tool is another tool aiming to raise awareness of the sustainability impact of products. This tool appears in the processes of the business development &

sales stage. The tool guides the user through a weighted, lifecycle-based scoring of a product based on ecological aspects related to waste, energy, and circularity. In addition to the sustainability tools, some socio-ecological criteria are proposed in a new concept selection matrix template for the conceptual Design stage. This template has not been implemented in the official processes but has been confirmed for implementation. The evaluation matrix includes aspects concerning circularity, safety, waste and material criticality.

4.4.2 Current Criteria Integration

In order to identify gaps and opportunities for improvement for the development of the framework, the current integration of each criterion was assessed. Table 4.10 summarises the results of the level of integration for each criterion from the refined criteria list in Table 4.9. The criteria are categorised by five different levels of integration: "Not integrated", "Voluntary: limited stages", "Voluntary: many stages", "Mandatory: limited stages", "Mandatory: fully embedded". Each categorisation is also assigned a score from 1 to 5. The categorisation is further explained in Section 3.6.1.

The criteria vary greatly in the level of implementation and the specific processes where they are integrated. The majority of the criteria (29 of 41 criteria) are directly or indirectly mentioned somewhere in the company's early-stage product development processes. The criteria were classified as mandatory if they were mentioned as a typical product requirement, appeared in documents concerning commercial and lifecycle gates, design reviews, the concept selection matrix template or the supplier code of conduct. Some criteria were also explicitly mentioned in the processes of certain stages, such as product development planning, pre study, or conceptual design.

Criteria were classified as voluntary if they were not found in the aforementioned processes but were mentioned in the sustainability tools, such as the EST and SIA. Although it is mandatory to apply these tools in certain stages, the specific criteria within the tools do not need to be considered and were therefore classified as voluntary. Similarly, the additional criteria in the new proposed concept selection template were classified as voluntary, since the template is not yet officially integrated into the concept development process.

From the criteria mapping, a few potential integration opportunities were identified where additional criteria could potentially be implemented:

- Design reviews
- Lifecycle and commercial gates
- Requirements engineering
- Concept selection matrix
- Current sustainability tools (EST and SIA tools)

Table 4.10: Current Criteria Integration Overview

Mandatory: fully embedded (score 5)	**Mandatory: limited stages (score 4)**	**Voluntary: many stages (score 3)**	**Voluntary: limited stages (score 2)**	**Not integrated (score 1)**
Weight: Mentioned throughout as a typical product requirement/ constraint, included in the current concept selection matrix, EST and SIA tool	**Use phase GHG emissions**: Fuel consumption analysed in pre study, mentioned in SIA tool	**Ease of recycling**: In new proposed concept selection matrix, EST and SIA tools	**Material circularity capability**: In new proposed concept selection matrix.	**Raw material consumption**
Product quality: In requirements, commercial gates, design reviews	**Serviceability**: Maintainability mentioned as a key design driver in design reviews	**Use of conflict minerals**: In new proposed concept selection matrix and SIA tool	**Use of critical materials**: In new proposed concept selection matrix	**Overall toxic and hazardous emissions to air, water, soil**
Product safety (operational): In requirements, commercial gates, lifecycle gates, design reviews, conceptual design etc.	**Repairability**: Maintainability mentioned as a key design driver in design reviews	**Material utilisation**: In EST and SIA tools, new concept selection matrix and mentioned in Lifecycle gate 2	**Water consumption**: Mentioned in lifecycle gate 2	**Raw material extraction GHG emissions**
Product performance: In requirements, commercial gates, pre study, conceptual design, selection criteria etc.	**Use of substances listed in REACH candidate list**: In product development planning, commercial gate, SIA tool	**Energy consumption**: In EST and SIA tools, also mentioned in lifecycle gate 2	**Carbon footprint scope 1 and 2**: Emissions during manufacturing mentioned in SIA	**Human toxicity: cancer and non cancer effects**
Durability: In requirements, concept selection matrix, SIA tool, etc.	**Labour abuse**: In supplier code of conduct	**Transportation**: In new proposed concept selection matrix, EST and SIA tools	**Use of substances listed in SIN list**: Mentioned in SIA tool	**Potential for secondary function**
Employee health and safety : In requirements, lifecycle gates, commercial gates, design reviews, SIA tool, new concept selection matrix	**Supplier compliance with regulations**: In supplier code of conduct	**Use of recycled material**: In EST and SIA tools	**Flexibility of supply chain**: Supply risk mentioned in SIA tool	**Improved functionality**
Qualified labour force: In lifecycle gates, product development planning	**Due diligence**: In supplier code of conduct	**Hazardous waste**: In new proposed concept selection matrix, and EST tool	**Noise to the surroundings**: Mentioned in business development and SIA tool	**Vertical range of manufacture**
	Risk of corruption: In supplier code of conduct			**Upgradeability**
				Risk of being exposed to dangerous substances
				Situations where human rights are at risk
				Freedom of association and collective bargaining
				Job creation/loss and skills development

To further explore the nature of current socio-ecological integration, the criteria were plotted with current implementation scoring on the x-axis and the average ease of implementation scoring from the focus groups on the y-axis. Figure 4.5 presents a bubble graph of ease of implementation as a function of current implementation with varying bubble size based on the potential ecological impact as scored by the sustainability experts. To further distinguish between the different ecological impact scoring, each bubble size is also colour coded with red, orange, yellow, green and blue representing very high, high, moderate, low and minimal ecological impact, respectively. The criteria with an ecological impact scoring of 4 or 5 are annotated in the figure. Figure 4.5 shows that the criteria with the highest ecological impact scoring of 5 have already been implemented to some degree in the company processes.

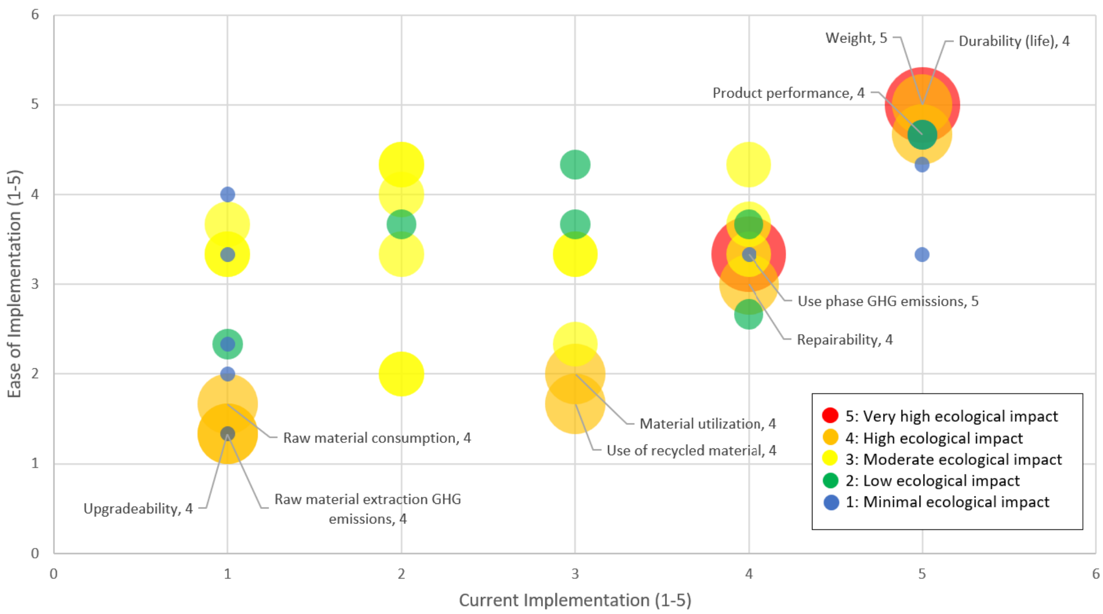

Figure 4.5: Current integration and ease of implementation: highlighting potential ecological impact.

Among the criteria with ecological impact scores of 4 or 5, there is a slight correlation between ease of implementation and current implementation, where the criteria that have an ease of implementation score of below 3 have not been implemented in the current processes to the same degree as the criteria scoring higher. This could be in part due to confirmation bias, where the participants of the focus groups view familiar criteria that have already been integrated as easier to integrate. In addition, the criteria that have to some degree already been integrated may not need the development of new assessment tools or the collection of additional data for further integration. Three criteria that have a potential ecological impact scoring of 4 were not found anywhere in the current processes, namely, upgradeability (C27), raw material consumption (C8) and raw material extraction GHG emissions (C14). These criteria highlight a blind spot and potential opportunity for improvement, in particular for further integration of criteria related to raw material extraction.

Similarly, Figure 4.6 presents ease of implementation as a function of current implementation, with the colour-coded bubble sizes representing potential social impact, with red, orange, yellow, green and blue representing very high, high, moderate, low and minimal potential social impact, respectively. Figure 4.6 displays less of a correlation between ease of implementation and current implementation among high-scoring criteria. The criteria risk of being exposed to dangerous substances (C32) and human toxicity: cancer and non-cancer effects (C16) have not been integrated and appear to be "low hanging fruit" with an ease of implementation score of above 3 and a potential social impact score of 4 or 5. Similarly, the regulatory criteria use of substances listed in REACH candidate list (C28) received high ease of implementation scoring but was only explicitly found in two places in the company processes, aside from being mentioned in the SIA tool: once in business development and once in product development planning.

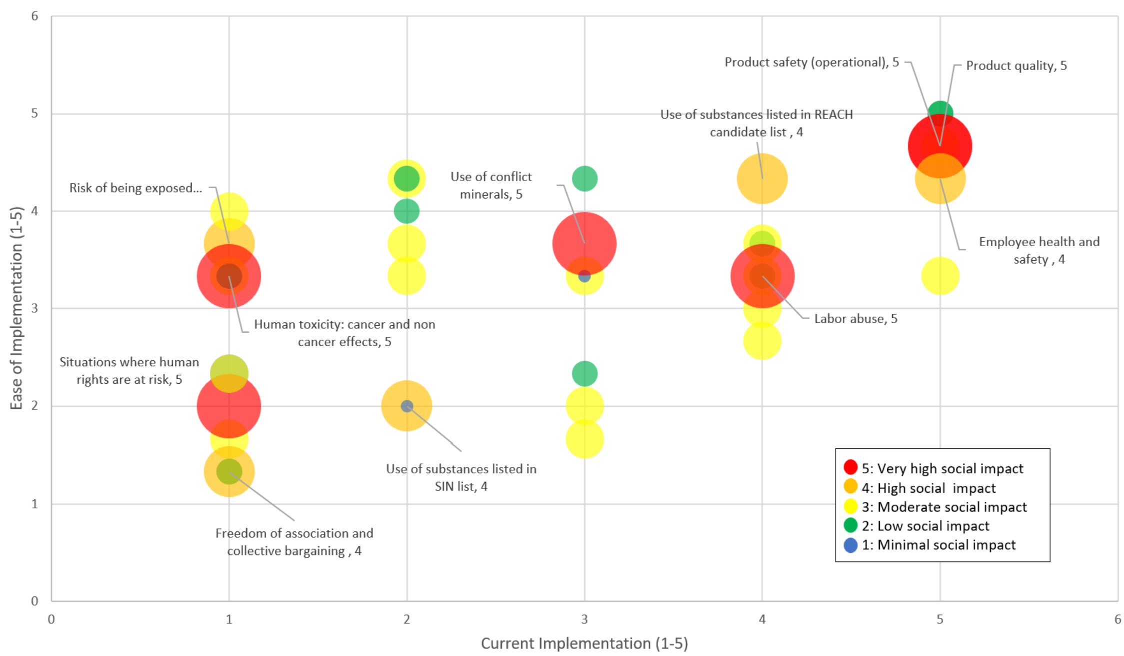

Figure 4.6: Current integration and ease of implementation: highlighting potential social impact.

The mapping of current criteria integration provides an overview of the degree to which the proposed criteria are already integrated into the company processes. This is presented in the context of the ease of the focus group scoring results in Figures 4.5 and 4.6.

4.4.3 Stakeholder Needs for Implementation Framework

The needs for the integration framework were derived from the initial stakeholder needs interviews, as well as insights from the focus groups. The stakeholder needs for the framework are presented in Table 4.11 with importance scores from 1-5. The first primary need is that the framework must facilitate the integration of socio-ecological criteria into the product development process. Another primary need for the framework is flexibility, meaning that the framework can be applied to a wide range of products. The third primary need outlined in Table 4.11 is that the framework must be compatible with the current product development process at GKNA. Similarly, as stated by framework stakeholder need 4, the framework should be applicable in the early stages of the product development process, ranging from technology development to conceptual design. As stated by the fifth need, the framework should provide support in trade-off scenarios. This need was expressed consistently throughout the stakeholder needs interviews and focus groups. Lastly, the stakeholder group of engineers expressed concern for the lack of time and resources to address additional criteria due to the already high number of functional requirements for each product. For this reason, a need for simplicity was added to the needs list. A simple framework that does not require much added effort and workload by the design teams could ease its integration and lead to a more positive reception. This final need has a lower importance score and is viewed as a "nice to have" rather than an integral requirement for the framework.

Table 4.11: Stakeholder Needs List for the Framework

No.	Stakeholder need	Imp.
1	The framework facilitates the integration of socio-ecological criteria into the PD process.	5
2	The framework is flexible.	5
3	The framework is compatible with the existing PD process.	5
4	The framework is applicable in the early stages of PD.	4
5	The framework supports trade-off scenarios.	4
6	The framework is simple in application.	3

4.4.4 Framework System Concept Development

Table 4.12 presents an overview of the system-level concepts generated. Concepts A and B propose an already ranked list of criteria that is the same for each stage or customised for each stage, respectively. These concepts provide trade-off support by providing the design teams with ranked criteria lists, making it clear which criteria should be prioritised. The drawback of these concepts is that it is very difficult to propose a ranked criteria list that would apply to all GKNA products. This would make the framework rigid and most likely only valid for a subset of products.

Concepts C, D and E propose unranked lists of criteria with different strategies of implementation. Concept C proposes the same unranked criteria list for each stage, where the design team needs to select and prioritise criteria for each product and each development stage. In concept D, the relevant criteria are selected and ranked in the business development stage, after which this ranked list is integrated into pre study and conceptual design stages. These concepts offer more flexibility, as criteria can be ranked for each product. However, this comes at the expense of making the framework more complicated and less supportive in trade-off scenarios in practise, as the design teams would need to conduct the prioritisation.

Lastly, concept E proposes two sets of criteria: one with mandatory primary criteria that need to be considered for all products, and a second case-by-case list from which relevant criteria can be selected for each product at each development stage. This concept provides less trade-off support in comparison to concepts A and B, but more support than concepts C or D, since it specifies which set of criteria should be of primary focus.

Table 4.12: System-level Framework Concepts

System-level concept	Description
Concept A	The same ranked list of criteria is integrated into every stage.
Concept B	Different ranked lists of criteria customised for each stage.
Concept C	The same unranked list of criteria is integrated into every stage. For each product, the relevant criteria are selected and ranked at each stage.
Concept D	An unranked list of criteria is presented at the business development stage, where relevant criteria are selected and ranked. This ranked list is then integrated in pre study, conceptual design and onwards.
Concept E	Two sets of unranked criteria, one of mandatory and one of case-by-case criteria, are integrated into each stage. The mandatory criteria need to be considered, while the case-by-case criteria are only considered if relevant to the product.

Table 4.13 presents the concept scoring using the Pugh decision matrix [72] with Concept A as a reference. The system-level concepts were ranked based on framework stakeholder needs 1, 4 and 5. Concept B is very similar to concept A and therefore received the same scoring. Concept C is more flexible but offers no trade-off support and would be complex for the engineering teams to conduct, receiving an overall score of -1. Concept D is simpler in practise than concept C, since the ranking by the design team only needs to be conducted once in the business development stage; however, this compromises the concept in terms of flexibility, since the same criteria might not be applicable across all development stages. In comparison to concept A, however, Concept D received the same scoring as concept C.

Table 4.13: Decision Matrix with Concept A as Reference

System-level concept	Flexibility	Trade-off support	Simplicity	Total
Concept A	0	0	0	0
Concept B	0	0	0	0
Concept C	+	-	-	-1
Concept D	+	-	-	-1
Concept E	+	-	+	+1

Lastly, concept E is more flexible than concept A but offers less trade-off support. It might at first seem like Concept E would be more complex in practise, since the engineering teams do not have a concrete ranking of the criteria; however, the ranking might create contradicting scenarios as some of the criteria are tradable and interdependent. For this reason, Concept E was scored higher than Concept A in terms of simplicity, receiving the highest total score of +1. To test the sensitivity of the decision matrix, the highest scoring concept, Concept E, was set as the reference concept in Table 4.14 and the same analysis was performed. In this second comparison analysis, Concept E was again the top-scoring concept due to its potential flexibility and simplicity in application. Concept E was therefore selected for further development.

Table 4.14: Decision Matrix with Concept E as Reference

System-level concept	Flexibility	Trade-off support	Simplicity	Total
Concept A	-	+	-	-1
Concept B	-	+	-	-1
Concept C	+	-	-	-1
Concept D	0	-	-	-2
Concept E	0	0	0	0

Figure 4.7 displays a diagram showcasing system-level concept E, which was further developed through subsystem concept development.

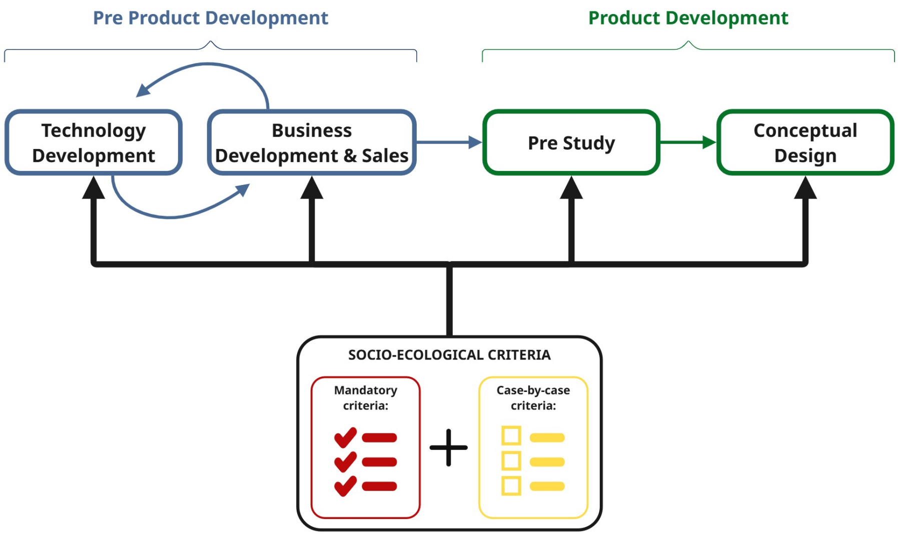

Figure 4.7: System-level diagram of Concept E.

4.4.5 Framework Subsystem Concept Development

Based on the mapping of the company processes described in Section 3.6.1, the framework was developed in more detail for each development stage. In this step of the development process, focus was placed on robust integration of the criteria, the utilisation of existing processes, and integrating criteria into each of the early development stages from technology development to conceptual design to fulfil framework needs 1, 3 and 4 respectively (from Table 4.11). Two subsystem concepts were generated based on the identified integration opportunities outlined in Section 3.6.1. The subsystem concepts E1 and E2 are summarised in Table 4.15.

Table 4.15: Overview of Subsystem Framework Concepts

Subsystem concepts:	**Concept E1**	**Concept E2**
Description	Integrate the mandatory criteria into the stage-gate process and design reviews. Integrate the case-by-case criteria into the sustainability tools EST and SIA.	Integrate the mandatory and case-by-case criteria into requirements engineering and concept selection matrices.
Pros	- Compatible with current processes. - Integrates criteria into early PD stages. - Relatively simple to implement.	- Compatible with current processes. - Integrates criteria into early PD stages. - Robust integration of criteria. - Addresses the current inconsistency of criteria.
Cons	- Risk of neglecting important criteria.	- More complex to integrate.

The first concept, E1, proposes the integration of the mandatory criteria directly into the stage-gate process and design reviews and adding the case-by-case criteria into the current company sustainability tools. The lifecycle gates and design reviews already include some of the proposed socio-ecological criteria. Similarly, many of the criteria are already included in the current company sustainability tools. This framework of integration would therefore be relatively simple and compatible with the current processes. A downside of this framework concept is that this would not offer significant improvement to the current processes, and the segregated integration of the criteria in the stage-gate process on the one hand and the sustainability tools on the other could lead to neglect of the case-by-case criteria entirely.

The second concept, E2, proposes the inclusion of both mandatory and case-by-case criteria into requirements engineering and concept selection matrices. In requirements engineering, the list of criteria would act as an additional consideration next to customer, regulatory and other aspects. The mandatory criteria would be integrated as "Absolute" or "Constraint" requirements, while the case-by-case criteria could act as "Trade-off" or "Wish" requirements if applicable to the product. By integrating the criteria into the requirements, they would automatically be reviewed in the stage-gate process and the design reviews. The current sustainability tools could act as support and guidance material for applying the criteria.

This concept is more robust and addresses the current inconsistency of criteria between the different stages by embedding them from the start of the development process in requirements. The downside of Concept E2 is that it requires further research and development, as each criterion would need distinct metrics and, in some cases, assessment tools. Due to the higher potential for systematic improvement and a more robust criteria integration, Concept E2 was selected for further development. Figure 4.8 displays a diagram of further clarification of the framework Concept E2 for each development stage, including technology development, business development, pre study and conceptual design.

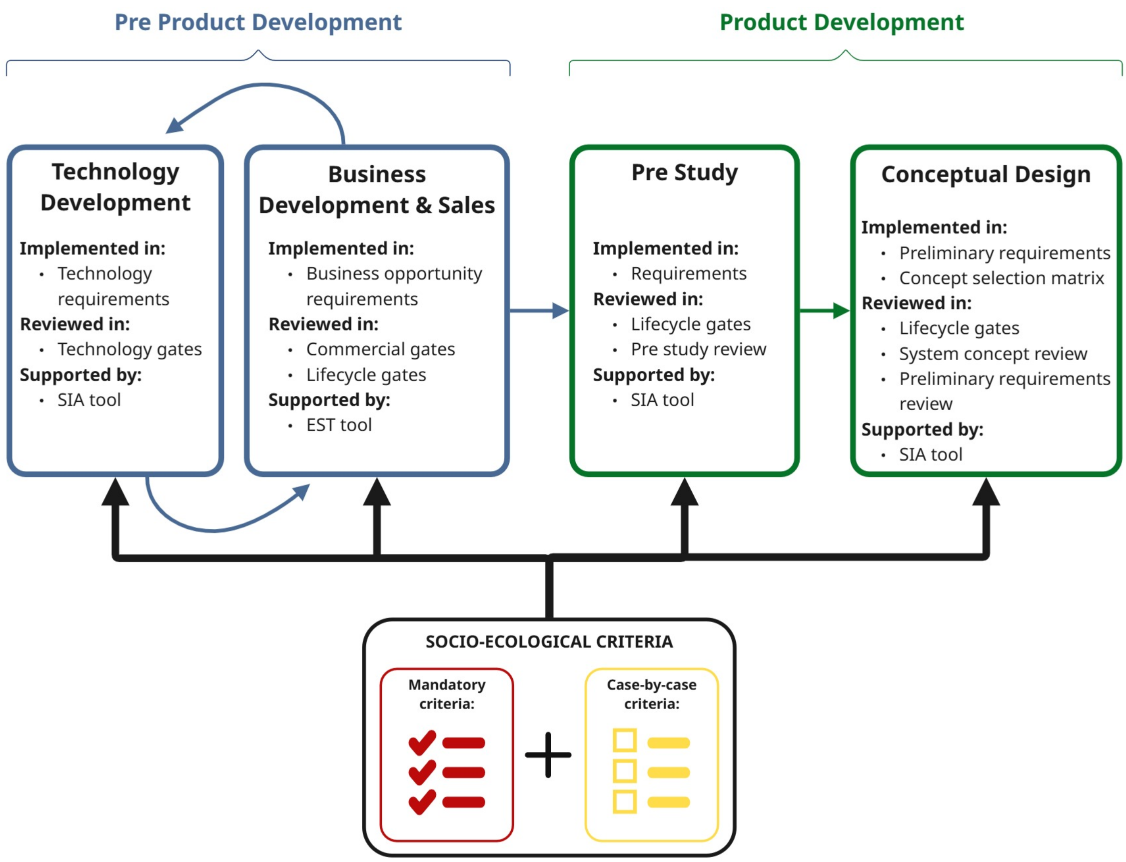

Figure 4.8: Diagram of subsystem level Concept E2.

4.4.6 Selection of Mandatory Criteria

For the selected framework concept, a set of mandatory criteria required to be considered for all products at all development stages was developed. The selection of mandatory criteria was based on three primary inputs: (1) weighted scoring matrix, (2) regulations and laws, and (3) DEMATEL analysis. The purpose of including these different approaches was to ensure mandatory criteria were not selected purely based on high socio-ecological relevance, but also from the perspective of ease of implementation. The selection of all mandatory criteria can be seen in Table 4.16.

Table 4.16: Mandatory Criteria List

Mandatory Criteria	Source
C28: Use of substances listed in REACH candidate list	Regulatory [115–117] DEMATEL
C30: Employee health and safety	Regulatory [118–120]
C32: Risk of being exposed to dangerous substances	Regulatory [115, 119, 120]
C33: Situations where human rights are at risk	Regulatory [121, 122]
C34: Freedom of association and collective bargaining	Regulatory [123, 124]
C35: Labour abuse	Regulatory [125, 126]
C37: Supplier compliance with regulations	Regulatory [121, 127]
C16: Human toxicity: cancer and non-cancer effects	Regulatory [115, 117, 119]
C6: Weight	DEMATEL, Concept scoring matrix
C7: Material utilisation	Concept scoring matrix
C13: Use phase GHG emissions	Concept scoring matrix
C20: Product safety (operational)	Concept scoring matrix
C19: Product quality	Concept scoring matrix
C21: Product performance	DEMATEL, Concept scoring matrix
C26: Repairability	DEMATEL
C24: Durability	Concept scoring matrix

The weighted scoring matrix assessed each criterion based on the scoring results from the focus groups. In the weighted scoring matrix, each factor was given the following weight:

- Strategic alignment: 0.1 (10%)
- Relevance to GKNA products: 0.3 (30%)
- Potential ecological impact: 0.3 (30%)
- Potential social impact: 0.3 (30%)

Based on the total weighted scores, the top criteria ranked 1 and 2 were selected. The full scoring matrix is presented in Appendix C.

The second input was based on identified regulations and compliance related to REACH compliance, hazardous substances, employee health and safety, which apply to the aerospace industry. They were prioritised because failure to address them could lead to risks to health and safety, penalties, and legal violations.

The third input was based on the DEMATEL analysis, where criteria were selected based on the most influential socio-ecological and the most important overall. The results were evaluated using the following indicators:

- Influence level (D)
- Causal relationship score (D-R)
- Overall prominence (D+R)

The causal relationship criteria with positive values were selected because they influence other criteria more than they are influenced by them. The prominence score was selected based on the overall importance of each criterion, taking into account both the influence it has and the influence it received. The influence level refers to the criteria that have the greatest influence, regardless of whether they are net drivers or receivers.

4.5 Preliminary Validation

Preliminary validation of the criteria list and the integration framework concept was conducted to assess the feasibility of the output and its alignment with academic literature. The framework concept was first validated through interviews with practitioners at the company to assess its feasibility and whether it meets the needs of its potential users/stakeholders. A summary of the interview output is presented in Section 4.5.1. The framework concept and its development method were also validated against academic studies on sustainable product development as presented in Section 4.5.3. Lastly, the list of criteria was validated against lifecycle-focused academic literature as presented in Section 4.5.2.

4.5.1 Framework Validation through Case Study Interviews

Seven semi-structured interviews were conducted with practitioners at GKNA who are currently working with, or have previously worked with, technology development, business development, and product development. The purpose with these interviews was to evaluate the application of the framework, assess if it is meaningful and feasible, and identify challenges. Discussions were also held to gather feedback on areas for refinement. The mandatory and case-by-case criteria were also evaluated based on their relevance at the different development stages, along with discussions on whether they should remain consistently applied criteria or be adapted depending on context.

The overall perception of the framework was positive, and it was considered relevant and feasible given GKNA's current sustainability ambitions. Similar views highlighted that sustainability considerations should be integrated earlier in product development processes and that the framework can support and enable such integration and decision-making in the early stages. The presented socio-ecological criteria were generally supported, with agreement that they should be applied across multiple development stages, rather than treated as a separate activity, as sustainability efforts are currently fragmented across tools and processes. Several practitioners mentioned that in the technology development stage, reviews are performed to ensure technical fulfilment, and gates are for management to check that they have been fulfilled. A suggestion was to integrate sustainability requirements and add checkpoints in the reviews; this would result in them becoming visible before the concept reviews, rather than introducing a parallel decision-making activity or process.

There were mixed opinions regarding the validation of the mandatory criteria. Some criteria were considered tradeable, while others were strongly supported as mandatory. Specifically, the criteria of weight (C6) and product performance (C21) were brought up as tradeable for use phase GHG emissions (C13). The wording of the criteria of weight (C6) was challenged by several practitioners, suggesting that it should be clearly defined and should not act as a stand-alone socio-ecological criterion, but rather as a design objective linked to environmental performance. Similarly, the criteria of durability (C24) and repairability (C26) were highlighted as highly relevant but often linked or even contradictory, since a more durable material can be more difficult to repair. Material utilisation (C7) was mostly viewed as a relevant mandatory criterion, but some participants expressed the need for an additional circularity criterion, such as ease of recycling (C1), in addition to material utilisation to inform about end of life considerations.

One suggestion was to include clarification of the criteria: definition, ownership responsibility, and measurable indicators. Following this, it was proposed that requirements should be divided into responsibility areas, assigning them to functions such as purchasing, procurement, project management, and designers or engineering teams. For example, the materials-related criteria were argued to be a responsibility of purchasing because designers have limited control over material selection. Instead, such considerations should be purchasing requirements and included in procurement specifications. Other participants argued that splitting requirements into different functions risks the neglect of procurement and manufacturing-related criteria due to the dominance of design-related criteria in decision-making.

The validation of the case-by-case criteria was overall positive, with the practitioners mostly agreeing that they should remain flexible. The criteria regarding recycling, water consumption, and noise were considered mostly relevant for specific projects but not overall. The criterion of supply chain flexibility (C16) was highlighted by several as becoming mandatory since it is highly important and relevant for the designer. One participant noted that a lack of supplier flexibility is currently a challenge in product development, as it influences multiple aspects. Therefore, studies on the number of potential suppliers have been conducted to explore potential back-up suppliers to further resilience. The criterion of serviceability (C25) was also viewed as highly relevant.

Overall, there were discussions regarding practical implementation, emphasising that data availability, responsibility ownership, and measurability should be clear, visible, and traceable. A recurring theme within the technology development was that the criteria may be relevant; however, they can be difficult to assess and measure due to the low technology maturity. Some criteria, such as weight (C6) and material utilisation (C7), were considered difficult to measure at low Technology Readiness Levels (TRLs), when the product does not yet exist, but become more meaningful and relevant in product development when a product or concept is available. Therefore, some criteria should have the option to be marked as "not applicable" to ensure they are not ignored in later stages and therefore do not restrict early-stage decision-making.

4.5.2 Criteria Validation through Literature

As discussed in Section 2.1.2, use phase emissions have been estimated to contribute up to 94% of the total lifecycle CO_2 and NO_x emissions due to direct fuel combustion [25]. A review on strategies to mitigate carbon emissions for sustainable aviation by Hu et al. [128] highlights that the main mitigation strategies are multifaceted, including demand for air travel, technological improvement, the use of alternative fuels and aircraft design factors such as aerodynamic efficiency, engine efficiency, aircraft weight and aircraft size. Since GKNA deals with component and structure design of engines and airframes, the company has the most impact on design factors at the sub-system level, not the aircraft as a whole or high-level operational factors such as transport distance or the number of passengers. Of the leading emission mitigation strategies suggested by Hu et al. [128], the factors of engine efficiency, aerodynamic efficiency and aircraft weight fall to some extent within the influence of product development at GKNA. The criteria of performance (C21) can include both aspects of engine efficiency and aerodynamic efficiency, depending on the type of product, whether the product is an engine component or is subject to airflow and the associated fluid dynamic forces.

Within these three factors (weight, engine efficiency, aerodynamic efficiency), there exist several trade-off scenarios in terms of fuel combustion and associated CO_2 and NO_x emissions. A widely reported engine efficiency trade-off is that of CO_2 vs NO_x emissions. Gains in engine thermal efficiency are achieved by increasing gas turbine pressure and temperature, which enables a higher bypass ratio, the ratio of air passed through the fan system to that passed through the engine core, which in turn improves the propulsive efficiency of the engine [129]. The combination of improved thermal efficiency and the improved propulsive efficiency from higher bypass ratios leads to lower total fuel combustion and associated CO_2 emissions, but an increase in NO_x generation within the combustion process [129], [130], [131]. Some studies, however, suggest that the focus should be placed on CO_2 emission reduction despite the trade-off in NO_x emissions [132], [133]. Freeman et al. [133] argues through climate model case studies that NO_x pollution should mostly be of concern on ground level for human health impact, but that an increase in fuel consumption for decreased NO_x impacts should be avoided. The results of one climate model scenario highlight that a 20% reduction in NO_x emissions leads to a 2% fuel penalty, resulting in a worse overall climate impact due to the additional CO_2 emissions. For an overall benefit, a 2% fuel penalty would need to result in over 45% decrease in NO_x emissions [133].

In addition to increased NO_x emissions, higher bypass ratios can result in an increase in engine weight and drag. In a study on the impact of bypass ratios on NO_x emissions, Hemmer et al. [129] found that in cases of ultra high bypass ratios, this can outweigh the specific fuel consumption benefits, leading to an overall higher fuel consumption over a typical aircraft mission. Product weight is relevant to all products and can be directly translated into fuel consumption. A reduction of aircraft weight by 1 kg saves 0.02 - 0.03 over a distance of 1000 km according to Steinegger [134]. Despite this, in certain scenarios, an increased weight can result in overall lower use phase emissions due to improved performance. Poll [135] argues that to reduce aircraft fuel consumption, improving the aerodynamic efficiency through increased aspect ratios should be prioritised at the expense of weight gain through an analysis of mathematical models and confirmation through historical data, estimating that over a period of 50 years, about 10% of operational empty weight has been traded for increased aspect ratio with close to 20% improvement in the energy to revenue work ratio (ETRW).

This discussion on trade-offs between aircraft weight, engine efficiency and aerodynamic efficiency validates the criteria of product weight (C6) and performance (C21) as the key design criteria to address use phase emissions while highlighting the importance of viewing these criteria as trade-off criteria where the improvement of one could compromise the other, depending on the type of product. A potential way to address this reality in the mandatory criteria list is by setting the criteria of use-phase emissions (C13) as the primary criteria, with the accompanying trade-off criteria of weight (C6) and performance (C21).

In the aerospace industry, reducing fuel burn and use phase emissions is often prioritised at the expense of increased impact in other lifecycle phases such as raw material extraction, manufacturing and end of life. An example of this is the use of composite materials for weight reduction. Studies on both aero-structures and aero-engines have shown that replacing aluminium with carbon fibre reinforced plastic (CFRP) composites has the potential to significantly lower climate impact over the lifecycle of products, despite an increase in the environmental impact in the raw material extraction, manufacturing and end of life stages [136], [137], [138]. This is due to the high strength-to-weight ratio of the CFRP composites, which enables a significant reduction in the weight of the components studied. The drawbacks of CFRP include the highly energy-intensive fibre production and moulding processes in the manufacturing stage, as well as the difficulty in recycling at the end of life stage [136]. Whereas the recycling of aluminium is highly efficient without altering the properties of the material, thermoset CFRP composites have an average rate of 24% due to damage and degradation of the fibres during the recycling process [136]. Through a comparative LCA study on six different wing skin panels with aluminium and five CFRP options, Atescan-Yuksek et al. [136] found that the switch to CFRP options from aluminium results in a reduction in emissions of between 2040-3420 $tCO_2eq.$ over the lifecycle of the product, depending on the CFRP option. In a separate study on GKNA aero-engine components, Léonard and Nylander [137] found that using composite hybrid materials reduced the products' lifecycle $CO_2eq.$ emissions by 162t in comparison to aluminium and by 172t when compared to titanium. This further highlights the importance of prioritising use phase emissions during trade-off scenarios in aircraft structure and engine design, confirming the inclusion of product weight as a mandatory design criterion.

This use phase focus is relevant in the current reality of fossil fuel-driven aircraft, but may require a shift in the future, in the case of the electrification of the propulsion systems. Through a lifecycle assessment of a utility aircraft, a study by Pollet et al. [139] compares a conventional Kodiak 100 with an altered version with a hybrid-electric powertrain. Due to the associated fuel savings, the hybrid-electric variant resulted in decreased climate change impacts but a significant increase in material resource depletion impact due to the battery production. Based on this result, Pollet et al. [139] argues that the electrification of propulsion systems will shift impacts from the use phase to the component manufacturing phase, making the design process more complex, as trade-offs among added weight, component efficiency, materials, and production processes must be considered.

The concept of durability is often ill-defined in literature. It can be defined as "useful life", or the ability of a product to perform its function, including service and repair, until the product has reached its limiting stage where repair is no longer possible [140]. Durability can also be defined as the ability of a product to perform its function without reliance on maintenance or repair [140]. The first definition includes the criteria of repairability and serviceability in the concept of durability, while the second definition emphasises the robustness of a product alone.

In general, the criteria of durability (C24), repairability (C26) and serviceability (C25) can be viewed as lifetime extending criteria. In a literature review on the environmental impact of product lifetime extension, Maldini et al. [141] concludes that for most of the product types studied, durability is a key element in furthering sustainable consumption and production, since a longer product life leads to less replacement of the product, leading to overall less production resource use. However, Maldini et al. [141] highlights that this logic does not necessarily apply to products with high environmental impact during the use phase. In cases of high-use-phase emissions, replacing the product with a more energy-efficient solution might result in a lower overall climate impact. It could therefore be argued that products that influence engine or aerodynamic efficiency may benefit from earlier replacement depending on the efficiency improvements. A product's optimal lifetime may not be the longest possible, but rather an environmentally optimised lifetime in which the trade-off between efficiency improvements and increased material-related impact has been considered.

This may, however, not apply to all GKNA products, as they are often components of larger systems and therefore have strict lifetime requirements tied to the system lifetime. For some products, particularly life-limited products that are frequently replaced throughout the lifetime of an aircraft, maximised product durability may play a larger role in the products' lifecycle impact [142].

Academic lifecycle-focused literature within the aerospace industry generally places the emphasis on use phase emission reduction through the design criteria of weight reduction and performance improvement. In the context of fossil fuel-driven aircraft, the use phase criteria dominate the overall lifecycle climate impact of products over other criteria related to, e.g. raw material extraction and manufacturing. This might, however, change in the future with increased electrification of propulsion systems, indicating that the prioritisation of socio-ecological criteria should be flexible and adjusted with technological shifts.

Validating the prioritisation of the more socially significant criteria through literature is more challenging, since there is currently a lack of social lifecycle assessment research in the aerospace industry. There is, however, research on the social impacts due to fossil fuel and raw material consumption associated with aircraft components. Malik et al. [143] estimates that in 2018, the demand for raw materials in the EU was associated with 243 cases of accidents at work and 36 thousand cases of modern slavery impacts. 95% of the modern slavery footprint originates from imports from outside the EU. This highlights the substantial labour rights violation risks associated with international raw material supply chains. Similarly, a report by PBL Netherlands Environmental Assessment Agency highlights social impacts such as human rights abuse and health risks from pollution to air, water and soil due to the mining of raw materials relevant to the aerospace industry, namely nickel and cobalt [144]. In a broader context, Siqueiros-García et al. [145] argues that ecological impacts are inherently social impacts, as the environmental changes and degradation associated with climate change significantly impact cultures and the lives of populations by creating a sense of inefficiency of shared know-how, lack of control and agency, leading to conditions of depression, hopelessness and inaction.

4.5.3 Framework Validation through Literature

As stated in Section 3.7.3, the proposed framework was validated through early-stage literature alignment, FSSD, and success criteria. Table 4.17 displays the framework success criteria by Vicente and Camocho [60].

Table 4.17: Framework Success Criteria

No.	Success criteria
1	Facilitate the integration of principles, strategies and criteria of sustainability in a systematic way into the design process
2	Focus on one or more phases of the design process, to improve the circularity and sustainability performance of the solution under development
3	Must go through 3 main steps: input, processing, output
4	Must be aligned with the needs of designers, available resources and project objectives
5	Must allow to be used autonomously by designers, without recourse to non- designers specialists

Evaluated against the first success criterion, the framework supports the systematic integration of socio-ecological criteria. The selected criteria are divided into mandatory and case-by-case criteria and can be integrated into requirements and concept selection matrices, creating a structured decision-making process. Allowing sustainability aspects to be considered and influence both requirements and concept evaluation. Furthermore, the framework proposes a review of criteria at the technology, life cycle, and commercial gates, supported by the SIA and EST tools. As a result, sustainability is systematically integrated into GKNA's existing process rather than treated as a standalone activity.

Regarding the validation of the second success criterion, the proposed framework focuses on several early-stage development phases, including technology development, business development, pre-study and conceptual design. By integrating into several decision-making stages, sustainability considerations can be effectively integrated into early-stage product development. By proposing their implementation in requirements and concept selection matrices, as well as reviews at gates, the framework enhances traceability and reduces the risk of sustainability being overlooked.

The framework can be described as the sequence of success criteria three proposes: input, processing, output. The inputs are the identified and prioritised socio-ecological criteria divided into mandatory and case-by-case criteria, including regulations and stakeholder needs. The processing can be viewed as integrating the criteria into requirements and concept selection matrices, later reviewed at different gates. The output results in a systematic sustainability integration, sustainability-informed requirements and concept selection, and increased sustainability considerations.

Before the development of the framework, stakeholder interviews were conducted to identify needs and develop personas. These activities were carried out to better understand how different stakeholder groups perceive sustainability and what their needs are for a framework. The framework is aligned with the resources available within the existing company process, rather than proposing a new application or software.

The fifth success criterion was fulfilled partially. The socio-ecological criteria were provided as mandatory and case-by-case, and existing company requirements and concept selection processes were utilised, along with supporting tools. This reduces the dependency on sustainability experts during decision-making. Although this supports the application of the criteria, several limitations remain, such as a lack of clear metrics and a lack of or limited sustainability knowledge or expertise, which may result in difficulties in assessing the criteria. Similarly, trade-off scenarios may be difficult to evaluate without enough expertise or support.

The framework was focused on the early stages, which is consistent with existing literature such as Lövdahl et al. [146], highlighting the importance of early-stage decisions in the product innovation process. Specifically, decisions made in the early phases of product development have the greatest potential to influence the sustainability performance of a product throughout its lifecycle, whereas later phases offer a lower degree of design freedom.

Validation through strategic sustainability thinking using the FSSD framework was conducted to assess how sustainability principles and perspectives can be integrated into organisational decision-making. The proposed framework was evaluated for alignment with the purpose of the FSSD by embedding socio-ecological criteria directly into the company, rather than treating them as separate considerations. This examined the framework's capacity to support holistic decision-making and address long-term sustainability implications alongside organisational objectives.

According to Broman and Robèrt [47], the purpose of FSSD is to integrate sustainability considerations into existing decision processes and tools rather than replacing them. This principle was used as a basis for evaluating the proposed framework, specifically by assessing the integration of socio-ecological criteria into company processes rather than proposing a stand-alone method. The framework was also evaluated against FSSD's principle of managing trade-offs strategically rather than based on short-term considerations. The division of socio-ecological criteria into mandatory and case-by-case was examined as a basis for prioritising and discussing sustainability aspects.

Vicente and Camocho [60] highlight that most sustainability tools are not adopted due to misalignment with designers' needs and project objectives, as well as poor fit within existing design processes and limited integration into practical design work. These insights were used as a basis for developing the proposed framework, to ensure alignment with company context, compatibility, and applicability with existing processes.

5

Discussion

5.1 Interpretation of Results

The main results of this thesis include the benchmarking report, the refined list of criteria, the focus group scoring results, the DEMATEL method results and the integration framework concept.

The industry sustainability integration benchmarking report presented in Section 4.1 outlines to what degree different aerospace manufacturing companies have considered several socio-ecological aspects according to their annual sustainability reports. The report indicates that GKNA is not ahead of the industry in all sustainability aspects, as there are some areas where other companies display further initiative in their sustainability reporting. The identified opportunities for improvement for GKNA relative to other aerospace manufacturers include assessment of EU Taxonomy eligibility and alignment, estimation of product use phase emissions, further monitoring and tracking of hazardous substances and further assessment of supplier compliance with social and environmental aspects.

The refined list of criteria in Section 4.3.4 provides a set of criteria previously used in academic literature that have been screened and refined with the input from sustainability experts at GKNA. This list has been refined for the application within the aerospace industry and specifically GKNA, and therefore has the potential to guide further sustainability integration into company processes.

The prioritisation of the criteria by company practitioners presented in Section 4.3.2 provides an insight into how the different stakeholder groups view the outlined socio-ecological criteria. The scoring of the sustainability experts in terms of potential social and ecological impact is mostly consistent with academic literature. Criteria relating to use phase emissions were scored the highest in terms of potential ecological impact. This is consistent with life-cycle focused literature as discussed in Section 4.5.2. The scoring of criteria in terms of potential social impact also aligns with the literature, as supply chain-related criteria concerning human rights and toxic substances were among the highest scored. The practitioners within the stakeholder group of engineers viewed many of the criteria as not applicable to GKNA products. The low scoring of the criteria may indicate that the engineers are unfamiliar with them or that the criteria are more relevant for other roles, such as in program/project management or procurement. The practitioners within the manager stakeholder group scored the majority of the criteria highly in terms of strategic alignment, indicating that the criteria list is mostly consistent with the company's goals and strategy, which is critical for the possibility of the potential integration of the criteria into company processes.

The scoring of the criteria in terms of ease of implementation indicates that the three stakeholder groups have inconsistent interpretations of the criteria. Less than a third of the criteria received consistently high (4-5) or consistently low (1-2) scores by all three stakeholder groups. Most of the criteria received inconsistent or opposing scores by the stakeholder groups. This result highlights which of the criteria require further development to achieve a common language and understanding of socio-ecological aspects within the company, which is essential for their effective implementation into product development.

The DEMATEL results provide a deeper and more valuable understanding of the criteria, not solely as independent, but rather its influence and dependency to other criteria. This analysis revealed a cause-and-effect relationship between the criteria, which act as the so-called "drivers within the system", and the ones that are dependent. The key takeaway from the analysis is that not all criteria have the same strategic role. Focusing on the drivers of the system may provide a greater overall sustainability impact than treating all criteria as equally important. While criteria scoring through the focus groups revealed stakeholder groups' perspectives on which criteria were considered important, the DEMATEL provided additional insight into the degree of influence. Highlighting the criteria that are dependent may support more informed decision-making during the early stages of product development.

The integration framework, as presented in Section 3.6 provides broad and overarching guidance for the integration of the outlined criteria into company processes in the technology development, business development, pre study and conceptual design stages. Accompanying this framework is a list of mandatory criteria in Section 4.4.6 that are proposed as mandatory to consider for all products at all development stages. In addition to, and as a basis for the integration framework, an analysis of the current level of integration of the criteria in the company's process maps is outlined in Section 4.4.2. The mapping of current criteria integration highlights the inconsistency of the current consideration of socio-ecological criteria. Different criteria appear across the development stages in various formats, which could cause misalignment between the various teams involved in the development of a product on which criteria should be prioritised. This could lead to ineffective integration of the criteria throughout the design process. The integration framework concept is in a preliminary development stage, providing overarching guidance on how the criteria could be integrated, reviewed and supported. The mandatory criteria list suggests a set of criteria to be set as mandatory considerations in product development for all products at all stages of development. This list provides some trade-off support by highlighting criteria of primary importance based on scoring by company practitioners and EU regulations.

5.2 Limitations of Methods and Results

This section outlines the main limitations of the methods and results presented in this thesis, including the limitations of developing the criteria list and integration framework, data collection methods, prioritisation approach, and validation process.

The method of using publicly available company sustainability reports to conduct industry benchmarking has inherent limitations. These reports can only provide an idea of how companies operate and might be missing vital information. The reports are made by internal parties with the partial purpose of advertising the companies. There is therefore an inherent conflict of interest embedded in the sustainability reports due to the incentive of their authors to present the companies in a positive light. The benchmarking report should be viewed with this context in mind.

There are several limitations of the methods used to develop the criteria list and integration framework. The list of criteria was developed through a literature review of papers mainly within the manufacturing, aerospace and general product development fields. Due to limited research specifically on the development of socio-ecological criteria, the list of criteria was mostly collected from papers that used the criteria in sustainable product development research. The list was therefore not collected with a specific purpose in mind; rather, it presents a broad collection of criteria already used in sustainable product development research. The list could have been developed more intentionally by using LCA and SLCA indicators and translating them into design criteria. This may have provided a more consistent and scientifically grounded list, but it would have been difficult and time-consuming to accomplish. In addition, the list was prioritised by relying on expert opinion instead of lifecycle assessment research. The only time when lifecycle-focused research was consulted was in the validation of the proposed criteria list in Section 4.5.2. Another limitation of the criteria list is its interdependence and inconsistency, as some criteria are broad impact categories, while other criteria are specific design properties or deliverables. Some of the design-specific criteria are contradictory and can be viewed as trade-offs for the broader impact criteria. This makes the criteria difficult to prioritise and implement.

The reliance on expert opinion for interviews, focus groups and DEMATEL exercise has several limitations. Firstly, most of the practitioners consulted are employed at the Engines division of GKNA in Trollhättan, with only two interviewees from the global division of the company. The two interviews with global practitioners implied that the Trollhättan branch has separate processes from the rest of the company and is considered one of the more environmentally forward branches of the company. Therefore, the results from this study do not reflect the entire company. While the input from company experts was important to gain an insight into the applicability of the criteria to company products and processes, this might have an associated confirmation bias, as the practitioners may have ranked familiar criteria that have already been implemented at the company higher than unfamiliar criteria. In general, relying on expert opinion always risks subjectivity due to conflicts of interest and cognitive biases. Despite the high credentials of the consulted practitioners, the results should be viewed with these inherent biases in mind. The results could have been strengthened by including expert opinion from outside of GKNA, such as academic experts or practitioners from other aerospace companies.

Even though practitioners from the same branch of the company were consulted in the focus group scoring, the three different stakeholder groups, engineers, managers and sustainability experts, interpreted and scored the criteria very differently. This is particularly evident in Table 4.7 where the results of the ease of implementation scoring from the three stakeholder groups are compared. This is likely due to the inconsistent familiarity and interpretations that the three groups have of the socio-ecological criteria. For example, the sustainability experts are more familiar with the impact-related criteria and their assessment methods. The participants could therefore be more inclined to score some criteria higher than other stakeholder groups. This could also lead to the engineers and managers overestimating the ease of implementation of certain criteria, as they may not be aware of the full extent of data and tools required to assess some of the criteria. Similarly, sustainability experts may be less familiar with the practicalities of some of the design-related criteria. To combat this inconsistency, each of the criteria should have been introduced and explained to each participant before the scoring. Due to time constraints for each focus group, only simplified explanations of the criteria were provided before the scoring exercise. Due to the limitations of the scoring exercise, the results from the engineer scoring are more indicative of the level of familiarity of the stakeholder groups with the criteria and the inconsistencies between the stakeholder groups, rather than the practical ease of implementation of each criterion, their relevance to GKNA products or early-stage product development.

Although the DEMATEL method provided insights into criteria influences and interdependencies, the results should be interpreted with caution. The analysis was solely based on sustainability expert judgement from a limited number of participants, which may not fully represent the company's overall perspective. Furthermore, the results also depend on participants' interpretations, experience, and professional backgrounds, which may lead to variation in results and potential bias. The inclusion of sustainability experts ensured strong expertise in sustainability; however, it limited the inclusion of other perspectives. Stakeholder groups, such as engineers and managers, could also have been included, as these groups may assess criteria differently due to their focus on cost or technical feasibility. A larger and more diverse group could have resulted in different influence patterns.

An important limitation is that the method does not validate causality. For example, an expert may state that the criteria product quality influences repairability; however, no real-world data was provided, therefore the method cannot verify this relationship. The large number of criteria may also have been mentally demanding for the sustainability experts to assess within a limited amount of time. As a result, some of the scores may have been simplified, or a decision may have been made based on initial intuition. Another limitation is related to how the relationships were extracted. Participants were asked to draw coloured arrows between criteria rather than assigning influence values directly in the matrix. This approach may have encouraged experts to focus on the most obvious ones, which could have led to weaker influences being overlooked, even though they may have had important relationships. The level of detail was also reduced, as the criteria were not assessed pairwise, as in the traditional DEMATEL method, resulting in a less comprehensive representation of the relationships. Following this, the results of the individual assessments were reviewed and refined by the participants, which may have improved consensus and generated new insights but could also have overshadowed or limited minority viewpoints and opinions.

The initial plan for validating the framework and the proposed criteria was through a case study of one or more GKNA products in the early stages of development. However, it was difficult to find a product in technology development, business development, pre study, or conceptual design that was not confidential. It was therefore decided to validate the results through interviews with practitioners experienced with early-stage product development. The interviews provided perspectives and suggestions for improvement based on a broad set of experiences and expertise in a short amount of time. One limitation of this method is that it relies on the memories and perceptions of the practitioners, instead of raw product data. To strengthen the validation, the criteria were also validated based on lifecycle-focused academic research and the framework was validated based on research on sustainable product development tools. The validation of criteria through literature confirmed the importance of criteria that influence products' use phase emissions, validating the top-scoring criteria in terms of ecological impact by the sustainability experts. The academic validation also confirmed the significance of social criteria in relation to the supply chain, particularly human rights and health and safety.

The implementation framework concept is broad and uniform across the different development stages, as it was not developed with unique requirements for each stage. This might result in difficulties when implementing the framework, as each stage might pose unique challenges. As an example, the validation interviews revealed that in the technology development stage, the criteria list might not be relevant for the early technology readiness levels when the technology does not yet have a working prototype. Another limitation of the framework is its lack of support in trade-off scenarios. The framework only provides partial support by highlighting the primary criteria which should apply to all products and case-by-case criteria that can be evaluated if applicable. This does not address trade-off situations that can occur between the criteria. In addition, the framework does not provide clarity on the ownership of each criterion and the nature of the regulatory criteria. The regulatory criteria could be applied as go/no go criteria based on compliance with regulations associated with each criterion. This could, however, limit the potential of the criteria, as they could also be used for the company and its products to get ahead of regulations by setting targets above the regulatory thresholds.

Although the proposed framework may support the integration of socio-ecological criteria considerations into the company's processes, its successful implementation also depends on organisational culture, ownership, competence, and management system. While sustainability-related information or criteria may be available, if they are not viewed as a shared responsibility across different departments, they may not be used consistently.

5.3 Systematic Improvements for Sustainability Integration

One of the biggest findings from the interviews with the different stakeholder groups was the lack of common language and understanding between departments. This was due to different levels of familiarity and experience with the criteria, requiring the need for clearer definitions of the criteria, assessment methods, and cross-functional collaboration and information-sharing. This could result in challenges during the translation of sustainability requirements into decision-making in product development. The result suggests that successful integration of sustainability is not solely based on selecting the correct criteria, but rather dependent on the organisation's ability to support the integration by developing the right capabilities. This includes structures for routines, responsibilities and decision-making.

Another challenge was identified as the lack of common understanding between departments, therefore hindering successful cross-functional collaboration and information-sharing. During the focus groups, it was revealed that the stakeholder groups interpreted the criteria differently, and without a consistent definition and explanation, this can lead to inconsistent decision-making during information-sharing.

Interviews also revealed a need for improved PLM system and clearer traceability, ownership, and information management. This indicates a challenge in information availability but also in the ability to access, maintain, and communicate the information. Improved sustainability integration within PLM systems could support knowledge management, lifecycle thinking, compliance, and cross-functional collaboration. The stakeholder groups highlighted the sustainability data; although it may be available, it was considered not traceable. The ownership and traceability of REACH was mentioned several times; practitioners explained that the lack of ownership can make it difficult to ensure that REACH considerations are maintained and updated through a project.

5.4 Future Work and Recommendations

Before the integration of the proposed list of criteria and the implementation framework into the product development process, these tools require several clarifications and refinements. For the criteria list to be practically implemented into product requirements, each criterion would require a metric, an assessment method, and the required product-related data to assess products based on the criterion. For some of the criteria, this information has already been developed at the company, but for others, this would require extensive research and development. As suggested by several practitioners in the framework validation interviews presented in section 4.5.1, further classification of the criteria is required to signal which criteria are trade-off design criteria and which criteria are overarching impact criteria. As an example, the trade-off of weight (C6) and product performance (C21) can be optimised to improve the criteria of use phase GHG emissions (C13). Another suggestion by the practitioners was to classify the criteria by department or role, which should be responsible for each criterion. It is unclear if all criteria should appear directly in design requirements or if they should be split up into design, program, project management, manufacturing, and procurement requirements. If the criteria are split up into different roles and departments, there is a risk of certain criteria getting lost and not being considered. By including all criteria into design requirements, it is ensured that all of the criteria will be considered in the design process; however, this might be overwhelming for design teams since they are already dealing with large amounts of functional requirements that need to be met for each product. One benefit of categorising criteria based on responsible teams/roles is that it enables the required data collection for the criteria. As an example, some of the supplier-related criteria will likely require additional collection of data from suppliers, which the engineering teams are not responsible for. Allocating the criteria to procurement allows for systematic data collection, which can then be communicated to the design teams to enable design-related decisions.

There is also a trade-off of including all socio-ecological criteria in the product requirements from the start of the design process, which ensures their consideration but adds additional load on the design teams, versus designing products based on purely functional requirements first, and adding socio-ecological requirements once functionally feasible solutions have been developed. At a later stage, more information and data about the product are also available, making it easier to assess competing solutions based on the criteria. Regarding technology development specifically, the criteria may not apply to all technology readiness levels. The list of criteria requires additional refinement for technology development to determine at which TRL the criteria should apply. In addition, the current sustainable development tools would need to be adjusted to support each of the added criteria, providing explanations and assessment methods for the criteria so that the implementation framework can be used by the design teams independently, without the support and resources of sustainability specialists.

For further future work, the proposed framework could be implemented and tested in actual product cases or projects to assess its practical usability. Comparative case studies can be conducted to analyse the outcomes of implementing the framework in terms of sustainability considerations, trade-off management, and decision-making. These comparisons can provide empirical evidence of the framework's use and value in an industrial context.

6
Conclusion

6.1 Answers to Research Questions

To guide the development process of the thesis, three research questions (RQ) were posed in Chapter 1. This section summarises how the thesis has answered each of the research questions.

RQ1: What socio-ecological criteria are the most critical to consider during the early product development stages within the aerospace industry?
To answer RQ1, a list of socio-ecological criteria was developed through an initial literature review followed by systematic funnelling with guidance from sustainability experts with experience in the aerospace industry. After funnelling and refinement, the criteria list was prioritised through focus group sessions and an analysis using the DEMATEL method. These prioritisation methods were conducted with practitioners associated with GKN Aerospace to ensure that the output applies to the aerospace industry. Following their prioritisation, the socio-ecological criteria were divided into 16 mandatory and 25 case-by-case criteria. The mandatory criteria list outlines criteria that are critical to consider in the early stages of product development. This list includes the top-scoring criteria from the conducted scoring methods as well as aspects that appear in EU regulations. This mandatory list was validated through lifecycle-focused academic literature. The results of the validation confirmed the importance of prioritising use phase-related criteria within the aerospace industry, as product operation dominates the lifecycle emissions over other phases such as raw material extraction or manufacturing. In terms of social impacts, literature highlights the negative human rights implications associated with the global raw material supply chain.

RQ 2: How should the criteria be prioritised to support decision-making and navigating trade-off situations in the product development process?
To answer RQ2, the study applied methods to prioritise the list of socio-ecological criteria and to assess criteria relationships and interdependencies. Through evaluation with stakeholder groups in focus groups, each criterion was scored based on different factors, such as ease of implementation, strategic alignment, relevance to GKNA products, and potential for socio-ecological impact. This approach enabled an understanding of different stakeholder perspectives on criteria importance and prioritisation. The DEMATEL method facilitated an understanding of the criteria relationships,

identify-
ing those that act as system drivers and those that are dependent on others. This analysis was an interesting approach as it provided further insight into criteria prioritisation and proved to be an effective support for the framework development.

Dividing the socio-ecological criteria into mandatory and case-by-case can support trade-off management. Distinguishing them can provide a practical framework where non-negotiable targets and rules can be set as a baseline to ensure sustainability for all products at all development stages. The distinction is necessary as they are not equally important. The mandatory set of criteria represents sustainability aspects that are consistently relevant for the aerospace industry, addressing regulations and highly prioritised socio-ecological criteria. In contrast, the case-by-case approach can allow designers and engineers to be flexible in different projects and select the most relevant criteria for the specific context. The categorisation integrated into the framework allows for a practical prioritisation approach for early-stage product development, which enables consistency through the development stages.

RQ3: How can the identified criteria be systematically integrated into the design and decision-making processes of GKN Aerospace?
To explore how the identified criteria can be integrated into the product development process of GKN Aerospace, an integration framework concept was developed. During the framework development process, a company mapping was conducted to identify to what degree the proposed criteria are already integrated into the current processes and where there are opportunities for further integration. Several systematic integration opportunities were identified, including in lifecycle gates, design reviews, concept selection, product requirements and the current sustainable product development tools.

Based on the company mapping, a framework was developed which suggests the integration of criteria into product requirements and concept selection matrices in the early development stages of technology development, business development & sales, pre study and conceptual design. The framework utilises existing processes instead of proposing a standalone sustainability activity by suggesting that the criteria are reviewed in lifecycle gates and design reviews and supported by the existing sustainable product development tools. A preliminary validation of the framework was conducted through case study interviews, where practitioners discussed that for successful integration, there is a need for clear definitions and measurements, ownership, traceability, information/data availability, and improved information-sharing that is consistent. The study revealed that successful sustainability integration depends not only on the selection of criteria but also on establishing an effective organisational structure, a common culture and shared language.

6.2 Final Concluding Statement

This project is a part of the ongoing collaboration between GKN Aerospace and Chalmers University of Technology, furthering sustainable product development for the aerospace industry to meet the increasing pressure from environmental regulations and targets. Is is critical to address sustainability aspects in the early stages of product development while the design space remains flexible, but this is inherently challenging due to the high degree of uncertainty and limited data availability. This thesis aims to address this issue by exploring how socio-ecological criteria can be systematically embedded in early-stage product development.

The main contributions of this thesis are twofold: a prioritised list of socio-ecological criteria and a preliminary framework to integrate the criteria into the early stages of product development within GKN Aerospace. The criteria list was developed and prioritised through a structured approach, including literature reviews, stakeholder interviews, expert screening and scoring of criteria, and the DEMATEL method. The integration framework was developed through company mapping to integrate the proposed criteria into the existing company development stages and activities. The company mapping revealed opportunities to implement the criteria into product requirements and concept selection matrices, and to review them in lifecycle gates and design reviews. This approach was validated through case study interviews with practitioners in the early stages of development to assess its feasibility and practicality.

For future work, before the proposed list of socio-ecological criteria and framework can be implemented, further refinement of the criteria is needed, as well as the development of clear metrics, assessment methods and the required data to practically assess products based on the criteria. The framework can also be developed further to provide trade-off support through the classification of criteria by design-related trade-off criteria and overarching impact criteria. In addition, the application of the framework can be simplified by assigning clear ownership roles to the criteria.

This thesis contributes to the ongoing sustainable product development research within the aerospace industry by outlining a set of socio-ecological design criteria, exploring several prioritisation methods and proposing a preliminary framework by which the criteria can be implemented into early-stage product development. Successful socio-ecological criteria integration into early-stage product development not only depends on selecting a list of criteria, but also on creating a shared organisational language and understanding of sustainability considerations, establishing clear ownership of the criteria, and developing measurable indicators.

References

[1] United Nations Environment Programme, "*Emissions Gap Report*," 2025, accessed: Dec. 3, 2025. [Online]. Available: https://wedocs.unep.org/rest/api/core/bitstreams/4830e1a8-14c0-44a5-a066-cdd2ba5b3e10/content

[2] M. Watz and S. I. Hallstedt, "Towards sustainable product development – insights from testing and evaluating a profile model for management of sustainability integration into design requirements," *Journal of Cleaner Production*, vol. 346, p. 131000, 2022, doi: https://doi.org/10.1016/j.jclepro.2022.131000.

[3] S. I. Hallstedt, O. Isaksson, J. W. Nylander, P. Andersson, and S. Knuts, "Sustainable product development in aeroengine manufacturing: challenges, opportunities and experiences from gkn aerospace engine system," *Design Science*, vol. 9, 2023, doi: 10.1017/dsj.2023.22.

[4] European Union Aviation Safety Agency, "*Aviation environmental impacts*," n.d., accessed: Nov. 4, 2025. [Online]. Available: https://www.easa.europa.eu/en/domains/environment/eaer/aviation-environmental-impacts

[5] J. L. Banks and B. P. O'Rourke, "Community impacts of aviation noise: a pilot survey," *Journal of Exposure Science and Environmental Epidemiology*, vol. 35, no. 1, pp. 80–90, 2025, doi: 10.1038/s41370-024-00737-z.

[6] S. I. Hallstedt, C. Villamil, J. Lövdahl, and J. W. Nylander, "Sustainability fingerprint - guiding companies in anticipating the sustainability direction in early design," *Sustainable Production and Consumption*, vol. 37, pp. 424–442, 2023, doi: https://doi.org/10.1016/j.spc.2023.03.015.

[7] GKN Aerospace, "Gkn aerospace sweden," GKN Aerospace, 2026, accessed: 30 April 2026. [Online]. Available: https://www.gknaerospace.com/se/

[8] ——. (2024) Gkn aerospace's carbon reduction targets validated by sbti. Accessed: 2026-06-02. [Online]. Available: https://www.gknaerospace.com/news-insights/news/gkn-aerospace-s-carbon-reduction-targets-validated-by-sbti/

[9] B.-Y. Bae, S. Kim, J.-W. Lee, N. Van Nguyen, and B.-C. Chung, "Process of establishing design requirements and selecting alternative configurations for conceptual design of a vla," *Chinese Journal of Aeronautics*, vol. 30, no. 2, pp. 738–751, 2017, doi: https://doi.org/10.1016/j.cja.2017.02.018.

[10] J. M. Bonde, O. Isaksson, T. Kipouros, M. Kokkolaras, and P. Andersson, "Exploring design trade-offs among sustainability, performance, and manufacturability when considering integration of new technologies," *Proceedings of the Design Society*, vol. 5, p. 1635–1644, 2025, doi: 10.1017/pds.2025.10177.

[11] United Nations, "Sustainability," 1987, accessed: 26 Jan. 2026. [Online]. Available: https://www.un.org/en/academic-impact/sustainability

[12] C. Sneddon and R. B. Howarth, "Sustainable development in a post-brundtland world," *Ecological Economics*, vol. 57, no. 2, pp. 253–268, 2006, doi: 10.1016/j.ecolecon.2005.04.029.

[13] S. I. Hallstedt, O. Isaksson, and J. Schulte, "Developing products for a sustainability transition," in *The Routledge Companion to Marketing and Sustainability*, K. Peattie, R. De Angelis, N. Koenig-Lewis, and C. Strong, Eds. London: Routledge, 2025, pp. 108–122.

[14] K. T. Ulrich, S. D. Eppinger, and M. C. Yang, *Product Design and Development*, 7th ed. New York, NY: McGraw-Hill, 2019.

[15] S. Benn, D. Dunphy, and A. Griffiths, *Organizational Change for Corporate Sustainability.* Routledge, 2014, doi: 10.4324/9781315819181.

[16] T. McAloone and A. Tan, "Sustainable product development through a life-cycle approach to product and service creation," 01 2005, pp. 1–12.

[17] J.-P. Schöggl, R. J. Baumgartner, and D. Hofer, "Improving sustainability performance in early phases of product design: A checklist for sustainable product development tested in the automotive industry," *Journal of Cleaner Production*, vol. 140, pp. 1602–1617, 2016, doi: 10.1016/j.jclepro.2016.09.195.

[18] M. Arena, N. Duque Ciceri, S. Terzi, I. Bengo, G. Azzone, and M. Garetti, "A state-of-the-art of industrial sustainability: Definitions, tools and metrics," *International Journal of Product Lifecycle Management*, vol. 4, no. 1–3, pp. 207–251, 2009, doi: 10.1504/IJPLM.2009.031674.

[19] S. I. Hallstedt, "Sustainability criteria and sustainability compliance index for decision support in product development," *Journal of Cleaner Production*, vol. 140, pp. 251–266, 2017, systematic Leadership towards Sustainability.

[20] J. Elkington, *Cannibals with Forks: The Triple Bottom Line of 21st Century Business.* Oxford, UK: Capstone Publishing, 2000.

[21] E. Dallara, J. Kusnitz, and M. Bradley, "Parametric life cycle assessment for the design of aircraft," *SAE International Journal of Aerospace*, vol. 6, no. 2, pp. 736–745, 2013, doi: 10.4271/2013-01-2277.

[22] T. Planès, S. Delbecq, V. Pommier-Budinger, and E. Bénard, "Simulation and evaluation of sustainable climate trajectories for aviation," *Journal of Environmental Management*, vol. 295, p. 113079, 2021, doi: 10.1016/j.jenvman.2021.113079.

[23] M. V. Chester and A. Horvath, "Environmental assessment of passenger transportation should include infrastructure and supply chains," *Environmental Research Letters*, vol. 4, no. 2, p. 024008, 2009, doi: 10.1088/1748-9326/4/2/024008.

[24] C. Facanha and A. Horvath, "Evaluation of life-cycle air emission factors of freight transportation," *Environmental Science & Technology*, vol. 41, no. 20, pp. 7138–7144, 2007, doi: 10.1021/es070989q.

[25] L. Rupcic, E. Pierrat, K. Saavedra-Rubio, N. Thonemann, C. Ogugua, and A. Laurent, "Environmental impacts in the civil aviation sector: Current state and guidance," *Transportation Research Part D: Transport and Environment*, vol. 119, p. 103717, 2023, doi: https://doi.org/10.1016/j.trd.2023.103717.

[26] S. Howe, A. J. Kolios, and F. P. Brennan, “Environmental life cycle assessment of commercial passenger jet airliners,” *Transportation Research Part D: Transport and Environment*, vol. 19, pp. 34–41, 2013, doi: 10.1016/j.trd.2012.12.004.

[27] E. Pierrat, L. Rupcic, M. Z. Hauschild, and A. Laurent, “Global environmental mapping of the aeronautics manufacturing sector,” *Journal of Cleaner Production*, vol. 297, p. 126603, 2021, doi: 10.1016/j.jclepro.2021.126603.

[28] D. Lee, D. Fahey, A. Skowron, M. Allen, U. Burkhardt, Q. Chen, S. Doherty, S. Freeman, P. Forster, J. Fuglestvedt, A. Gettelman, R. De León, L. Lim, M. Lund, R. Millar, B. Owen, J. Penner, G. Pitari, M. Prather, R. Sausen, and L. Wilcox, “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018,” *Atmospheric Environment*, vol. 244, p. 117834, 2021, doi: https://doi.org/10.1016/j.atmosenv.2020.117834.

[29] D. G. Ullman, *The Mechanical Design Process*, 4th ed. New York, NY: McGraw-Hill, 2010.

[30] G. Pahl and W. Beitz, *Engineering Design: A Systematic Approach*, 3rd ed. London, UK: Springer London, 2007.

[31] P. G. Smith and D. G. Reinertsen, *Developing Products in Half the Time.* New York, NY, USA: Van Nostrand Reinhold, 1991.

[32] C. Herstatt and B. Verworn, *The ‘Fuzzy Front End’ of Innovation.* London: Palgrave Macmillan UK, 2004, pp. 347–372. [Online]. Available: https://doi.org/10.1057/9780230512771_16

[33] S. Vilochani, T. C. McAloone, and D. C. Pigosso, “Consolidation of management practices for sustainable product development: A systematic literature review,” *Sustainable Production and Consumption*, vol. 45, pp. 115–125, 2024, doi: https://doi.org/10.1016/j.spc.2024.01.002.

[34] M. Watz and S. I. Hallstedt, “Integrating sustainability in product requirements,” in *Proceedings of the International Design Conference, DESIGN 2018*, D. Marjanović, M. Štorga, S. Škec, N. Bojčetić, and N. Pavković, Eds. The Design Society, 2018, pp. 1405–1416, doi: 10.21278/idc.2018.0377.

[35] I. Staack, K. Amadori, and C. Jouannet, “A holistic engineering approach to aeronautical product development,” *The Aeronautical Journal*, vol. 123, no. 1268, p. 1545–1560, 2019, doi: 10.1017/aer.2019.51.

[36] H. Jiang, “Key findings on airplane economic life,” Presentation, Aviation System Analysis, Boeing Commercial Airplanes, Mar. 2013, associate Technical Fellow, Aviation System Analysis.

[37] V. Voth and O. Bertram, “Aircraft system design: A model-based and collaborative approach,” in *Proceedings of the 34th Congress of the International Council of the Aeronautical Sciences (ICAS)*, Braunschweig, Germany, September 2024.

[38] S. Gradel, P. Hansmann, and E. Stumpf, “Systemxf: a novel approach for holistic system modeling in aircraft conceptual design,” *CEAS Aeronautical Journal*, vol. 14, 12 2022, doi: 10.1007/s13272-022-00629-8.

[39] A. Hamed, K. Maister, S. Hebbur Murali, A. Paternostro, L. Radwan, and A. Ciroth, “Product social impact life cycle assessment (psilca v4) - database

documentation," 08 2025, doi: 10.13140/RG.2.2.18549.08164.

[40] H. Afshari, S. Agnihotri, C. Searcy, and M. Jaber, "Social sustainability indicators: A comprehensive review with application in the energy sector," *Sustainable Production and Consumption*, vol. 31, pp. 263–286, 2022, doi: https://doi.org/10.1016/j.spc.2022.02.018.

[41] F. Richter, W. Gawenko, U. Götze *et al.*, "Toward a methodology for social sustainability assessment: A review of existing frameworks and a proposal for a catalog of criteria," *Schmalenbach Journal of Business Research*, vol. 75, pp. 587–626, 2023, doi: 10.1007/s41471-023-00174-y.

[42] J. Rockström, W. Steffen, K. Noone, Persson, F. S. Chapin III, E. Lambin, T. Lenton, M. Scheffer, C. Folke, and H. Schellnhuber, "Planetary boundaries: Exploring the safe operating space for humanity," *Ecol Soc*, vol. 14, 01 2009.

[43] F. Moisiadis, "The fundamentals of prioritising requirements," in *Proceedings of the 35th Annual Hawaii International Conference on System Sciences (HICSS-35)*. Big Island, Hawaii, USA: IEEE, 2002, doi: 10.1109/HICSS.2002.994035.

[44] G. Pahl, W. Beitz, J. Feldhusen, and K.-H. Grote, *Product Planning, Solution Finding and Evaluation*. London: Springer London, 2007, pp. 63–124, doi: 10.1007/978-1-84628-319-2_3.

[45] T. Hunger, M. G. Arnold, S. Engesser, and K. Gerald van den Boogaart, "Integrating sustainability facets into the early stages of new product development using multi-criteria tools - a critical review," *Journal of Cleaner Production*, vol. 517, p. 145834, 2025, doi: https://doi.org/10.1016/j.jclepro.2025.145834.

[46] G.-H. Tzeng, C.-H. Chiang, and C.-W. Li, "Evaluating intertwined effects in e-learning programs: A novel hybrid mcdm model based on factor analysis and dematel," *Expert Systems with Applications*, vol. 32, no. 4, pp. 1028–1044, 2007, doi: 10.1016/j.eswa.2006.02.004.

[47] G. I. Broman and K.-H. Robèrt, "A framework for strategic sustainable development," *Journal of Cleaner Production*, vol. 140, pp. 17–31, 2017, doi: https://doi.org/10.1016/j.jclepro.2015.10.121.

[48] *Environmental management — Life cycle assessment — Principles and framework*, International Organization for Standardization Std. ISO 14 040:2006, 2006. [Online]. Available: https://www.iso.org/standard/37456.html

[49] M. Owsianiak, A. Bjørn, A. Laurent, C. Molin, and M. W. Ryberg, "Lca applications," in *Life Cycle Assessment: Theory and Practice*, M. Z. Hauschild, R. K. Rosenbaum, and S. I. Olsen, Eds. Springer, 2018, pp. 31–40, doi: 10.1007/978–3–319–56 475–3_4, doi: 10.1007/978-3-319-56475-3_4.

[50] V. Camañes, R. Tobajas, and A. Fernandez, "Methodology of eco-design and software development for sustainable product design," *Sustainability*, vol. 16, no. 7, 2024, doi: 10.3390/su16072626. [Online]. Available: https://www.mdpi.com/2071-1050/16/7/2626

[51] S. Wang, D. Su, Y. Wu, and Z. Chai, "Application of life-cycle assessment to the eco-design of led lighting products," *Euro-Mediterranean Journal for Environmental Integration*, vol. 5, 08 2020, doi: 10.1007/s41207-020-00180-0.

[52] J. Simanovska, K. Valters, and G. Bazbauers, “Development of a set of criteria as an eco-design tool for evaluation of environmental impact of material choice,” *Scientific Journal of Riga Technical University. Environmental and Climate Technologies*, vol. 3, pp. 102–110, 01 2009, doi: 10.2478/v10145-009-0014-7.

[53] E. Pavlovskaia, “Sustainability criteria: their indicators, control, and monitoring (with examples from the biofuel sector),” *Environmental Sciences Europe*, vol. 26, no. 1, p. 17, 2014, doi: 10.1186/s12302-014-0017-2.

[54] “6 - life cycle assessment of equipment for electricity transmission and distribution networks,” in *Eco-Friendly Innovation in Electricity Transmission and Distribution Networks*, J.-L. Bessède, Ed. Oxford: Woodhead Publishing, 2015, pp. 123–133, doi: https://doi.org/10.1016/B978-1-78242-010-1.00006-9.

[55] M. Schäfer and M. Löwer, “Ecodesign—a review of reviews,” *Sustainability*, vol. 13, no. 1, p. 315, 2021, doi: 10.3390/su13010315.

[56] International Organization for Standardization, “Environmental management systems — guidelines for incorporating ecodesign (iso 14006:2020),” 2020, international Standard, accessed 2026-03-16. [Online]. Available: https://www.iso.org/standard/72644.html

[57] UNEP, *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*, C. Benoît Norris, M. Traverso, S. Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A. Lehmann, M. Finkbeiner, and G. Arcese, Eds. Paris: United Nations Environment Programme (UNEP), 2020. [Online]. Available: https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf

[58] S. Partelow, “What is a framework? understanding their purpose, value, development and use,” *Journal of Environmental Studies and Sciences*, vol. 13, 04 2023, doi: 10.1007/s13412-023-00833-w.

[59] M. Erlhoff, T. Marshall, L. Bruce, and S. Lindberg, *Design Dictionary: Perspectives on Design Terminology*, 01 2008, pp. –472.

[60] J. Vicente and D. Camocho, “Design for sustainability tools: Definition and criteria towards practical use,” *Journal of Cleaner Production*, vol. 479, p. 144041, 2024, doi: https://doi.org/10.1016/j.jclepro.2024.144041.

[61] A. Cartile, C. Marsden, and S. Liscouët-Hanke, “Digital transformation in aircraft design and certification: Developing requirements for modeling regulatory documentation,” *Aerospace*, vol. 12, no. 8, 2025, doi: 10.3390/aerospace12080724.

[62] European Commission, “Reducing emissions from aviation,” 2023, accessed: 2026-03-18. [Online]. Available: https://climate.ec.europa.eu/eu-action/transport-decarbonisation/reducing-emissions-aviation_en

[63] C. R. Nava, L. Meleo, E. Cassetta, and G. Morelli, “The impact of the eu-ets on the aviation sector: Competitive effects of abatement efforts by airlines,” *Transportation Research Part A: Policy and Practice*, vol. 113, pp. 20–34, 2018, doi: https://doi.org/10.1016/j.tra.2018.03.032.

[64] European Chemicals Agency (ECHA). (2024) Understanding reach. Accessed:

2026-03-30. [Online]. Available: https://www.echa.europa.eu/regulations/reach/understanding-reach

[65] European Union Aviation Safety Agency (EASA). (2026) Reach and aviation. Accessed: 2026-03-30. [Online]. Available: https://www.easa.europa.eu/en/domains/environment/reach-and-aviation

[66] European Commission. (2026) Eu taxonomy for sustainable activities. Accessed: 2026-03-30. [Online]. Available: https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/eu-taxonomy-sustainable-activities_en

[67] Melrose Industries PLC, “Sustainability report 2024,” Melrose Industries PLC, Tech. Rep., 2024, accessed: 2026-02-10. [Online]. Available: https://gknaerospace.com

[68] GE Aerospace, “2025 sustainability report: Moving innovation forward,” GE Aerospace, Tech. Rep., 6 2025, accessed: 2026-02-10. [Online]. Available: https://www.geaerospace.com/sites/default/files/2025-sustainability-report.pdf

[69] AB SKF, “Skf annual report 2024: Sustainability report,” AB SKF, Tech. Rep., 2025, accessed: 2026-06-02. [Online]. Available: https://cdn.skfmediahub.skf.com/api/public/09b054891e767c40/pdf_preview_medium/09b054891e767c40_pdf_preview_medium.pdf

[70] MTU Aero Engines AG, “Esg factbook 2024/25,” MTU Aero Engines AG, Report, September 2025, accessed: 2026-02-10. [Online]. Available: https://www.mtu.de/responsibility/sustainability-reports-and-documentation/

[71] Safran SA, “2024 universal registration document: Including the annual financial report,” Safran SA, Tech. Rep., 3 2025, accessed: 2026-02-10. [Online]. Available: https://www.safran-group.com/sites/default/files/2025-04/2024-safran-universal-registration-document.pdf

[72] S. Pugh, *Total Design: Integrated Methods for Successful Product Engineering.* Reading, Mass.: Addison-Wesley, 1991.

[73] P. Marwedel, *Evaluation and Validation.* Cham: Springer International Publishing, 2021, pp. 239–293, doi: 10.1007/978-3-030-60910-8_5.

[74] Ellen MacArthur Foundation, “Circularity indicators: Methodology,” Ellen MacArthur Foundation, Cowes, UK, Tech. Rep., 2019. [Online]. Available: https://content.ellenmacarthurfoundation.org/m/77e62bc9924c20d0/original/Circularity-Indicators-Methodology.pdf

[75] A. Shahhoseini, S. Heydari, and S. Pedrammehr, “Manufacturing and assembly for the ease of product recycling: A review,” *Designs*, vol. 7, p. 42, 03 2023, doi: 10.3390/designs7020042.

[76] C. Feng, S. Huang, and G. Bai, “A group decision making method for sustainable design using intuitionistic fuzzy preference relations in the conceptual design stage,” *Journal of Cleaner Production*, vol. 243, p. 118640, 2020, doi: 10.1016/j.jclepro.2019.118640.

[77] S. M. Li, F. T. S. Chan, Y. P. Tsang, and H. Y. Lam, “New product idea selection in the fuzzy front end of innovation: A fuzzy best-worst method and group decision-making process,” *Mathematics*, vol. 9, no. 4, 2021, doi: 10.3390/math9040337.

[78] S. Xing, Z. Jiang, X. Zhang, and Y. Wang, “Product design scheme generation and optimization decisions while considering remanufacturability,” *Mathematics*, vol. 10, no. 14, 2022, doi: 10.3390/math10142477.
[79] A. C. Benabdellah, A. Benghabrit, I. Bouhaddou *et al.*, “Design for relevance concurrent engineering approach: integration of iatf 16949 requirements and design for x techniques,” *Research in Engineering Design*, vol. 31, no. 3, pp. 323–351, 2020, doi: 10.1007/s00163-020-00339-4.
[80] X. Ai, Z. Jiang, H. Zhang, and Y. Wang, “Low-carbon product conceptual design from the perspectives of technical system and human use,” *Journal of Cleaner Production*, vol. 244, p. 118819, 2020, doi: https://doi.org/10.1016/j.jclepro.2019.118819.
[81] L. Cong, F. Zhao, and J. W. Sutherland, “A design method to improve end-of-use product value recovery for circular economy,” *Journal of Mechanical Design*, vol. 141, no. 4, p. 044502, 04 2019, doi: 10.1115/1.4041574.
[82] C. Favi, L. Murgese, S. Gallozzi, C. Chiacchietta, M. Marconi, and M. Mandolini, “Definition of a life cycle engineering tool to support the ecodesign in additive manufacturing: application to fdm technology,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, nov 2025, doi: 10.1007/s12008-025-02432-1.
[83] A. Bertoni, S. Hallstedt, S. Wejletorp, and P. Andersson, “Integration of value and sustainability assessment in design space exploration by machine learning: an aerospace application,” *Design Science*, vol. 6, 01 2020, doi: 10.1017/dsj.2019.29.
[84] S. Purker, C. R. Lalyer, and B. Giese, “Decision support for selection of new materials considering socio-economic and broader environmental aspects,” *Sustainable Production and Consumption*, vol. 39, pp. 438–450, 2023, doi: 10.1016/j.spc.2023.05.032.
[85] S. Y. Kwok, J. Schulte, and S. I. Hallstedt, “Approach for sustainability criteria and product life-cycle data simulation in concept selection,” *Proceedings of the Design Society: DESIGN Conference*, vol. 1, p. 1979–1988, 2020, doi: 10.1017/dsd.2020.297.
[86] European Commission, “Conflict minerals regulation: The regulation explained,” 2021, accessed: 2026-05-24. [Online]. Available: https://policy.trade.ec.europa.eu/development-and-sustainability/conflict-minerals-regulation/regulation-explained_en
[87] S. I. Hallstedt and O. Isaksson, “Material criticality assessment in early phases of sustainable product development,” *Journal of Cleaner Production*, vol. 161, pp. 40–52, 2017, doi: https://doi.org/10.1016/j.jclepro.2017.05.085.
[88] European Commission, “Critical raw materials,” 2023, accessed: 2026-05-24. [Online]. Available: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
[89] A. Gilbrook, Y. Ma, and A. Elham, “Effect of ultra-high aspect ratio wings and distributed propulsion on the viability of fully electric regional aircraft,” *Aircraft Engineering and Aerospace Technology*, vol. 97, 01 2025, doi: 10.1108/AEAT-06-2024-0160.
[90] M. A. Gunduz, S. Demir, and T. Paksoy, “Matching functions of supply chain

management with smart and sustainable tools: A novel hybrid bwm-qfd based method," *Computers Industrial Engineering*, vol. 162, p. 107676, 2021, doi: https://doi.org/10.1016/j.cie.2021.107676.

[91] H. Gholami, A. Hashemi, J. K. Y. Lee, G. Abdul-Nour, and A. A. Salameh, "Scrutinizing state-of-the-art i4.0 technologies toward sustainable products development under fuzzy environment," *Journal of Cleaner Production*, vol. 377, p. 134327, 2022, doi: https://doi.org/10.1016/j.jclepro.2022.134327.

[92] L. Klaaßen and C. Stoll, "Harmonizing corporate carbon footprints," *Nature Communications*, vol. 12, no. 1, p. 6149, 10 2021, doi: 10.1038/s41467-021-26349-x.

[93] S. Ahmad, J. Ouenniche, B. W. Kolosz, P. Greening, J. M. Andresen, M. M. Maroto-Valer, and B. Xu, "A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways," *International Journal of Production Economics*, vol. 238, p. 108156, 2021, doi: https://doi.org/10.1016/j.ijpe.2021.108156.

[94] S. Durante, M. Comoglio, and N. Ridgway, *Life Cycle Assessment in Nanotechnology, Materials and Manufacturing*, 12 2015, ch. 34, pp. 775–804, doi: 10.1016/B978-0-323-31149-6.00034-7.

[95] Karahan Özgün, R. Tasli, E. Dulekgurgen, and E. Gorgun, "Estimation of hazardous waste factors," *Desalination and Water Treatment - DESALIN WATER TREAT*, vol. 26, pp. 79–86, 02 2011, doi: 10.5004/dwt.2011.2113.

[96] J. A. Mesa and A. González-Quiroga, "Development of a diagnostic tool for product circularity: a redesign approach," *Research in Engineering Design*, vol. 34, no. 3, pp. 401–420, 2023, doi: 10.1007/s00163-023-00415-5.

[97] International Organization for Standardization, *Quality management systems — Fundamentals and vocabulary*, Std. ISO 9000:2015, 2015. [Online]. Available: https://iso.org

[98] N. H. Arian, A. Pooya, F. Rahimnia *et al.*, "Assessment the effect of rapid prototyping implementation on supply chain sustainability: a system dynamics approach," *Operations Management Research*, vol. 14, no. 3, pp. 467–493, 2021, doi: 10.1007/s12063-021-00228-6.

[99] "Product safety and security in the global supply chain: Issues, challenges and research opportunities," *Journal of Operations Management*, vol. 29, no. 7, pp. 707–720, 2011.

[100] T. Osteras, D. N. Murthy, and M. Rausand, "Product performance and specification in new product development," *Journal of Engineering Design*, vol. 17, no. 2, pp. 177–192, 2006, doi: 10.1080/09544820500275735.

[101] D. Siwiec and A. Pacana, "Improvement of renewable energy products by balancing quality, environmental, societal, and cost aspects," *Energies*, vol. 18, no. 18, 2025, doi: 10.3390/en18184840.

[102] J. S. McGee and L. R. Bassett, "Vertical integration revisited," *The Journal of Law & Economics*, vol. 19, no. 1, pp. 17–38, 04 1976. [Online]. Available: http://www.jstor.org/stable/725311

[103] A. Villemeur, *Reliability, Availability, Maintainability and Safety Assessment.* Wiley, 1992.

[104] R. Slim, R. Houssin, A. Coulibaly, and H. Chibane, "Lean system design

framework based on lean functionalities and criteria integration in production machines design phase," *FME Transactions*, vol. 49, pp. 575–586, 06 2021, doi: 10.5937/fme2103575S.

[105] B. DHILLON, "Chapter 1 - introduction," in *Engineering Maintainability*. Houston: Gulf Professional Publishing, 1999, pp. 1–12, doi: https://doi.org/10.1016/B978-088415257-6/50001-6.

[106] M. A. Khan, S. Mittal, S. West, and T. Wuest, "Review on upgradability – a product lifetime extension strategy in the context of product service systems," *Journal of Cleaner Production*, vol. 204, pp. 1154–1168, 2018, doi: https://doi.org/10.1016/j.jclepro.2018.08.329.

[107] European Commission, "REACH regulation," 2007, accessed: 2026-05-24. [Online]. Available: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en

[108] ChemSec, "The sin list," 2026, accessed: 2026-05-24. [Online]. Available: https://sinlist.chemsec.org/

[109] European Union, "Council Directive 89/391/EEC of 12 June 1989 on the introduction of measures to encourage improvements in the safety and health of workers at work," *Official Journal of the European Communities*, vol. L 183, pp. 1–8, 1989. [Online]. Available: https://eur-lex.europa.eu/eli/dir/1989/391/oj/eng

[110] A. Hamed, K. Maister, S. Hebbur Murali, A. Paternostro, L. Radwan, and A. Ciroth, "Product social impact life cycle assessment (psilca v4) - database documentation," 08 2025.

[111] G. Torralba-Carnerero, M. García-Nieto, J. M. Ramón-Jerónimo, and R. Flórez-López, "Supply chain management control in the aerospace sector: An empirical approach," *Logistics*, vol. 8, no. 4, 2024. [Online]. Available: https://www.mdpi.com/2305-6290/8/4/132

[112] International Organization for Standardization, *Acoustics — Determination of sound power levels and sound energy levels of noise sources using sound pressure — Engineering methods for an essentially free field over a reflecting plane*, Std. ISO 3744:2010, 2010. [Online]. Available: https://www.iso.org/standard/52055.html

[113] ——, *Acoustics — Determination of sound power levels and sound energy levels of noise sources using sound pressure — Survey method using an enveloping measurement surface over a reflecting plane*, Std. ISO 3746:2010, 2010. [Online]. Available: https://iso.org

[114] National Contact Point OECD Guidelines, Netherlands Ministry of Foreign Affairs, "Due diligence," 2023, accessed: 2026-05-24. [Online]. Available: https://www.oecdguidelines.nl/oecd-guidelines/d/due-diligence

[115] European Parliament and Council of the European Union, "Regulation (ec) no 1907/2006 concerning the registration, evaluation, authorisation and restriction of chemicals (reach)," 2006, official Journal of the European Union, L 396, 30 December 2006. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2006/1907/oj/eng

[116] European Chemicals Agency, "Candidate list (substances of very high concern)," 2026, accessed: 4 June 2026. [Online]. Available: https:

//chem.echa.europa.eu/obligation-lists/candidateList
[117] European Parliament and Council of the European Union, “Regulation (ec) no 1272/2008 on classification, labelling and packaging of substances and mixtures (clp),” 2008, official Journal of the European Union, L 353, 31 December 2008. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2008/1272/oj/eng
[118] European Agency for Safety and Health at Work (EU-OSHA), “Directive 89/391/eec - osh "framework directive",” 1989, accessed: 2026-06-04. [Online]. Available: https://osha.europa.eu/en/legislation/directives/the-osh-framework-directive/1
[119] European Parliament and Council of the European Union, “Directive 2004/37/ec on the protection of workers from the risks related to exposure to carcinogens or mutagens at work,” 2004, official Journal of the European Union, L 158, 30 April 2004. [Online]. Available: https://osha.europa.eu/en/legislation/directive/directive-200437ec-carcinogens-or-mutagens-work
[120] ——, “Directive 2009/148/ec on the protection of workers from the risks related to exposure to asbestos at work,” 2009, official Journal of the European Union, L 330, 16 December 2009. [Online]. Available: https://osha.europa.eu/en/legislation/directives/2009-148-ec-exposure-to-asbestos-at-work
[121] ——, “Directive (eu) 2024/1760 on corporate sustainability due diligence,” 2024, official Journal of the European Union, L 2024/1760, 5 July 2024. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2024/1760/oj/eng
[122] United Nations Human Rights Office of the High Commissioner (OHCHR), “Guiding principles on business and human rights: Implementing the united nations "protect, respect and remedy" framework,” 2011, united Nations, New York and Geneva. [Online]. Available: https://www.ohchr.org/sites/default/files/documents/publications/guidingprinciplesbusinesshr_en.pdf
[123] International Labour Organization (ILO), “Freedom of association and protection of the right to organise convention, 1948 (no. 87),” 1948, iLO Convention C087. [Online]. Available: https://normlex.ilo.org/dyn/nrmlx_en/f?p=NORMLEXPUB:12100:0::NO::P12100_INSTRUMENT_ID:312232
[124] ——, “Right to organise and collective bargaining convention, 1949 (no. 98),” 1949, iLO Convention C098. [Online]. Available: https://normlex.ilo.org/dyn/nrmlx_en/f?p=NORMLEXPUB:12100:0::NO::P12100_INSTRUMENT_ID:312243
[125] European Parliament and Council of the European Union, “Regulation (eu) 2024/3015,” 2024, official Journal of the European Union, 2024. [Online]. Available: https://eur-lex.europa.eu/eli/reg/2024/3015/oj/eng
[126] International Labour Organization (ILO), “Forced labour convention, 1930 (no. 29),” 1930, iLO Convention C029. [Online]. Available: https://normlex.ilo.org/dyn/nrmlx_en/f?p=NORMLEXPUB:12100:0::NO::P12100_ILO_CODE:C029
[127] European Parliament and Council of the European Union, “Directive (eu) 2022/2464 as regards corporate sustainability reporting (csrd),” 2022, official Journal of the European Union, L 322, 16 December 2022. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2022/2464/oj/eng

[128] Y.-J. Hu, L. Yang, H. Cui, H. Wang, C. Li, and B.-J. Tang, “Strategies to mitigate carbon emissions for sustainable aviation: A critical review from a life-cycle perspective,” *Sustainable Production and Consumption*, vol. 33, pp. 788–808, 2022, doi: https://doi.org/10.1016/j.spc.2022.08.009.

[129] H. Hemmer, T. Otten, M. Plohr, M. Lecht, and A. Döpelheuer, “Influence of the bypass ratio on low altitude no_x emissions,” 09 2007, pp. 1185–1193.

[130] R. Friedl, “Aviation meteorology | aircraft emissions,” in *Encyclopedia of Atmospheric Sciences (Second Edition)*, second edition ed., G. R. North, J. Pyle, and F. Zhang, Eds. Oxford: Academic Press, 2015, pp. 153–159, doi: https://doi.org/10.1016/B978-0-12-382225-3.00061-X.

[131] B. Li, M. Wang, D. Wang, Q. Zhang, L. Shi, X. Wei, W. Xue, and J. Jiang, “Real-world aviation emissions of ultrafine particles and nitric oxide: The trade-off between fuel efficiency and pollutant emissions,” *Atmospheric Environment*, vol. 372, p. 121897, 2026, doi: https://doi.org/10.1016/j.atmosenv.2026.121897.

[132] A. Skowron, D. S. Lee, R. R. De León, L. L. Lim, and B. Owen, “Greater fuel efficiency is potentially preferable to reducing NO_x emissions for aviation’s climate impacts,” *Nature Communications*, vol. 12, no. 1, p. 564, 2021, doi: 10.1038/s41467-020-20771-3.

[133] S. Freeman, D. S. Lee, L. L. Lim, A. Skowron, and R. R. De León, “Trading off aircraft fuel burn and nox emissions for optimal climate policy,” *Environmental Science & Technology*, vol. 52, no. 5, pp. 2498–2505, 2018, doi: 10.1021/acs.est.7b05719.

[134] R. Steinegger, “Fuel economy for aircraft operation as a function of weight and distance.” ZHAW Zurich University of Applied Sciences, Tech. Rep., 2017, doi: 10.21256/ZHAW-3466.

[135] D. I. A. Poll, “On the application of light weight materials to improve aircraft fuel burn – reduce weight or improve aerodynamic efficiency?” *The Aeronautical Journal*, vol. 118, no. 1206, p. 903–934, 2014, doi: 10.1017/S0001924000009611.

[136] Y. Atescan-Yuksek, A. Mills, D. Ayre *et al.*, “Comparative life cycle assessment of aluminium and cfrp composites: the case of aerospace manufacturing,” *The International Journal of Advanced Manufacturing Technology*, vol. 131, pp. 4345–4357, 2024, doi: 10.1007/s00170-024-13241-3.

[137] P. L. Y. Léonard and J. W. Nylander, “Sustainability assessment of composites in aero-engine components,” *Proceedings of the Design Society: DESIGN Conference*, vol. 1, p. 1989–1998, 2020, doi: 10.1017/dsd.2020.29.

[138] L. Scelsi, M. Bonner, A. Hodzic, C. Wilson, R. Scaife, and K. Ridgway, “Potential emissions savings of lightweight composite aircraft components evaluated through life cycle assessment,” *Express Polymer Letters*, vol. 5, pp. 209–217, 01 2011, doi: 10.3144/expresspolymlett.2011.20.

[139] F. Pollet, F. Lutz, T. Planès, S. Delbecq, and M. Budinger, “A generic life cycle assessment tool for overall aircraft design,” *Applied Energy*, vol. 399, p. 126514, 2025, doi: https://doi.org/10.1016/j.apenergy.2025.126514.

[140] F. Campean and C. Eckert, “Durability as a techno-socio-economic concept,”

Proceedings of the Design Society, vol. 4, p. 1219–1228, 2024, doi: 10.1017/pds.2024.124.

[141] I. Maldini, I. G. Klepp, and K. Laitala, "The environmental impact of product lifetime extension: a literature review and research agenda," *Sustainable Production and Consumption*, vol. 56, pp. 561–578, 2025, doi: https://doi.org/10.1016/j.spc.2025.04.020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352550925000958

[142] A. Oestreicher, A. Rahn, J. Ramm, J. Städing, C. Keller, K. Wicke, and G. Wende, "Sustainable engine maintenance: Evaluating the ecological impact of life limited part replacement," Braunschweig, Germany, 11 2024.

[143] A. Malik, G. Lafortune, C. J. Mora, S. Carter, and M. Lenzen, "Carbon and social impacts in the eu's consumption of fossil and mineral raw materials," *Journal of Environmental Management*, vol. 369, p. 122291, 2024, doi: https://doi.org/10.1016/j.jenvman.2024.122291.

[144] S. De Haes and H. Brink, "Social impacts of mining critical raw materials: Challenges and entry points for governance," PBL Netherlands Environmental Assessment Agency, Tech. Rep., June 2025. [Online]. Available: https://www.pbl.nl/en/publications/social-impacts-of-mining-critical-raw-materials

[145] J. M. Siqueiros-García, D. Manuel-Navarrete, H. Eakin, L. Mojica, L. Charli-Joseph, P. Pérez-Belmont, and B. Ruizpalacios, "Sense of agency, affectivity and social-ecological degradation: An enactive and phenomenological approach," *Frontiers in Psychology*, vol. Volume 13 - 2022, 2022, doi: 10.3389/fpsyg.2022.911092. [Online]. Available: https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2022.911092

[146] J. Lövdahl, J. Schulte, and S. I. Hallstedt, "A literature review of approaches for assessing product sustainability performance in early phases of the product innovation process," in *Proceedings of the 78th NordDesign Conference (NDes 2024)*, Karlskrona, Sweden, 2024.

[147] L. Rihar and J. Kušar, "Implementing concurrent engineering and qfd method to achieve realization of sustainable project," *Sustainability*, vol. 13, p. 1091, 01 2021, doi: 10.3390/su13031091.

[148] F. Kiling, S.-J. Shin, M.-K. Lee, and P. Meilanitasari, "An energy-related products compliant eco-design method with durability-embedded economic and environmental assessments," *International Journal of Precision Engineering and Manufacturing-Green Technology*, vol. 8, 04 2020, doi: 10.1007/s40684-020-00213-7.

[149] K. Anagnostopoulu, D. Sotiropoulos, I. Sioutis, and K. Tserpes, "Sustainability-driven design optimization of aircraft parts using mathematical modeling," *Aerospace*, vol. 13, p. 95, 01 2026, doi: 10.3390/aerospace13010095.

[150] A. Filippatos, D. Markatos, A. Theochari, and S. Pantelakis, "Integrating sustainability in aircraft component design: Towards a transition from eco-driven to sustainability-driven design," *Aerospace*, vol. 12, no. 2, 2025, doi: 10.3390/aerospace12020140.

A

Criteria from Literature Review and Expansion

Table A.1: Criteria from the Original Literature Review

Avoid needing special treatments for recycling [84]	Ease of recycling [77]	Materials/components returned for remanufacturing and recycling [34, 83]	Recycling of components at EoL [82]
Recycling of scrap materials from post processing [82]	Scrap recyclability [34, 85]	Easy recyclability: use recyclable parts, nontoxic harmless materials, efficient and reasonable recovery [78]	Easy to recycle [80]
Non-recyclable solid waste [84]	Recyclability [6]	Recycled materials [83, 147]	Share of recyclability [45]
Share of recycled materials [45]	The recyclability of parts [79]	Use of recycled material [6]	Use recycled materials as input [34, 85]
Rare element usage [84]	Avoid critical materials [34, 85]	Critical materials [83]	Optimised product weight [34, 83]
Weight [80, 82]	Weight reduction [89]	Material load [148]	Material consumption [98]
Material use [91]	Material utilisation [76]	Volume [80]	Sustainable resource use [101]
Amount of resource consumption in its life cycle [80]	Less resource consumption [80, 147]	Mineral resource depletion [84]	Resources [149]
Resource availability/scarcity [45]	Resource depletion, mineral, fossil and renewable [45]	Strategic securing of resources [45]	Energy consumption [77]
Energy consumption from renewable energy [84]	Energy efficiency/power consumption [76]	Energy load [148]	Energy use [90]
Amount of energy consumption in its life cycle [80]	Less energy consumption [80]	The energy used during the extraction [79]	Transport length [45]
Use of renewable source of energy [76]	Emissions from energy consumption [6]	Reduction of dependencies on resources, energy, time [84]	Renewable energy sources are used in the production processes [34]
Carbon footprint [77]	GWP total [149]	The low-carbon property of the recovery method [80]	CO2 emission [98]
Consumer health and safety protection [101]	Employee safety [84]	Health [101]	Health and safety during production stage [34, 85]
Health and wellness effect [76]	Health and safety [90]	Human health [149]	Occupational health and safety [101]
Operational safety [76]	Safety [45]	Safety and health impact (product safety) [79]	No structural obstacles for people's health, influence, competence, impartiality and meaning-making [34]

Ionising radiation, human health [45]	No organisational practices at the suppliers of raw materials that create structural obstacles for people's health, influence, competence, impartiality and meaning-making [34]	Noise to the surroundings [34, 83]	Waste and emissions [91]
Emission [90]	Emission load [148]	Emissions and waste from end of life phase must not contribute to an accumulation in nature [34]	Emissions of greenhouse gases [34]
Emissions to air, water, soil [84]	Emissions, waste products and chemicals listed in REACH / IAEG / SIN lists [34, 83]	GHG contribution [84]	GHG emission savings [93]
Toxic and hazardous emissions during production and use [79]	Less emission of toxic substances [80]	Overall hazardous emissions [84]	Reduce the emissions [104]
Pollution [90]	Pollution prevention [101]	Soil and water pollution [93]	Handling of waste [6]
Hazardous waste [6]	Hazardous waste/ material/ substances [45]	Minimise waste [104]	Waste [90]
Waste generation [98]	Use of water in a water-scarce region [84]	Wastewater [84]	Water consumption [84]
Water eutrophication through nitrogen and phosphorus soil acidification [84]	Availability of fresh water for ecosystems [84]	Resource depletion, water [45]	Human toxicity, cancer effects [45]
Human toxicity, non-cancer effects [45]	Ecotoxicity (freshwater) [45]	Ecotoxicity (terrestrial and marine) [45]	Land use [45]
No new land areas, otherwise used for renewable resources and recreation, are used for transportation of materials, substances and/or products. [34]	Land use change impact [93]	Traceability [93]	Tracking/Transparency [45]
Secondary function [96]	Potential for dual use [84]	Share of re-usage [45]	Re-usability [6]
Easy to reuse [80]	Remanufacturability/ reusability [76]	Product quality [98]	product quality and durability (reliability and maintenance) [91]
Perception of quality [101]	Performance [101]	Performance & Durability [45]	Functional effectiveness [76]
Functional performance (product customizability) [91]	Functionality [101]	Functionality and performance [45]	Improved functionality [84]
Circular material use rate (RMI) [45]	Material efficiency [6]	Material efficiency/ circularity [45]	Raw material and use for domestic consumption and investments (RMC) per capita [45]
The number of materials to be extracted from the earth needed for packaging [79]	Total raw material productivity [45]	The complexity of material [80]	Vertical range of manufacture [84]
Ratio of in-house/ external manufacturing of NM [84]	Risk of remanufacturing [34, 83]	Special manufacturing technology [84]	No physical degradation from use of raw materials/chemicals, production, end of life [34]

No production of product or product components used that cause degradation of nature by physical means [34]	Avoid needing special measures for disposal [84]	Disposability [76]	Disposal options [45]
Share of compostability or biodegradability [45]	Durability [96]	Improve the product durability [104]	Service/ Durability [76]
Effect on products service life [84]	Service life / psychological life time [45]	Service life / technical life time [45]	Useful life [82]
Modularity [76]	Repair impact [82]	Ease of serviceability [101]	Number of parts [80]
Dis/ reasembliability [96]	Disassembly [76]	Discrimination and vulnerable groups [101]	Dismantability [45]
Assembly [76]	Assembly/ Disassembly impact [82]	Repairability [45]	Optimise end-of-life and life cycle [104]
Access to essential services [101]	Acidification [45]	Additional costs for users [84]	Aesthetics [101]
Anti-corruption[101]	Avoiding complicity [101]	Breakthrough potential [84]	Life-cycle factor [76]
Civil and political rights [101] Compatibility (correctness) [101]	Climate change, mitigation and adaptation [101] Consumer data protection and privacy [101]	Commonality [96] Consumption patterns (misleading effects) [45]	Community engagement [101] Contribution on an enabling technology [84]
Contribution to circular economy [84]	Contribution to economy [93]	Contribution to sustainable development goals [84]	Cultural impacts of production process [45]
Customer service, support, complaint and dispute resolution [101]	Diversity of technological options for important societal services [84]	Due diligence [101]	Ease the sorting process [79]
Easy cleaning: surface features easy to clean, shape as flat as possible, selecting suitable coatings [78]	Easy classification: standardised parts, reduce use types, mark similar materials [78]	Easy disassembly and assembly: improving reliability, selection of retrofittable structures, modular design, detachable structure, minimum disassembly workload, reduced number of connections [78]	Easy transportation: reduction of structural protrusions, reasonable structure [78]
Ecological balance and efficiency [76]	Economic, social and cultural rights [101]	Ecosystems [149]	Education and awareness [101]
Education and culture [101]	Effect on social/ economic inequality [84]	Efficiency of operations [45]	Employment [84]
Employment and labour relations [101]	Environmental harm (toxicity, water, land, climate) [45]	Environmental impact indicator [45]	Environmental protection, biodiversity and habitat restoration [101]
Ethical responsibility [76]	Eutrophication, aquatic [45]	Extraction technologies [45]	Fair competition [101]
Fair marketing, factual and unbiased information, and fair contractual practices [101]	Feedstock sustainability [93]	Food security [93]	Fundamental principles and rights at work [101]
Human life insurance costs [84]	Impact on local communities [45]	Import dependence on critical countries [45]	Improve the efficiency of system and equipment [104]
Ionising radiation, ecosystems [45]	Job creation and skills development [101]	Labour abuse [90]	Manufacturing methods [76]
Maximise Circularity [150]	Minimise environmental footprint [150]	Minimise Social impact [150]	Net income/ wages [84]

Novel/ innovative functionality [84]	On the job staff development and training [101]	Ozone depletion [45]	Photochemical ozone formation [45]
Packaging [76]	Particulate matter / respiratory inorganics [45]	Perks and benefits [90]	Product end of life management efficiency (reuse, recovery) [91]
Product level climate impact [6]	Profitability [84]	Promoting social responsibility in the value chain [101]	Qualified labour force [84]
Rebound/ side effects [45]	Reduce environmental impact [104]	Regulation (forecasts/ restrictions) [45]	Regulations and certifications effectiveness (e.g. product EoL certifications) [91]
Relative cost of spare parts [96]	Reliability [101]	Renewable fuels used for distribution of materials, substances and products [34]	Resolving grievances [101]
Respect for indigenous rights and cultural heritage [45]	Respect for property rights [101]	Responsible political engagement [101]	Risk of being exposed to dangerous substances [34, 83]
Simplicity [96]	Situations where human rights are at risk [101]	Social acceptability [93]	Social dialogue [101]
Social impact [76]	Social investment [101]	Social responsibility [90]	Social standards and working conditions [45]
Societal needs or objectives [84]	Societal resilience [84]	Standardization [96]	Storage [76]
Sustainable consumption [101]	System level climate impact [6]	Technological advancement [84]	Technology development and access [101]
The efficiency of transport [79]	Transportation [6]	Upgradeability [76]	User behaviour & cultural acceptance [45]
Wealth and income creation [101]	Workforce skill and knowledge [98]	Working conditions and social protection [101]	

Table A.2: Added Social Criteria

Appropriate working hours [41]	Auditing suppliers on sustainability aspects (number of supplier assessments) [41]	Compliance with regulations [40]	Diversity and equal opportunity [41]
Fair trading relationships [41]	Freedom of association and collective bargaining [41]	Job satisfaction [41]	Management reorganisation impact [41]
No child labour [41]	No forced labour [41]	No sexual harassment: preventing unwanted, sexually determined behaviour that violates the dignity of the person involved [41]	Privacy [41]
Supplier compliance with regulations [40]			

B

Criteria Screening

	Filtering				
Criteria (possible metric/clarification)	Redundant /repetitive	Not relevant to GKN Aerospace	Not relevant to early stages	N/A due to other reasons	Comment
Ease of recycling (scoring)	☐	☐	☐	☐	
Recyclability of components at EoL (recyclable/non-recyclable)	☑	☐	☐	☐	
Recyclability of scrap material from post processing	☑	☐	☐	☐	
Material circularity capability (scoring)	☐	☐	☐	☐	
Use of recycled material (%)	☐	☐	☐	☐	
Use of critical materials (scoring)	☐	☐	☐	☐	
Weight (kg)	☐	☐	☐	☐	
Material consumption (volume)	☑	☐	☐	☐	
Material utilization (% of waste)	☐	☐	☐	☐	
Material efficiency (buy-to-fly)	☑	☐	☐	☐	
Raw material consumption (weight/No.)	☐	☐	☐	☐	
Material complexity (No. components)	☐	☑	☐	☐	
Contribution to material resource depletion	☐	☐	☑	☑	too complex
Emissions from energy consumption (CO_2eq.)	☐	☐	☐	☐	
Energy consumption (kWh)	☐	☐	☐	☐	
Energy consumption from renewable sources (%)	☐	☐	☑	☐	
Land use (area)	☐	☑	☐	☐	
Use of land otherwise used for renewable resources and recreation (yes/no)	☐	☑	☐	☐	
Use of water in a water-scarce region (yes/no)	☐	☐	☑	☐	
Water consumption (volume)	☐	☐	☐	☐	
Wastewater (volume)	☐	☐	☑	☑	less relevant
Biodiversity impact (land use change)	☐	☐	☑	☐	
Ecosystem impact (resource consumption)	☐	☐	☑	☐	
Carbon footprint - scope 1 and 2 (CO_2eq.)	☐	☐	☐	☐	
Carbon footprint - scope 3 (CO_2eq.)	☐	☐	☑	☐	
System level climate impact	☑	☐	☐	☑	not relevant to component level
Component level climate impact	☑	☐	☐	☐	
Overall toxic and hazardous emissions to air, water, soil (risk assessment)	☐	☐	☐	☐	
Use phase GHG emissions	☐	☐	☐	☐	
Raw material extraction GHG emissions	☐	☐	☐	☐	
Manufacturing GHG emissions	☑	☐	☐	☐	
Maintenance GHG emissions	☐	☑	☐	☐	
Transportation (emissions)	☐	☐	☐	☐	
EoL GHG emissions	☐	☐	☐	☑	less relevant
Accumulation of product emissions and waste in nature (risk assessment)	☐	☐	☑	☐	
Water eutrophication through nitrogen and phosphorous soil acidification (risk assessment)	☐	☑	☑	☐	
Terrestrial and marine ecotoxicity impact (risk assessment)	☐	☑	☑	☐	
Human toxicity: cancer and non cancer effects (risk assessment)	☐	☐	☐	☐	
Acidification (risk assessment)	☐	☑	☑	☐	
Ionizing radiation	☐	☑	☑	☐	
Particulate matter/respiratory inorganics (risk assessment)	☑	☐	☐	☐	
Hazardous waste: avoid needing special measures for disposal	☐	☐	☐	☐	

Figure B.1: Criteria screening matrix, part 1.

Share of compost ability or biodegradability	☐	☑	☐	☐	
Handling of waste	☑	☐	☐	☐	
Traceability	☐	☐	☐	☑	very difficult to measure
Tracking/transparency	☐	☐	☐	☑	very difficult to measure
Potential for dual use/secondary function	☐	☐	☐	☐	relevant for technologies
Re-usability	☐	☑	☐	☐	
Product quality	☐	☐	☐	☐	
Product safety (operational)	☐	☐	☐	☐	
Product performance	☐	☐	☐	☐	
Improved functionality	☐	☐	☐	☐	
Vertical range of manufacture (ratio of in-house/external manufacturing)	☐	☐	☐	☐	
Risk of remanufacturing	☐	☐	☐	☑	not relevant
Special manufacturing technology (e.g. AM)	☐	☐	☐	☑	oversimplification not relevant
Degradation of nature from use of raw materials / chemicals, production, end of life (risk assessment)	☐	☐	☑	☐	
Durability (life)	☐	☐	☐	☐	
Service life	☑	☐	☐	☐	
Useful life	☐	☐	☑	☐	
Ease of servicability	☐	☐	☐	☐	
Number of parts	☑	☐	☐	☐	
Repair impact	☐	☐	☐	☑	not relevant
Repairability	☐	☐	☐	☐	
Disassembly impact	☐	☐	☐	☑	not relevant
Ease of disassembly and reassembly	☑	☐	☐	☐	
Relative cost of spare parts	☑	☐	☐	☐	
Modularity	☑	☑	☐	☐	we have ease of repairability
Commonality	☐	☑	☐	☐	
Standardization	☐	☑	☐	☐	
Ease of cleaning	☐	☑	☐	☐	
Simplicity	☐	☑	☐	☐	
Upgradeability	☐	☐	☐	☐	
Regulations and certifications effectiveness; compliance levels, supply chain transparency (EoL certifications, REACH)	☐	☐	☑	☐	complex/unclear
Use of substances listed in REACH candidate list	☐	☐	☐	☐	
Use of substances listed in IAEG Aerospace and Defense Declarable Substances List (AD-DSL) list	☑	☐	☐	☐	
Use of substances listed in SIN list (risk assessment)	☐	☐	☐	☐	
Access to essential services	☐	☐	☑	☐	
Employee health and safety	☐	☐	☐	☐	
Qualified labor force (workforce skill and knowledge)	☐	☐	☐	☐	
No labor abuse	☑	☐	☐	☐	
Net income/wages	☐	☐	☐	☑	
On the job staff development and training	☑	☐	☐	☐	

Figure B.2: Criteria screening matrix, part 2.

Perks and benefits	☐	☐	☑	☐	
Risk of being exposed to dangerous substances	☐	☐	☐	☐	
Situations where human rights are at risk (risk assessment)	☐	☐	☐	☐	
No sexual harassment: preventing unwanted, sexually determined behavior that violates the dignity of the person involved	☐	☐	☑	☐	
Freedom of association and collective bargaining	☐	☐	☐	☐	
Labor rights violation risk (child, forced labor etc.)	☐	☐	☐	☐	
No forced labor	☑	☐	☐	☐	
Job satisfaction	☐	☐	☑	☐	
Diversity and equal opportunity	☐	☐	☑	☐	
Privacy	☐	☑	☐	☐	
Appropriate working hours	☑	☐	☐	☐	
Management reorganization impact	☑	☐	☐	☐	
Fair trading relationships	☑	☐	☐	☐	
Auditing suppliers on sustainability aspects (number of supplier assessm	☐	☐	☑	☐	
Supplier compliance with regulations	☐	☐	☐	☐	
Promoting social responsibility in the value chain	☐	☐	☑	☐	
Community engagement	☐	☐	☑	☐	
Cultural impacts of production process	☐	☑	☐	☐	
Job creation/negative impact and skills development	☐	☐	☐	☐	
Noise to the surroundings	☐	☐	☐	☐	
Respect for indigenous rights and cultural heritage	☐	☑	☑	☐	
Effect on social/economic inequality	☐	☐	☑	☐	
Structural obstacles for people's health, influence, competence, impartiality and meaning making	☐	☐	☑	☐	
Technological advancement	☐	☐	☑	☐	
Wealth and income creation	☐	☐	☑	☐	
Diversity of technological options for important societal services	☐	☐	☑	☐	
Contribution on an enabling technology	☐	☐	☑	☐	
Additional costs	☐	☑	☐	☐	
Customer service, support and compliant and dispute resolution	☑	☑	☐	☐	
Due diligence (assessment of customers)	☐	☐	☐	☐	
Fair marketing, factual and unbiased information, and fair contractual pr	☐	☐	☑	☐	
Consumer health and safety	☑	☑	☐	☐	
Consumer data protection and privacy	☑	☑	☐	☐	
Aesthetics	☑	☑	☐	☐	
Risk of corruption (country risk)	☐	☐	☐	☐	
Risk of ethical business violations (corruption, competition)	☐	☐	☑	☐	
Responsible political engagement	☐	☑	☐	☐	
Risk of complicity	☑	☐	☐	☐	
Civil and political rights violation	☐	☐	☑	☐	
Respect for property rights	☐	☐	☑	☐	
Compliance with regulations	☐	☐	☐	☐	

Figure B.3: Criteria screening matrix, part 3.

C

Criteria Scoring

Criteria (possible metric/clarification)	Strategic alignment (1-5), aspect weight = 10%	Relevance to GKN products (1-5), aspect weight = 30%	Potential ecological impact (1-5), aspect weight = 30%	Potential social impact (1-5), aspect weight = 30%	Total weighed score	Rank
Weight (kg)	5	5	5	2	4.1	1
Material utilization (% of waste)	5	5	4	3	4.1	1
Use phase GHG emissions	5	5	5	2	4.1	1
Product quality	5	5	2	5	4.1	1
Product safety (operational)	5	5	2	5	4.1	1
Product performance	5	5	4	3	4.1	1
Durability (life)	5	5	4	2	3.8	2
Flexibility of supply chain (multiple suppliers, multi sourcing)	4	5	3	3	3.7	3
Repairability	3	4	4	3	3.6	4
Use of conflict materials	5	3	2	5	3.5	5
Improved functionality	5	5	3	2	3.5	5
Use of substances listed in REACH candidate list	5	3	3	4	3.5	5
Risk of being exposed to dangerous substances	5	3	3	4	3.5	5
Potential for dual use/secondary function	4	5	2	3	3.4	6
Ease of serviceability	3	5	3	2	3.3	7
Use of recycled material (%)	3	3	4	3	3.3	7
Energy consumption (kWh)	5	5	2	2	3.2	8
Human toxicity: cancer and non cancer effects (risk assessment)	5	3	1	5	3.2	8
Labor rights violation risk (child, forced labor etc.)	5	3	1	5	3.2	8
Raw material consumption (weight/No.)	2	3	4	3	3.2	8
Overall toxic and hazardous emissions to air, water, soil (risk assessment)	5	3	3	3	3.2	8
Supplier compliance with regulations	5	3	3	3	3.2	8
Hazardous waste: avoid needing special measures for disposal	4	3	3	3	3.1	9
Use of critical materials (scoring)	5	3	2	3	2.9	10
Employee health and safety	5	3	1	4	2.9	10
Due diligence (assessment of customers)	5	3	2	3	2.9	10
Situations where human rights are at risk (risk assessment)	5	1	1	5	2.6	11
Material circularity capability (scoring)	5	3	3	1	2.6	11
Use of substances listed in SIN list (risk assessment)	1	1	3	4	2.5	12
Job creation/negative impact and skills development	4	3	1	3	2.5	12
Raw material extraction GHG emissions	3	1	4	2	2.4	13
Upgradeability	3	1	4	2	2.4	13
Noise to the surroundings	3	1	3	3	2.4	13
Ease of recycling (scoring)	3	3	3	1	2.4	13
Water consumption (volume)	5	1	3	2	2.3	14
Carbon footprint - scope 1 and 2 (CO_2eq.)	5	1	3	2	2.3	14
Freedom of association and collective bargaining	5	1	1	4	2.3	14
Risk of corruption (country risk)	5	1	2	3	2.3	14
Transportation (emissions)	3	1	3	2	2.1	15
Qualified labor force (workforce skill and knowledge)	5	1	1	3	2	16
Vertical range of manufacture (ratio of in-house/external manufacturing)	2	1	1	3	1.7	17

Figure C.1: Criteria scoring matrix results

	Scoring (sustainability)	Scoring (managers)	Scoring (engineers)	
Criteria (possible metric/clarification)	Ease of implementation (1-5)	Ease of implementati on (1-5)2	Ease of implementatio n (1-5)3	Average
Ease of recycling (scoring)	4	5	1	3.333333
Material circularity capability (scoring)	2	3	1	2
Use of recycled material (%)	3	1	1	1.666667
Use of conflict materials	4	3	4	3.666667
Use of critical materials (scoring)	3	4	4	3.666667
Weight (kg)	5	5	5	5
Material utilization (% of waste)	2	2	2	2
Raw material consumption (weight/No.)	2	2	1	1.666667
Emissions from energy consumption (CO_2eq.) (GKN)	3	3	3	3
Energy consumption (kWh) (GKN)	3	5	5	4.333333
Water consumption (volume)	2	5	5	4
Carbon footprint - scope 1 and 2 (CO_2eq.)	4	4	5	4.333333
Overall toxic and hazardous emissions to air, water, soil (risk assessment)	2	3	5	3.333333
Use phase GHG emissions	4	1	5	3.333333
Raw material extraction GHG emissions	2	1	1	1.333333
Transportation (emissions)	3	3	1	2.333333
Human toxicity: cancer and non cancer effects (risk a	2	3	5	3.333333
Hazardous waste: avoid needing special measures fo	3	2	5	3.333333
Potential for dual use/secondary function	5	1	1	2.333333
Product quality	4	5	5	4.666667
Product safety (operational)	4	5	5	4.666667
Product performance	4	5	5	4.666667
Improved functionality	2	3	5	3.333333
Vertical range of manufacture (ratio of in-house/exte	2	5	5	4
Durability (life)	5	5	5	5
Ease of servicability	3	3	5	3.666667
Repairability	2	4	3	3
Upgradeability	2	1	1	1.333333
Use of substances listed in REACH candidate list	3	5	5	4.333333
Use of substances listed in SIN list (risk assessment)	2	3	1	2
Employee health and safety	4	5	4	4.333333
Qualified labor force (workforce skill and knowledge)	4	5	1	3.333333
Risk of being exposed to dangerous substances	3	5	3	3.666667
Situations where human rights are at risk (risk assess	2	3	1	2
Freedom of association and collective bargaining	2	1	1	1.333333
Labor rights violation risk (child, forced labor etc.)	2	5	3	3.333333
Flexibility of supply chain (multiple suppliers, multi so	4	4	5	4.333333
Supplier compliance with regulations	2	5	3	3.333333
Job creation/negative impact and skills development	2	2	3	2.333333
Noise to the surroundings	4	3	3	3.333333
Due diligence (assessment of customers)	3	2	3	2.666667
Risk of corruption (country risk)	3	5	3	3.666667
Compliance with regulations	2	4	5	3.666667

Figure C.2: Ease of implementation scoring results for all stakeholder groups.

D

DEMATEL Direct Influence Matrix

Cause \ Effect	Weight	Use of critical materials	Use of conflict materials	Raw material utilisation	Raw material consumption	Use phase GHG emissions	Potential for dual use	Product quality	Product safety
Weight	0	3	3	0	0	4	0	0	0
Use of critical materials	0	0	0	0	0	0	0	0	0
Use of conflict materials	0	0	0	0	0	0	0	0	0
Raw material utilisation	0	3	0	0	0	0	0	4	0
Raw material consumption	0	0	0	3	0	0	0	0	0
Use phase GHG emissions	0	0	0	0	0	0	0	0	0
Potential for dual use	0	0	0	0	0	0	0	0	0
Product quality	0	0	0	0	0	0	0	0	4
Product safety	0	0	0	0	0	0	0	0	0
Product performance	3	2	2	0	0	4	1	0	0
Durability	0	0	0	0	0	3	0	0	0
Repairability	0	1	1	4	4	0	0	0	0
Use of substances listed in REACH	2	0	0	0	0	0	0	0	0
Use of substances listed in SIN	0	0	0	0	0	0	0	0	0
Risk of being exposed to dangerous substances	0	0	0	0	0	0	0	0	0
Flexibility of supply chain	0	2	2	2	0	0	0	2	0
Noise to the surroundings	0	0	0	0	0	0	0	0	0

Cause \ Effect	Product performance	Durability	Repairability	Use of substances listed in REACH	Use of substances listed in SIN	Risk of being exposed to dangerous substances	Flexibility of supply chain	Noise to the surroundings
Weight	0	0	0	0	0	0	0	0
Use of critical materials	0	0	0	0	0	0	2	0
Use of conflict materials	0	0	0	0	0	0	2	0
Raw material utilisation	0	0	0	0	0	0	0	0
Raw material consumption	0	0	0	0	0	0	0	0
Use phase GHG emissions	0	0	0	0	0	0	0	0
Potential for dual use	2	0	0	0	0	0	0	0
Product quality	0	0	0	0	0	0	0	0
Product safety	0	0	0	0	0	0	0	0
Product performance	0	3	0	0	0	0	0	2
Durability	3	0	0	0	0	0	0	0
Repairability	0	3	0	0	0	0	0	0
Use of substances listed in REACH	0	0	0	0	3	3	2	0
Use of substances listed in SIN	0	0	0	0	0	3	0	0

Figure D.1: Direct Influence Matrix developed from the DEMATEL exercise.

E

DEMATEL Normalised Matrix

Cause \ Effect	Weight	Use of critical materials	Use of conflict materials	Raw material utilisation	Raw material consumption	Use phase GHG emissions	Potential for dual use	Product quality	Product safety
Weight	0.000000	0.176471	0.176471	0.000000	0.000000	0.235294	0.000000	0.000000	0.000000
Use of critical materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Use of conflict materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Raw material utilisation	0.000000	0.176471	0.000000	0.000000	0.000000	0.000000	0.000000	0.235294	0.000000
Raw material consumption	0.000000	0.000000	0.000000	0.176471	0.000000	0.000000	0.000000	0.000000	0.000000
Use phase GHG emissions	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Potential for dual use	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product quality	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.235294
Product safety	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product performance	0.176471	0.117647	0.117647	0.000000	0.000000	0.235294	0.058824	0.000000	0.000000
Durability	0.000000	0.000000	0.000000	0.000000	0.000000	0.176471	0.000000	0.000000	0.000000
Repairability	0.000000	0.058824	0.058824	0.235294	0.235294	0.000000	0.000000	0.000000	0.000000
Use of substances listed in REACH	0.117647	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Use of substances listed in SIN	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Risk of being exposed to dangerous substances	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Flexibility of supply chain	0.000000	0.117647	0.117647	0.117647	0.000000	0.000000	0.000000	0.117647	0.000000
Noise to the surroundings	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Cause \ Effect	Product performance	Durability	Repairability	Use of substances listed in REACH	Use of substances listed in SIN	Risk of being exposed to dangerous substances	Flexibility of supply chain	Noise to the surroundings
Weight	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Use of critical materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.117647	0.000000
Use of conflict materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.117647	0.000000
Raw material utilisation	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Raw material consumption	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Use phase GHG emissions	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Potential for dual use	0.117647	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product quality	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product safety	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product performance	0.000000	0.176471	0.000000	0.000000	0.000000	0.000000	0.000000	0.117647
Durability	0.176471	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Repairability	0.000000	0.176471	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Use of substances listed in REACH	0.000000	0.000000	0.000000	0.000000	0.176471	0.176471	0.117647	0.000000
Use of substances listed in SIN	0.000000	0.000000	0.000000	0.000000	0.000000	0.176471	0.000000	0.000000
Risk of being exposed to dangerous substances	0.000000	0.000000	0.000000	0.176471	0.176471	0.000000	0.000000	0.000000
Flexibility of supply chain	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Noise to the surroundings	0.117647	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000

Figure E.1: Normalised Matrix developed from the DEMATEL exercise.

F

DEMATEL Total Relation Matrix

Cause \ Effect	Weight	Use of critical materials	Use of conflict materials	Raw material utilisation	Raw material consumption	Use phase GHG emissions	Potential for dual use	Product quality	Product safety
Weight	0.000000	0.182396	0.181507	0.005037	0.000000	0.235294	0.000000	0.006222	0.001464
Use of critical materials	0.000000	0.016789	0.014271	0.014271	0.000000	0.000000	0.000000	0.017629	0.004148
Use of conflict materials	0.000000	0.016789	0.014271	0.014271	0.000000	0.000000	0.000000	0.017629	0.004148
Raw material utilisation	0.000000	0.179433	0.002518	0.002518	0.000000	0.000000	0.000000	0.238405	0.056095
Raw material consumption	0.000000	0.031665	0.000444	0.176915	0.000000	0.000000	0.000000	0.042071	0.009899
Use phase GHG emissions	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Potential for dual use	0.021898	0.019083	0.018990	0.000527	0.000000	0.038214	0.007299	0.000651	0.000153
Product quality	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.235294
Product safety	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product performance	0.186131	0.162204	0.161413	0.004479	0.000000	0.324818	0.062044	0.005533	0.001302
Durability	0.032847	0.028624	0.028485	0.000790	0.000000	0.233791	0.010949	0.000976	0.000230
Repairability	0.005796	0.115520	0.066226	0.279332	0.235294	0.041257	0.001932	0.068241	0.016057
Use of substances listed in REACH	0.122271	0.039751	0.037025	0.015447	0.000000	0.028770	0.000000	0.019082	0.004490
Use of substances listed in SIN	0.003930	0.001278	0.001190	0.000497	0.000000	0.000925	0.000000	0.000613	0.000144
Risk of being exposed to dangerous substances	0.022271	0.007240	0.006744	0.002814	0.000000	0.005240	0.000000	0.003476	0.000818
Flexibility of supply chain	0.000000	0.142707	0.121301	0.121301	0.000000	0.000000	0.000000	0.149843	0.035257
Noise to the surroundings	0.021898	0.019083	0.018990	0.000527	0.000000	0.038214	0.007299	0.000651	0.000153

Cause \ Effect	Product performance	Durability	Repairability	Use of substances listed in REACH	Use of substances listed in SIN	Risk of being exposed to dangerous substances	Flexibility of supply chain	Noise to the surroundings
Weight	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.042812	0.000000
Use of critical materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.121301	0.000000
Use of conflict materials	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.121301	0.000000
Raw material utilisation	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.021406	0.000000
Raw material consumption	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.003778	0.000000
Use phase GHG emissions	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Potential for dual use	0.124088	0.021898	0.000000	0.000000	0.000000	0.000000	0.004479	0.014599
Product quality	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product safety	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000
Product performance	0.054745	0.186131	0.000000	0.000000	0.000000	0.000000	0.038073	0.124088
Durability	0.186131	0.032847	0.000000	0.000000	0.000000	0.000000	0.006719	0.021898
Repairability	0.032847	0.182267	0.000000	0.000000	0.000000	0.000000	0.021382	0.003864
Use of substances listed in REACH	0.000000	0.000000	0.000000	0.039301	0.222707	0.222707	0.131303	0.000000
Use of substances listed in SIN	0.000000	0.000000	0.000000	0.033406	0.039301	0.189301	0.004220	0.000000
Risk of being exposed to dangerous substances	0.000000	0.000000	0.000000	0.189301	0.222707	0.072707	0.023916	0.000000
Flexibility of supply chain	0.000000	0.000000	0.000000	0.000000	0.000000	0.000000	0.031060	0.000000
Noise to the surroundings	0.124088	0.021898	0.000000	0.000000	0.000000	0.000000	0.004479	0.014599

Figure F.1: Total Relation Matrix developed from the DEMATEL exercise.

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