

Towards Greener Skies:

An Exploration of Sustainability Opportunities, Challenges and
Frameworks for Tier 2 and Tier 3 Suppliers Within the UK
Aerospace Manufacturing Sector on the Journey to Net-Zero 2050

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Abstract

The environmental impact of the aviation sector, particularly aerospace manufacturing, has prompted an urgent need for sustainability initiatives. Despite ambitious goals set by world leaders, notably 'Net-Zero 2050', tier 2 and tier 3 suppliers within the UK aerospace industry face challenges in navigating their sustainability journey. This dissertation aims to address such challenges by conducting a deep dive into sustainability within the aerospace manufacturing sector, providing guidance to assist the integration of sustainability into the operations of smaller aerospace manufacturers.

Through a thorough literature review, this study identifies key sustainability opportunities and challenges in aerospace manufacturing, highlighting the necessity for collaboration, innovation, and government support. While advancements in materials science and alternative propulsion technologies show promise, challenges such as regulatory compliance and financial constraints persist. To support manufacturers, various guidelines and frameworks are available, with 'The Sustainability Transitioning Framework' emerging as a valuable tool. However, its generic nature and potential oversight of organisational culture and stakeholder engagement raise concerns about its applicability.

A case study within a UK tier 2 supplier illustrates the practical application of the transitioning framework, offering insights and recommendations for improvement. Although, limitations such as the exclusive focus on CO2 emissions and the static nature of the roadmap timeline necessitate continuous monitoring and adaptation.

In summary, this dissertation provides a comprehensive overview for tier 2 and tier 3 manufacturers in the UK aerospace sector seeking to embark on their sustainability journey. However, further research is recommended to refine existing frameworks and practices, emphasising collaboration, innovation, and a holistic approach to sustainability for a more sustainable aerospace industry.

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List Of Abbreviations

AGP	Aerospace Growth Partnership
AI	Artificial Intelligence
AM	Additive Manufacturing
CAJU	Clean Aviation Joint Undertaking
CFRP	Carbon-Fibre Reinforced Polymers
CLEEN	Continuous Lower Energy, Emissions, and Noise
CNC	Computer Numerical Control
CSR	Corporate Social Responsibility
GVA	Gross Value Added
IATA	International Air Transport Association
KPI	Key Performance Indicator
LCA	Lifecycle Assessment
LED	Light-Emitting Diode
MQL	Minimal Quantity Lubrication
NASA	National Aeronautics and Space Administration
OEM	Original Equipment Manufacturer
OME	Operational Material Efficiency
ORC	Organic Rankine Cycle
SAFUG	Sustainable Aviation Fuel Users Group
SME	Small and medium-sized enterprises
TCFD	Task Force on Climate-related Financial Disclosures
TRL	Technology Readiness Level
UK	United Kingdom

1 Introduction

1.1 Background

With the challenges of climate change and environmental issues growing, the aviation industry finds itself at a pivotal moment where it must balance innovation with responsibility. As the demand for air travel continues to rise, the industry is increasingly grappling with the environmental impact of their operations (IATA, 2021). Given the industry's significant contribution to global greenhouse gas emissions (Ritchie, 2020), the need to balance technological advancements with environmental responsibility is clear. Aerospace manufacturing, responsible for developing and manufacturing components and sub-assemblies for the aviation sector, has become a central point in sustainability discussions (Ritchie & Roser, 2020), driven by its high-resource and high-carbon processes such as raw material extraction and end of life product disposal. The necessity to align the unprecedented growth of the aviation sector with the urgent global call for sustainability is greater than ever, this extends beyond just environmental concerns with broader economic and societal factors that must also be considered.

Achieving sustainable manufacturing within the aerospace sector is harnessed by changing consumer expectations and increasingly stringent regulations, making efforts to adopt sustainable practices a challenge (United Nations, 2020). Material selection, a crucial aspect of aerospace manufacturing, poses complexities in finding a balance between meeting performance requirements and considering environmental impacts. Additionally, optimising manufacturing processes for sustainability while ensuring economic viability is the ultimate challenge (Todescato, et al., 2023).

According to Morone & Yilan (2020), the pursuit of sustainability will require a paradigm shift, one that is driven by innovation. However, opportunities for innovation and improvement are abundant, ranging from advanced materials, green technologies, and collaboration endeavours within the aerospace supply chain.

1.2 Justification

This research paper emphasises the significance of environmental sustainability within the aerospace manufacturing sector, recognising that sustainability is not merely about meeting regulations but is a strategic necessity (Lagut & Ram, 2023). Embracing sustainability extends beyond fulfilling legal obligations; it offers manufacturers an opportunity to enhance their market positioning, operational efficiency, and resilience to evolving regulatory landscapes (Goworek, et al., 2018).

In exploring the sustainability challenges of the aerospace industry, it is essential to consider the role of tier 2 and tier 3 suppliers. While major aerospace OEMs (Original Equipment Manufacturers) often take centre stage in sustainability discussions, the contributions of these suppliers are equally significant and neglecting their environmental impact would present an incomplete picture of the industry's sustainability efforts.

Tier 2 and tier 3 suppliers face unique hurdles in implementing sustainable practices due to resource constraints. Nevertheless, integrating them into sustainability strategies is pivotal for aerospace manufacturers. By addressing the sustainability practices of these suppliers, companies can achieve more comprehensive environmental improvements across their value chains.

Therefore, focusing on the sustainability needs of tier 2 and tier 3 suppliers within aerospace manufacturing aligns with broader goals, such as enhancing market positioning, operational efficiency, and regulatory resilience (Rajesh, 2021). By addressing sustainability at every tier of the aerospace manufacturing ecosystem, companies can realise lasting environmental benefits while securing their long-term viability in an increasingly eco-conscious marketplace.

1.3 Aim

The aim of this paper is twofold. Firstly, the research conducted provides an insight into existing practices, opportunities and challenges faced by manufacturers within the aerospace manufacturing sector while aiming to meet stringent sustainability targets such as 'Net-Zero 2050'. Secondly, the dissertation aims to provide a framework for tier 2 and tier 3 suppliers within the aerospace manufacturing sector in the UK to assist with the implementation of sustainable practices and/or technologies within their organisations.

1.4 Objectives

The aims of this dissertation will be achieved through an extensive literature review supported by a case study within a tier 2 aerospace manufacturer within the UK. The specific objectives to be accomplished are:

- Identify existing sustainability practices used within the aerospace manufacturing sector.
- Highlight the opportunities and challenges faced by manufacturers within the aerospace manufacturing sector in achieving stringent sustainability targets such as ‘Net-Zero 2050’.
- Propose a sustainability transitioning framework to assist aerospace manufacturers in implementing sustainable technologies and practices.
- Perform a case study adopting the sustainability transition framework within a tier 2 aerospace supplier in the UK.

1.5 Scope and Limitations

This paper focuses on aerospace manufacturing and its pivotal role within the broader aviation industry. While the main objective is to offer guidance tailored for tier 2 and tier 3 manufacturers, the research will cast a wider net, examining the spectrum of aerospace manufacturing, which includes the OEM’s such as aircraft manufacturing giants Boeing and Airbus, and leading tier 1 suppliers within the industry who are responsible for providing assemblies (engines, seats, landing gear etc.) direct to the OEM’s. This broader approach enables manufacturers to grasp industry best practices for benchmarking purposes. Throughout the paper, limitations and risks will be addressed to present a comprehensive view. The research will consider the entire life cycle of aerospace products, including material selection, manufacturing processes, and end-of-life considerations. Specific aspects of sustainability take precedence, including the environmental impact of manufacturing processes, materials selection and utilisation, and the integration of sustainable practices throughout the product life cycle. Although social and economic dimensions are acknowledged, they are not the primary focus but are considered within the broader context of sustainable manufacturing.

2 Literature Review

2.1 Environmental Impact of Aviation

Global climate change is not a problem of the future. Since 1880, when global temperature records were first recorded, Earth's temperature has been rising by an average of 0.08°C per decade, and since 1981, this rate has doubled. Although these temperature changes seem minute, the effects are proving to be catastrophic, whereby sea levels are rising, heatwaves are getting longer, and sea ice is melting at an accelerated rate (NASA, 2021). As a result, a million of Earth's species are now at risk, deaths during heatwaves are significantly increasing and a third of the most precious habitats on Earth are under threat (Manning & Ingram, 2021). It is evident that more must be done globally to protect our planet, lives, and livelihoods (United Nations, 2020).

The aviation sector, a significant driver in the race to Net-zero 2050, accounted for 2.5% of all global emissions of the most dominant greenhouse gas, Carbon Dioxide (CO₂) in 2019.

Although this may seem minimal compared to other sectors; road transport: 11.9% iron and steel: 7.2%, chemical and petroleum: 3.6% (Ritchie & Roser, 2020), it is one of the fastest growing. Between the year's 2000 and 2019, there was a 5% average rise in flights per year, with more than 4.5 billion passengers flying during 2019 (Ritchie, 2020), pushing aviation's CO₂ emissions beyond 1 billion tonnes as shown in figure 2.1.

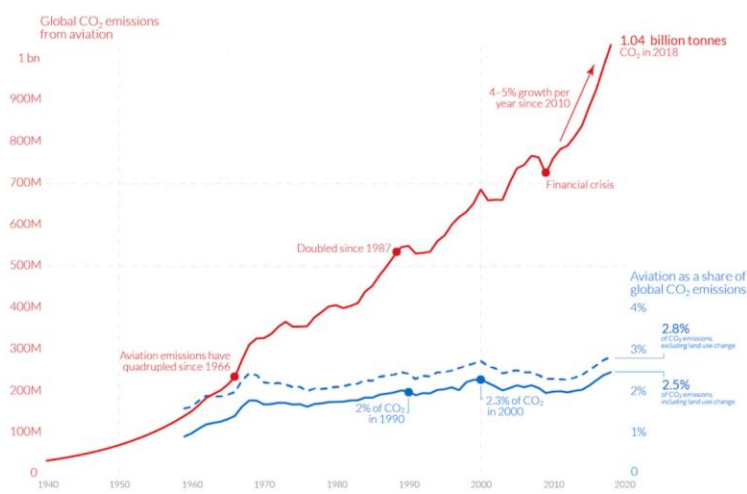


Figure 2.1 The rise of global CO₂ emissions in the aviation sector - 1940 to 2018 (Ritchie, 2020)

The International Air Transport Association (IATA) that represent 300 of the world's airlines, predict air passenger numbers will continue to significantly rise year on year, reaching 16 billion by 2050 (IATA, 2021), resulting in more aeroplanes in the sky to ensure airlines can keep up with such demand.

Aircraft manufacturers such as Airbus and Boeing, who between them hold 99% of the commercial aircraft market share (Sprague, 2019), are challenging the entire supply chain to make operations and products more sustainable, ensuring all stakeholders take responsibility in playing their part in achieving 'Net-Zero 2050'.

2.2 Carbon Footprint of Aerospace Manufacturing

Aerospace manufacturing relates to the manufacture of aircraft, sub-assemblies, and components to service the aviation industry and it plays a significant role in aviation's alarming impact on the environment due to resource consumption, energy use, and waste generation (Saha, 2017).

At the core of aerospace's environmental impact lies the extraction and processing of raw materials, a fundamental stage in the manufacturing process. As an example, aluminium is widely used in the aerospace industry and is known for its 'energy-intensive operations' as highlighted by Mahmud, et al., (2019). This process, often fuelled by non-renewable sources, results in the release of vast amounts of harmful gases into the atmosphere, a critical factor in aerospace manufacturing's contribution to climate change. Rupcic et al.'s recent study in 2023, titled 'Environmental impacts in the civil aviation sector: Current state and guidance,' underscores the critical role of the aerospace sector in climate change due to these emissions.

Furthermore, the extraction of raw materials poses challenges in terms of resource consumption. The demand for materials such as titanium, used in aircraft structures and components, necessitates extensive mining operations. The extraction of titanium ore involves significant energy inputs and can lead to habitat disruption and soil degradation. The subsequent processing of titanium ore into usable forms adds another layer of environmental impact, contributing to the overall carbon footprint of aerospace manufacturing (Williams & Boyer, 2020).

In addition, the extensive use of composite materials in aerospace manufacturing also plays a significant role in the industry's carbon footprint. Composite materials, such as carbon-fibre reinforced polymers (CFRP), are widely employed in the construction of aircraft components

due to their high strength-to-weight ratio. However, the production of these composites involves energy-intensive processes, including the manufacturing of carbon fibres and the polymer matrix that hold them together. For example, the production of carbon fibres often requires high-temperature processes using considerable amounts of energy, leading to increased greenhouse gas emissions (Johnson, 2021). The carbon footprint associated with composite materials extends beyond the manufacturing phase. The end-of-life disposal of composite materials can present significant environmental challenges. Unlike traditional materials like aluminium, recycling composite materials poses unique challenges due to their complex composition. Currently, most end-of-life composite materials end up in landfills, contributing to environmental degradation and highlighting the need for sustainable disposal solutions (Keiser, et al., 2023).

Beyond emissions, Chapman (2018) states that waste generation presents a significant environmental challenge for aerospace manufacturers, with by-products and harmful waste requiring careful consideration to ensure responsible waste management. Furthermore, the disposal of decommissioned aircraft and components presents a formidable challenge. Traditional materials like aluminium can be recycled, providing a degree of sustainability in the industry's end-of-life processes (Mahmud, et al., 2019). However, according to Wong, et al., (2017), the surge in the use of composite materials introduces complexities, as their recycling methods are lagging, leading to increased environmental impact and concerns about landfill space. Zhao, et al., (2020), underscores the urgency of developing effective strategies for managing the increasing amount of waste from retired aircraft.

The aerospace industry's environmental impact also encompasses the global nature of its supply chain. The transportation of components and finished products over long distance contributes to carbon emissions, and the industry's environmental footprint. The challenge lies in developing more sustainable transportation methods, optimising logistics, and considering the environmental implications of the entire supply chain (Ruiz-Benitez, et al., 2017).

2.3 The Paradigm Shift towards Sustainability

The aerospace sector is currently undergoing a significant paradigm shift towards sustainability, whereby industry practices are being re-evaluated to align with environmental goals. As previously discussed, the primary catalyst for this shift is the heightened awareness of the industry's environmental impact. In a study by Rupcic, et al., (2023), they emphasise the necessity for the aerospace sector to address its significant contribution to global carbon emissions and environmental degradation. The study suggests that the industry's commitment to sustainable practices is driven by the urgency to mitigate these environmental impacts and foster a more ecologically responsible approach.

Additionally, stringent regulatory frameworks have played a central role in steering the aerospace sector towards sustainability. Gangi, et al., (2022) investigated the impact of regulatory policies on the industry's commitment to sustainable practices. The study highlighted the influence of regulatory initiatives such as the European Green Deal, emphasising that these measures set emission reduction targets and create a regulatory environment encouraging aerospace manufacturers to integrate sustainability into their strategic planning. Technological innovation is another crucial driver, Zhang, et al., (2016) explore the technological barriers that have historically hindered the adoption of sustainable materials and manufacturing processes. The study underscores the necessity for advancements in materials science and manufacturing technologies to overcome these barriers, emphasising the role of technology in driving the industry towards more sustainable practices.

Economic considerations form another significant incentive for the aerospace manufacturing sector to embrace sustainability. Hallstedt, et al., (2015) highlights the cost implications of sustainable manufacturing practices within the industry. The research suggests that while initial investments in sustainable technologies may be higher, the long-term economic benefits, including operational cost reductions and enhanced corporate image, provide a compelling incentive for aerospace manufacturers to integrate sustainability into their business strategies.

Stakeholder pressure and the increasing emphasis on Corporate Social Responsibility (CSR) have emerged as influential factors in shaping sustainability initiatives within aerospace manufacturing. Marconnato & Luciano (2016), investigated the role of stakeholders, including consumers and investors, in demanding transparent and ethical practices from aerospace

manufacturers. The study underscores CSR as a strategic imperative that not only responds to stakeholder expectations but also shapes organisational behaviour towards sustainable practices.

2.4 The Significance of Tier 2 and Tier 3 Suppliers

In aerospace manufacturing, suppliers are often categorised into tiers based on their proximity to the final assembly of aircraft and the nature of the products or services they provide. As illustrated in figure 2.2, at the top of the aerospace supplier pyramid, sits the OEM's who design and manufacture the aircraft body (Airbus, Lockheed, Boeing etc.) Tier 1 suppliers typically engage in the assembly of major components or subsystems and play a direct role in the final production of aircraft, supplying directly to the OEM's. Tier 2 suppliers supply components and materials to tier 1 suppliers, while tier 3 suppliers provide raw materials, specialised components, and services to tier 2 suppliers and indirectly to the OEM's (Hamilton, 2021).

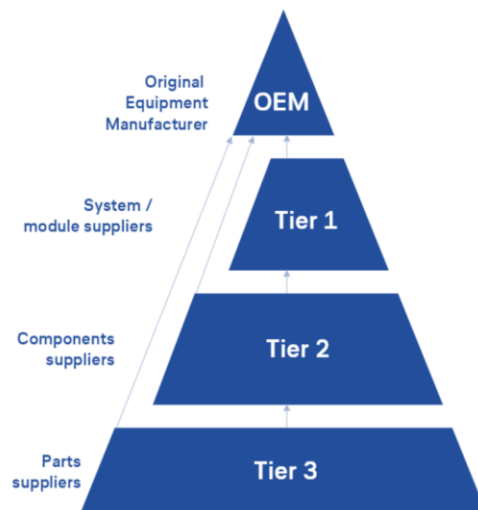


Figure 2.2 Illustration of the supplier pyramid in the aerospace sector (Yıllıkçı & Findik, 2013)

Hamilton (2021), considers tier 2 and tier 3 suppliers to be the backbone of the aerospace supply chain, providing a diverse range of materials, components, and services crucial for aircraft production. Their strategic position enables them to influence sustainability outcomes significantly through the adoption of eco-friendly practices, innovation in manufacturing processes, and collaboration with Tier 1 manufacturers (Sarkis, et al., 2011).

Many tier 2 and tier 3 suppliers encounter resource constraints that hinder their capacity to invest in sustainable technologies and practices (Gold, et al., 2010). Financial constraints for example pose significant hurdles, as transitioning toward sustainable manufacturing often necessitates substantial upfront costs such as investments in renewable energy sources, eco-friendly materials, and energy-efficient machinery (Seuring & Müller, 2008). For organisations that operate within narrow profit margins, securing financing for such investments can be daunting without external support.

Moreover, knowledge gaps persist despite the increasing awareness of sustainability issues among tier 2 and tier 3 suppliers (Pagell & Wu, 2009). Many lack the necessary expertise to implement effective sustainability initiatives, including understanding complex environmental regulations, identifying suitable sustainable alternatives, and integrating sustainability principles into their daily operations. Additionally, regulatory compliance poses a formidable challenge, with such suppliers grappling with complex regulatory landscapes across different jurisdictions (Zsidisin & Wagner, 2010). The evolving nature of environmental standards adds further complexity to sustainability efforts.

Despite the challenges faced, tier 2 and tier 3 suppliers remain crucial to the aviation industry's transition toward achieving net-zero emissions by 2050. Addressing these challenges necessitates a collaborative approach involving industry stakeholders, policymakers, and academia. By providing targeted support, enhancing knowledge transfer, and facilitating access to resources, stakeholders can help these suppliers overcome obstacles in becoming more environmentally responsible.

2.5 Existing Sustainable Practices within Aerospace Manufacturing

As the current literature demonstrates, the aerospace manufacturing sector, characterised by its precision, complexity, and innovation, is increasingly embracing sustainable practices to address environmental concerns and align with global sustainability goals. This section provides an analysis of some of these existing practices.

2.5.1 Advanced Materials and Processes

The integration of innovative materials and processes into aerospace manufacturing represents a paradigm shift, transforming the industry's approach to sustainability on multiple fronts.

Manufacturers are continually seeking ways to move away from conventional materials and manufacturing methods, drawing focus on innovative alternatives (Zhang, et al., 2003).

Within the literature, discussions of innovative composites are at the forefront when it comes to advanced materials. A notable example is Boeing's innovative use of carbon-fibre-reinforced materials in constructing the 787 Dreamliner, the first commercial aircraft to be made primarily of composite materials that are lighter and stronger than aluminium. This approach offers weight savings of up to 20% compared to the aircraft's predecessors. This strategic move significantly reduces the aircraft's weight, and ultimately its environmental impact (Johnson, 2019).

Hybrid structures that incorporate both metals and composites are also making progress. For example, the wings developed for Airbus A350 XWB consist of 70% advanced lightweight materials, of which 53% contains titanium composites and advanced aluminium alloys, this hybrid construction optimises both strength and weight making the aircraft significantly lighter and more fuel efficient (Kite-Powell, 2017).

Furthermore, the industry is embracing sustainable alternatives, such as bio-based materials. Arockiam, et al., (2018) discuss Boeing's research surrounding bio-composites that are made from renewable sources, such as plant fibres. These bio-inspired materials, when used in non-critical components, offer a renewable and sustainable alternative to traditional materials.

Alongside material evolution, the aerospace sector is undergoing a transformation within its manufacturing processes. For instance, additive manufacturing, commonly referred to as 3D printing, is making significant contributions. Renishaw, a global engineering technology company, specialises in metal additive manufacturing solutions that are supplied to the aerospace industry. Such technologies are used to creating intricate components with reduced waste, showcasing advancements in sustainable manufacturing (Renishaw, 2023).

Beyond these examples, the exploration of smart manufacturing and digital twins is gaining prominence. Digital twin technology has become an integral part of sustainable practices within

aerospace manufacturing. By creating virtual replicas of physical components, manufacturers can simulate and analyse performance before physical production begins. This minimises the need for prototype iterations and reduces material waste. Digital twin systems can also replicate production processes, enabling engineers to identify process failures before the process goes live (Arnautova, 2023).

Despite the progress made in recent times regarding advanced materials and processes, adoption within organisations presents notable risks. For instance, Reihlen, et al., (2019) argue that implementation will require substantial upfront investment and may create dependencies on specific suppliers, potentially leading to disruptions. Additionally, regulatory approval for new materials and processes is time-consuming and costly. Aerospace programs' extended lifecycles will also require careful assessment to avoid future obsolescence (Kite-Powell, 2017).

2.5.2 Lifecycle Assessments (LCA)

It is evident within the literature that sustainable practices in the aerospace industry are evolving, looking beyond just the production phase, encompassing the entire lifecycle of components. This holistic perspective involves the integration of Lifecycle Assessments (LCAs). Finnveden , et al., (2009) define LCA's as a systematic and comprehensive evaluation methodology used to assess the environmental impact of a product or process throughout its entire life cycle and considers them a useful tool to understand and quantify the potential environmental effects associated with a product or process, aiding in the identification of areas for improvement and guiding more sustainable decision-making.

Leading aircraft manufacturer, Boeing, introduced LCAs into the development of all future aircraft, with the 777X being the first to undergo a full LCA, entering service in 2025 (Boeing, 2021). Incorporating LCA's enables the company to understand the environmental impacts associated with its aircraft throughout the entire life cycle, from design and manufacturing to operation and disposal. Identifying areas where improvements could be made to enhance sustainability.

On the surface, LCAs are considered a key tool for manufacturers to reach sustainability goals. Although, their effectiveness is questioned by Keiser, et al., (2023), who argue that LCAs

involve complex methodologies, leading to inconsistencies and often focus narrowly on environmental impacts, neglecting social and economic factors. Furthermore, obtaining reliable data for LCAs can be challenging, more so for tier 2 and tier 3 suppliers that may rely on data provided by tier 1 suppliers or original equipment manufacturers (OEMs), which might not accurately represent their specific processes or materials (Weidema, et al., 2018). There is also a risk of greenwashing, whereby companies exploit LCAs for marketing without substantive change. LCAs may also overlook cumulative and indirect impacts, underestimating environmental footprints (Heijungs, et al., 2009).

2.5.3 Eco-Design

In tandem with LCAs, the aerospace industry is witnessing an increasing emphasis on eco-design principles. Eco-design, also known as ‘Design for Sustainability’, is an approach aimed at minimising the environmental impact of products, processes, and systems throughout their life cycle (Cicconi, 2020). This methodology integrates eco-friendly materials and practices into design and development to create products that are not only functional and economically viable but also environmentally responsible. Vallet, et al., (2013) state that waste reduction is a key focus in eco-design, ensuring products are designed for reusability, recyclability, and easy disassembly to align with circular economy principles. Additionally, eco-design considers social and ethical dimensions, evaluating the broader societal impacts of design choices (Charter & Tischner, 2001).

Airbus, have shown commitment to eco-design, as demonstrated during the design phase of the A380 aircraft, where recyclability, ease of disassembly, and the use of environmentally safe materials, were embedded during product development process (Airbus, 2021).

Eco-design principles are not limited to the OEM aircraft manufacturers; the literature demonstrates tier 2 and tier 3 suppliers are also embracing the concept. For example, Hexcel, a tier 2 aerospace composite manufacturer, apply eco-design principles into the development of their products, developing advanced composites that can be recycled. Traditional composite materials pose a big challenge in terms of recyclability due to complex combinations of fibres and resins. Hexcel addressed this by engineering composite materials that consist of components

that are easily separable, enabling easier disassembly during the end-of-life phase. This design consideration ensures that the materials can be efficiently recycled, minimising environmental impact at every stage of the product lifecycle (Hexcel, 2023).

Implementing eco-design practices into organisations such as tier 2 and tier 3 suppliers also present challenges. Mishra, & Gupta's study (2017), stated that financial constraints hinder investment, while a lack of technical expertise can prevent effective implementation. Additionally, due to the complexity of the aerospace supply chain, collaboration with suppliers who may be resistant to change can be challenging. Regulatory compliance adds further complexity, requiring resources for monitoring and reporting. Moreover, Pigosso, et al., (2018), state that convincing customers of the benefits of sustainable products amidst market perceptions remains a hurdle.

2.5.4 Closed-Loop Systems

Closed-loop systems, also known as circular systems, are designed to minimise waste and maximise resource efficiency by promoting the continual use and recycling of materials within a production cycle (Camilleri, 2019). In contrast to the traditional linear model of 'take, make, dispose,' closed-loop systems prioritise the reuse and recycling of materials, creating a sustainable and circular approach. Kara, et al., (2022), state that closed-loop systems are integral to achieving the goals of the circular economy by ensuring that materials remain within the production cycle for as long as possible.

Leading aircraft engine manufacturing, Rolls Royce, actively engage in closed-loop systems. For example, aluminium scraps leftover from their manufacturing processes, previously considered waste, are now collected, and processed using an advanced recycling technique. The end result is recycled aluminium that can be re-introduced back into the manufacturing process, ultimately creating a closed loop, rather than relying solely on new raw material (Smith-Gillespie, et al., 2018). Aerospace and defence company Safran are also making headway by introducing closed-loop systems, specifically in the recycling of end-of-life engine components. Once components reach the end of their operational life, valuable materials are extracted and reused in the

manufacturing of new engines, minimising environmental impact but also aligning to Safran's circular economy objectives (Saric, 2022).

Tier 2 aerospace and defence supplier, Thales, recycle electronic components, including circuit boards, from decommissioned aircraft, enabling recycled components to be used in new avionic systems. By doing so, the company not only addresses electronic waste concerns but also ensures the responsible reuse of valuable materials in the sector.

Despite the many environmental benefits that come with introducing circular systems, challenges are discussed within the literature, specifically for tier 2 and tier 3 suppliers. For example, Iacovidou, et al., (2017), considers technical complexities in material collection, sorting, and recycling pose operational inefficiencies and production delays. Adapting to new supply chain dynamics may also disrupt existing relationships, leading to uncertainties in supply and impacting customer satisfaction. Ensuring recycled materials meet stringent quality and performance standards is crucial, as any compromise could jeopardise safety and compliance (Kara, et al., 2022). Additional regulatory considerations, such as waste management regulations and environmental permits, also add complexity and risk (Saric, 2022). Limited market demand for sustainable products may hinder the justification for investment in closed-loop systems. Access to advanced technologies and innovation may also be constrained, further challenging implementation efforts (Iacovidou, et al., 2017).

2.6 Sustainability Challenges within Aerospace Manufacturing

While the aerospace manufacturing industry aims to minimise its environmental impact, there are a variety of challenges that manufacturers must overcome to achieve sustainability. This section provides an in-depth exploration of these key challenges, offering a comprehensive understanding of the obstacles faced by aerospace manufacturers.

2.6.1 Regulatory Compliance & Certification

Aerospace manufacturing is a heavily regulated industry due to the nature and risks that are associated with it, complying to such regulations while working towards a sustainable future poses a significant challenge for manufacturers. The stringent rules, especially concerning

materials and processes, create obstacles that complicate efforts to adopt environmentally friendly practices (Gangi, et al., 2022).

Hallstedt, et al., (2015), discusses how regulatory framework governing the approval and certification of new materials can be challenging. Aerospace manufacturers interested in embracing sustainable alternatives often face a lengthy and rigorous certification process. Introducing innovative materials, such as those with lower environmental impact or improved recyclability, requires extensive testing to ensure they meet safety and performance standards set by aviation authorities. The prolonged approval timelines and uncertainties in the certification process can hinder the swift integration of sustainable materials into manufacturing processes.

Transitioning to eco-friendly manufacturing processes presents similar challenges. Implementing new production techniques, such as those focused on reducing waste or energy consumption, demands careful consideration of regulatory compliance. Existing regulations, designed with traditional manufacturing methods in mind, may not readily accommodate or anticipate the change to such innovative processes (Goworek, et al., 2018). Manufacturers must navigate these complexities to ensure that sustainable practices align with existing regulations and regulatory changes to accommodate emerging technologies.

According to Litos, et al., (2023), the emphasis on safety in the aviation industry further intensifies these challenges. Any deviation from traditional materials or processes must undergo thorough risk assessments to ensure that safety standards are not compromised. This evaluation adds complexity and time to the adoption of new, sustainable approaches. Striking a balance between sustainability and safety within the limitations of regulatory compliance requires a comprehensive strategy.

Furthermore, Tonelli, et al., (2014), state that the dynamic nature of aerospace regulations further complicates matters. Frequent updates and revisions to compliance standards demand constant vigilance and adaptation. This poses a significant obstacle to manufacturers aiming for sustainability, as it requires ongoing efforts to ensure that environmentally friendly practices remain in line with evolving regulations.

Successfully overcoming these challenges requires not only innovation and commitment but also active engagement with regulatory bodies to create a more supportive environment for sustainable initiatives within the aerospace sector.

2.6.2 Technological Innovation Balance

Innovative technologies such as additive manufacturing, robotics, artificial intelligence (AI), and digital twin technology, are holding great promise for aerospace manufacturers seeking to boost sustainability (Basheer, 2020). However, adopting such technologies is not without its challenges, as integration may inadvertently contribute to an increase in energy consumption, waste generation, and additional carbon emissions. Therefore, achieving a balance between technological innovation and sustainability remains a complex task.

As discussed previously in section 2.5, a common topic within the literature is Additive Manufacturing (AM). Despite the many benefits associated with AM, Peng, (2016) argues its ‘energy-intensive nature’ poses a significant challenge, as the intricate layer-by-layer printing approach requires a considerable amount of energy, raising environmental concerns. To tackle this, manufacturers are actively investing in research and development to establish sustainable AM practices (Hegab, et al., 2023), with focus on sustainable printing materials and energy-efficient printing processes as key areas for innovation. Sustainable materials, such as bio-based polymers and recycled metals, are explored as alternatives to traditional materials, with the aim to reduce the environmental impact while meeting the stringent requirements of the aerospace manufacturing sector.

Integrating other innovative technologies such as robotics and automation into aerospace manufacturing processes also presents challenges, mainly related to responsible material sourcing and the potential environmental impact of automation systems (Ogbemhe, et al., 2017). Similarly, machine learning and Artificial Intelligence (AI), while contributing to predictive maintenance and process optimisation, necessitates robust cybersecurity measures to protect sensitive data (Grieves, 2014) and careful management of energy consumption to ensure that the benefits outweigh the environmental costs.

Achieving a balance between new technologies and their environmental impact is crucial for ensuring long-term sustainability within aerospace industry (Davenport, 2017).

2.6.3 The Cost Benefit Equation

According to a report by accounting firm PwC, aerospace suppliers face significant financial pressures due to the high capital intensity of the industry, making investments in sustainability initiatives a complex decision (PwC, 2023). While the benefits of sustainability are evident in terms of long-term environmental stewardship and market competitiveness, the immediate costs associated with implementing sustainable practices can pose significant barriers.

A study by Deloitte (2021), highlights the financial challenges faced by aerospace manufacturers, emphasising the need for careful cost-benefit analysis when considering sustainability investments. Tier 2 and tier 3 suppliers in the aerospace industry often operate on thin profit margins, making any additional expenditure a critical consideration. Sustainability initiatives, such as transitioning to renewable energy sources, investing in energy-efficient equipment, or sourcing eco-friendly materials, typically require substantial upfront investments. These costs can include capital expenses for technology upgrades, operational expenses for implementing new processes, and potentially higher procurement costs for sustainable materials. Moreover, the return on investment for sustainability initiatives is often uncertain and may not be realised immediately (O'Donnell, 2023). While there are potential long-term benefits such as cost savings from reduced energy consumption or improved brand reputation leading to increased market share, these benefits may take years to materialise. In the short term, suppliers may face financial strain as they absorb the initial costs without immediate returns. Jabbour, et al., (2013), claims the long payback periods associated with sustainability investments can deter companies from pursuing such initiatives, especially in industries with high levels of competition and cost pressures.

Furthermore, the competitive nature of the aerospace industry provides further complication to the cost-benefit challenge. Suppliers must contend with intense competition, price pressures, and the risk of losing contracts if they cannot offer competitive pricing. Such competition can deter suppliers from investing in sustainability, as they fear losing business to cheaper, less sustainable

alternatives. A study by McKinsey & Company (2020) underscores the importance of cost competitiveness in the aerospace industry, highlighting the challenges faced by suppliers in maintaining profitability while investing in sustainability.

Additionally, the complexity of the aerospace supply chain adds another layer of cost considerations. Tier 2 and tier 3 suppliers often operate within a global network, sourcing materials and components from various regions with different regulatory environments and cost structures. Coordinating sustainability efforts across this diverse supply chain requires investment in communication, collaboration, and potentially redesigning existing processes, adding further costs to the equation. A report by Accenture (2021), emphasises the need for supply chain collaboration to drive sustainability in the aerospace industry, citing challenges related to transparency, data sharing, and alignment of goals among stakeholders.

Within the literature, a variety of sustainability funding and support schemes were identified, each offering financial support and guidance to manufacturing organisations that are looking to boost their sustainability progress. Some of these schemes are discussed in more detail in section 2.7.3 (Government Support and Funding).

2.6.4 Culture and Mindset

Achieving sustainability isn't solely reliant on technological solutions; it also demands addressing the cultural and mindset aspects deeply ingrained within manufacturing organisations. These factors present significant challenges to sustainability efforts, impacting leadership dynamics, employee engagement, communication strategies, training initiatives, and more (Flint, 2017).

Leadership plays a pivotal role in shaping organisational culture and priorities. Often, leaders in aerospace manufacturing prioritise short-term economic gains over long-term sustainability due to pressures to meet production targets and financial objectives. This focus on profitability can foster a culture where sustainability is perceived as secondary or even conflicting with business goals. To address this, Hasan & Ahmad (2017), state that leadership must champion sustainability as a core value and integrate it into the organisation's mission and strategic vision.

According to Cowden, et al., (2018), employee engagement serves as the foundation for driving sustainable change from the ground up. However, cultural barriers such as resistance to change and a lack of awareness or understanding of sustainability issues can hinder employee buy-in and participation in sustainability initiatives. Effective communication strategies are essential for overcoming these barriers and fostering employee engagement. Organisations can enhance awareness of sustainability goals and initiatives, as well as their relevance to employees' roles, through regular communication channels such as newsletters, team meetings, and intranet platforms (Singh & Chauhan, 2020). Additionally, providing opportunities for two-way communication, such as feedback mechanisms and open forums, allows employees to express concerns, share ideas, and contribute to the development and implementation of sustainability strategies.

Braglia, et al., (2019), consider training and education to be instrumental in equipping employees with the knowledge, skills, and mindset necessary to support sustainability goals. However, traditional training programs may overlook sustainability topics or fail to contextualise them within the aerospace manufacturing sector. Tailoring training initiatives to address industry-specific sustainability challenges and opportunities can bridge this gap. Hands-on workshops, interactive simulations, and case studies relevant to aerospace manufacturing can enhance employee understanding of sustainability principles and their application in real-world scenarios. Furthermore, incorporating sustainability into performance evaluations and career development plans incentivises employees to prioritise sustainability in their daily work and professional growth (Cowden et al., 2018).

Culture and mindset within manufacturing organisations pose significant challenges to achieving sustainability in the aerospace manufacturing sector. Leadership factors, employee engagement, communication strategies, and training initiatives are essential components of overcoming these challenges and fostering a culture of sustainability (Hasan & Ahmad, 2017). By aligning leadership priorities, engaging employees, fostering open communication, and providing targeted training, organisations can drive sustainable change.

2.7 Sustainability Opportunities within Aerospace Manufacturing

2.7.1 Collaboration

According to Allal-Chérif, et al., (2022), collaboration is key if the aerospace sector is to succeed in reaching ambitious targets such as Net-Zero 2050. Initiatives like the Aerospace Technology Institute (ATI) and the Clean Aviation Joint Undertaking (CAJU) have demonstrated the power of working together, allowing stakeholders to combine their expertise and resources to tackle sustainability challenges. Ramirez-Peña, et al., (2020), state that such partnerships promote synergy, facilitating the exchange of knowledge, best practices, and resources, thus speeding up progress towards sustainability goals. Additionally, effective collaboration between aerospace manufacturers and suppliers is essential for embedding sustainability throughout the supply chain. By forging strong relationships with suppliers, manufacturers can implement environmentally responsible practices such as sustainable sourcing, streamlined logistics, and waste reduction.

However, critics warn of potential coordination challenges, differing priorities among stakeholders, and conflicts of interest, which could hinder effective decision-making and implementation (Freeth & Caniglia , 2019).

Initiatives like the Sustainable Aviation Fuel Users Group (SAFUG) demonstrate collaborative efforts aimed at advancing sustainable aviation fuels, thereby promoting sustainability across the aerospace supply chain (Xu, et al., 2022). Supply chain collaboration enhances transparency, accountability, and resilience, leading to tangible improvements in sustainability performance. On the contrary, there are potential challenges related to information sharing with supplier. For example, organisational culture differences, competitive dynamics, and geographical regulatory differences, which could hinder progress towards shared sustainability objectives (Carter & Rogers, 2008).

As a large and growing industry currently dependent on fossil fuels, the entire aerospace industry must collaborate to achieve Net-Zero 2050, this includes not only aircraft manufacturers and suppliers, but also energy companies, airports, regulators, and other stakeholders (Freeth & Caniglia , 2019).

2.7.2 Innovation

Innovation is crucial for manufacturers to stay competitive, meet evolving demands, and address industry challenges such as ‘Net-Zero 2050’. According to Abbas, et al., (2020), continuous innovation drives advancements in aircraft performance, safety, and efficiency. By continuously improving design, materials, and manufacturing processes, manufacturers can develop products that are lighter, more fuel-efficient, and environmentally sustainable. This not only reduces operating costs but also lowers emissions and enhances overall environmental stewardship.

As aviation regulations evolve and become more complex, innovation is also essential for meeting stringent regulatory requirements and safety standards. Manufacturers must innovate to remain compliant with ever changing regulations, while maintaining operational efficiency (Brown & Davies, 2018).

Moreover, innovation plays a vital role in driving economic growth and job creation within the aerospace industry. By investing in research and development, manufacturers stimulate innovation ecosystems, fostering collaboration with suppliers, research institutions, and startups (Yaghmaie & Vanhaverbeke, 2019). This collaboration leads to the creation of high-tech jobs, the development of new technologies, and the establishment of sustainable supply chains, contributing to economic success and global competitiveness.

According to Chen (2019), it is innovation that fosters creativity, agility, and competitiveness, enabling the development of transformative solutions to sustainability challenges. However, concerns about potential downsides of rapid technological advancement, including resource depletion, electronic waste generation, and societal inequalities stemming from technological disruptions are also highlighted.

2.7.3 Government Support and Funding

Government support and funding play a pivotal role in driving collaboration and innovation within the aerospace industry. Through public-private partnerships, research grants, and incentives, governments encourage stakeholders to invest in sustainable aviation initiatives. Initiatives like the European Green Deal and the Federal Aviation Administration's Continuous

Lower Energy, Emissions, and Noise (CLEEN) program provide crucial backing for projects aimed at enhancing environmental performance in aviation (European Commission, 2019).

In the UK, both the government and the Aerospace Growth Partnership (AGP) are committed to investing a minimum of £1.37 billion in research and development by 2026, with a focus on advancing ultra-low and zero emission technologies. This investment aims not only to surpass the R&D expenditure levels of 2019 but also to pinpoint opportunities for investing in UK suppliers, enhancing skills, and upgrading infrastructure to seize industrialisation opportunities arising from UK-based R&D initiatives. The overarching goal is to boost the UK's share of global aerospace workshare from 13% to 18% by 2050, while simultaneously strengthening the UK supply chain. This aligns with the objective of doubling the aerospace industry's estimated contribution to the UK economy to at least £17 billion Gross Value Added (GVA) annually by 2035 (Department for Transport, 2022).

According to Abhayawansa, et al., (2021), government support aligns industry efforts with broader societal goals, facilitating progress towards sustainability objectives. However, critics raise concerns about potential risks associated with excessive reliance on government funding, including regulatory capture, political interference, and misallocation of resources, which could undermine the effectiveness and autonomy of sustainability initiatives.

2.7.4 Sustainable Supply Chain

Sustainable supply chain management presents opportunities for aerospace manufacturers to mitigate environmental impacts and enhance long-term viability. One opportunity lies in the adoption of sustainable sourcing practices, which involve selecting suppliers that prioritise environmental responsibility and ethical conduct. By partnering with suppliers committed to sustainable practices, aerospace manufacturers can reduce their carbon footprint and minimise negative environmental impacts throughout the supply chain (Carter & Rogers, 2008).

Another opportunity is to optimise logistics and transportation processes to minimise emissions and resource consumption. This can include implementing efficient routing strategies, utilising alternative transportation modes such as rail, sea, or freight, and consolidating shipments to reduce the overall environmental footprint of transportation activities (Seuring & Müller, 2008).

Optimising logistics can reduce greenhouse gas emissions associated with transportation and contribute to meeting sustainability objectives.

Furthermore, aerospace manufacturers can leverage innovative technologies and materials to enhance sustainability within their supply chains. For example, the adoption of additive manufacturing techniques and lightweight materials like carbon fibre composites can lead to reductions in material waste and energy consumption during production (Li, et al., 2020). Additionally, investing in renewable energy sources, such as solar or wind power, for manufacturing facilities can further reduce environmental impacts and contribute to a more sustainable supply chain (Gopalakrishnan & Damanpour, 2013).

However, it is essential to recognise that pursuing sustainability in the supply chain may also pose challenges and risks for aerospace manufacturers. For instance, transitioning to sustainable sourcing practices may require significant investments in supplier development and compliance monitoring. Additionally, disruptions to the supply chain, such as changes in regulatory requirements or shifts in consumer preferences, could impact the availability and cost of sustainable materials and components (Carter & Rogers, 2008). Furthermore, implementing new technologies and processes to enhance sustainability may entail initial costs and require adjustments to existing operations, which could pose financial and operational challenges in the short term (Linton, et al., 2007).

2.7.5 Sustainable Factory

Efforts to minimise energy consumption and waste generation are increasingly crucial within manufacturing plants. Implementing sustainable practices not only reduces environmental impact but also enhances operational efficiency and cost-effectiveness (Pirouz, et al., 2020). Kovacova & Lewis, (2021), discuss the adoption of energy-efficient equipment and technologies. For instance, utilising LED lighting systems instead of traditional fluorescent bulbs. LED lights consume significantly less energy and have longer lifespans, thereby reducing both electricity usage and the frequency of bulb replacements.

Another example is the implementation of automated systems for monitoring and optimising energy usage. Smart sensors and control systems can regulate equipment operation based on real-

time energy demand, thereby reducing unnecessary energy consumption. For instance, in a manufacturing plant, automated HVAC systems adjust heating and cooling levels according to occupancy and production schedules, reducing energy waste during idle periods (Javied, et al., 2018).

Additionally, some manufacturing plants integrate advanced energy recovery systems such as Organic Rankine Cycle (ORC) to harness waste heat from industrial processes. The ORC system converts low-grade waste heat into usable energy, such as electricity or heat for other processes, improving overall energy efficiency (Nguyden, et al., 2023). For example, in a manufacturing plant with high-temperature processes like steelmaking or glass manufacturing, waste heat can be utilised to generate additional electricity or provide heating for other parts of the facility, thereby reducing the reliance on external energy sources.

Li & Zhang, (2017) discuss how lean manufacturing principles are used to streamline production processes and minimise material usage. For example, optimising cutting patterns in the fabrication of metal components can reduce scrap material significantly. The authors also highlight the use of closed-loop systems within the factory to reduce waste generation further. For example, wastewater treatment plants within manufacturing facilities, where treated water is reused for various processes, reducing both water consumption and wastewater discharge.

2.7.6 Frameworks, Roadmaps and Guidelines

A survey by Southwick, (2022), researching sustainability within the UK manufacturing industry, identified that sustainability is something that most companies care about, although the majority are still unsure what to do with it or where to start. According to data software company Brightest (2024), there are more than 600 global sustainability frameworks, roadmaps and guidelines that aim to help companies with this dilemma. However, having so many frameworks to choose from can be daunting for manufacturers in trying to find clear guidance on where and how to begin their sustainability journey.

Frameworks, roadmaps, and guidelines identified within the literature have been predominantly developed for sectors outside of aerospace manufacturing. For example, (Tonelli, et al., 2014), introduced a framework aimed at designing sustainable manufacturing systems, with a specific

focus on sustainability performance measurement and organisational change. Zhang, et al., (2016) presents a framework that combines systems thinking with life cycle assessment (LCA) to support decision-making at both planning and production stages. Furthermore, Pagone, et al., (2020) introduces a decision-making framework that integrates LCA and environmental sustainability alongside traditional metrics, utilising multiple-criteria decision analysis.

Additionally, the United Nations offer a sustainability roadmap as part of their Sustainable Development Goals (SDGs), which encompasses 17 interconnected goals aimed at addressing global sustainability challenges. These goals provide a high-level structure for addressing key sustainability issues, such as reducing carbon emissions and promoting responsible resource management. However, the SDGs are broad and require further interpretation to be effectively applied to the specific challenges faced by aerospace manufacturers in the UK.

Similarly, the Task Force on Climate-related Financial Disclosures (TCFD) framework provides guidance for integrating climate considerations into financial reporting and business strategy (Brown et al., 2020). This framework can help manufacturers to identify and assess climate-related risks and opportunities, enhancing transparency and resilience. However, implementing the TCFD framework would require significant resources and expertise, which is not always possible for smaller companies such as tier 2 and tier 3 suppliers within the aerospace supply chain.

In addition to these global frameworks, aerospace manufacturers within the UK can seek support from the Aerospace Technology Institute (ATI), who provide support for collaborative research and development projects aimed at improving the environmental sustainability of aerospace manufacturing processes and technologies in the UK. The ATI's initiatives offer practical recommendations for enhancing sustainability performance across various domains, including energy efficiency, waste reduction, and supply chain management (ATI, 2023). Again, the framework they have developed is a broad one and does not include a detailed roadmap or clear direction for smaller aerospace manufacturing companies (tier 2 and tier 3).

According to Carle & Rayna (2023), adopting a structured sustainability implementation framework can provide much-needed guidance for manufacturers who are considering adopting new technologies or practices. Haddada, et al., (2021), developed a framework that offers a systematic approach in identifying key areas for improvement and setting actionable goals. By

following such a framework, suppliers can leverage existing knowledge and best practices to streamline their sustainability efforts, facilitating smoother implementation into their operations. This not only enhances environmental and social impact but also boosts operational efficiency and competitiveness in the long run.

The remaining frameworks/roadmaps identified in the literature related to aerospace manufacturing were focused on countries outside of the UK and aimed towards the major aircraft OEM's (Boeing, Airbus etc.) This highlights a gap within the current research whereby no sustainability transitioning frameworks aimed at tier 2 and tier 3 suppliers within UK aerospace manufacturing have been published and will therefore become the basis of the case study in section 3.

2.8 Literature Review Conclusion

In conclusion, the literature sheds light on the complex dynamics that influence the environmental impact of the aerospace manufacturing industry and its journey towards sustainability. Highlighting issues such as resource consumption, energy use, and waste generation highlights the critical need for implementing sustainable practices to address its contribution to climate change.

A key takeaway from the literature is the increasing adoption of sustainable practices within aerospace manufacturing. From lifecycle assessments (LCAs) and eco-design principles to closed-loop systems and advanced materials, manufacturers are actively seeking ways to reduce their environmental footprint throughout the entire product lifecycle. Companies like Boeing, Rolls-Royce, and Thales, are leading by example, integrating sustainability into their operations and supply chains through innovative initiatives. However, despite progress, the literature highlights significant challenges hindering sustainability efforts. Regulatory compliance and certification processes pose hurdles for adopting sustainable materials and processes, while the balance between technological innovation and environmental impact remains a complex issue. Additionally, the cost-benefit equation presents financial challenges for aerospace manufacturers, especially smaller companies operating within tight profit margins.

Furthermore, shifting the industry culture towards sustainability requires a change in mindset and practices at all levels of the organisation. Overcoming these challenges requires collaboration, innovation, government support, and the development of sustainable supply chains. Initiatives such as the Clean Aviation Joint Undertaking (CAJU), and Sustainable Aviation Fuel Users Group (SAFUG) demonstrate the power of collaborative efforts in driving sustainability within the aerospace sector.

Innovations in materials science, lightweight structures, and alternative propulsion technologies offer significant opportunities for reducing environmental impacts. However, implementing these innovations requires careful consideration of their potential drawbacks and risks, such as increased energy consumption or resource depletion. Government support and funding play a crucial role in driving sustainability initiatives within the aerospace industry. Public-private partnerships and research grants enable stakeholders to invest in sustainable aviation projects and align industry efforts with broader societal goals. Frameworks and guidelines, such as the United Nations Sustainable Development Goals (SDGs) and the Task Force on Climate-related Financial Disclosures (TCFD) framework, provide valuable guidance for integrating sustainability into business strategy and decision-making processes. However, navigating the multitude of frameworks and applying them effectively to specific industry challenges remains a significant challenge.

To summarise, while the aerospace industry faces considerable challenges on its path towards sustainability, there is an abundance of opportunities available for manufacturers to progress. By embracing collaboration, innovation, and responsible practices, aerospace manufacturers can reduce their environmental footprint and contribute to a more sustainable future for aviation. Addressing the gaps identified in current research, particularly in developing frameworks and roadmaps tailored to the needs of tier 2 and tier 3 suppliers within the UK, will be critical in advancing sustainability efforts within the aerospace manufacturing sector.

3 Methodology

3.1 Methodology Introduction

As previously discussed, the aim of this dissertation is two-fold; firstly, present the existing practices, opportunities, and challenges faced by aerospace manufacturers on their journey towards Net-Zero 2050. This was completed in the previous section via an extensive literature review. Secondly, the dissertation aims to provide a framework for tier 2 and tier 3 aerospace manufacturers within the UK to assist them in prioritising sustainable practices and technologies.

As identified during the literature review, there is a gap within the research regarding sustainability implementation case studies within aerospace manufacturers in the UK. Therefore, in this section, a model referred to as the ‘Sustainability Transitioning Framework’ is put forward for scrutiny. Developed by Haddada, et al., (2021), the framework is a high-level theoretical methodology specifically designed for integrating environmentally friendly practices into manufacturing organisations. By synthesising tools from various disciplines, the authors created a methodology that they claim will facilitate a smoother transition to sustainability (Haddada, et al., 2021).

The selected framework will become the basis for a case study within a Tier 2 aerospace manufacturer in the UK who are seeking to transition more of their processes and products towards sustainability, the case study is presented in chapter 5. The next section will discuss the research design, followed by a detailed overview of the framework, leading into the case study, analysis/discussion, and conclusion.

3.2 Research Design

3.2.1 Rationale for Selecting the Sustainability Transitioning Framework

As identified in the survey by Southwick (2022), most manufacturers care about sustainability and are keen to play their part, although many are still unsure what to do with it or where to start, especially when considering implementing of sustainable technologies or practices within their organisations.

The framework that will be applied in the following case study was developed by its authors following a wider review of existing literature on sustainability methodologies, as well as consultations with industry experts regarding tools and techniques used in previous studies (Haddada, et al., 2021). Although the methodology can be applied broadly, the focus here is on its application in industrial settings due to the significant environmental impact of manufacturing processes. The sustainability transitioning framework has also been recognised and cited by peers within the academic community, highlighting the simplicity and effectiveness of this approach (Ziyad, et al., 2022; Litos, et al., 2023).

3.2.2 Research Approach

The research approach will be that of a case study. Case studies offer a flexible and powerful research method for exploring real-world phenomena in depth (Rashid, et al., 2018). They involve an in-depth examination of specific instances or situations, while enabling researchers to gather diverse qualitative data through methods like interviews, observations, document analysis, and surveys. They also facilitate the collection of quantitative data, including statistical analysis. This approach allows for a comprehensive understanding of organisational processes in their natural contexts, making them suitable for studying multifaceted phenomena, providing valuable insights for theory-building, hypothesis-testing, and practical decision-making (Hynett, et al., 2014).

There also limitations to consider when applying case studies. For example, subjectivity, limited control, replication difficulties, and researcher bias risks (Rashid, et al., 2018). Focusing narrowly on one case can makes broader conclusions tough, while controlling variables for replication is tricky due to unique circumstances. Ethical concerns arise, especially with sensitive topics. However, addressing these limitations is possible through rigorous methodologies, like employing multiple cases for comparison, using triangulation to minimise bias, ensuring thorough documentation for replication, and adhering to ethical guidelines. Despite challenges, case studies remain invaluable for providing insights into complex real-world phenomena (Hynett, et al., 2014).

In this case study, qualitative data will be collected through discussions with the case company's leadership team to understand their perspectives on the applied transitioning framework,

focusing on feasibility, potential challenges, and perceived benefits. In terms of quantitative data, resource and energy data will be considered to understand the company's waste generation and resource utilisation.

Overall, this approach aims to provide a comprehensive understanding of the manufacturers current practices and to inform future decision-making regarding the implementation of sustainable practices.

3.2.3 Case Company

The chosen company for the case study is a tier 2 aerospace company that design and manufacturer precision metal components for the aerospace industry, using energy intensive processes such as CNC milling/turning and laser cutting/marking. The company is based in the UK and is defined as an SME (Small/Medium Enterprise), with no more than 250 employees and a turnover less than £43m (gov.uk, 2023) making it a suitable candidate for this process as there are currently no case studies that focus on UK tier 2 suppliers in regard to sustainability transition frameworks in the existing literature.

3.2.4 Ethical Considerations

It is important to note that the case study presented in chapter 5 has ethical considerations, ensuring the well-being and rights of the case company are protected. Firstly, full consent was obtained from the company before proceeding with the research. Secondly, due to the sensitive nature of the data that is presented, the company and its products shall remain anonymous.

4 Sustainability Transitioning Framework

Prior to applying the transitioning framework, Haddada, et al., (2021) state that a clear end goal “should be explicitly set” and a time frame defined. For example, achieving net-zero by 2050, or reducing carbon emissions by 50% in 5 years. Once the end goal is defined, the sustainability transitioning framework can be applied.

The methodology, shown in Figure 4.1 below, consists of five sequential steps.

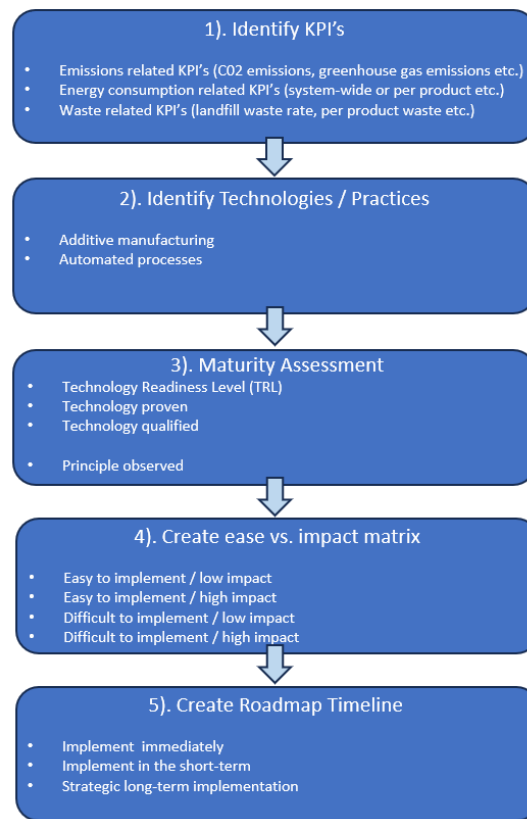


Figure 4.1 Sustainability Transitioning Framework (Haddada, et al., 2021)

4.1 Stage 1: Identify KPIs

The first stage of the framework is to identify specific Key Performance Indicators (KPIs). These KPIs serve as metrics that will enable the company to gauge and compare its performance in specific areas targeted for improvement against clearly defined targets. Selecting the right KPIs

is pivotal as it lays the groundwork for subsequent steps, and it should be tailored to fit the specific industrial context. Moreover, the choice of KPIs related to environmental performance stemming from manufacturing operations can vary based on organisational targets and objectives.

Considerable research exists regarding defining KPIs related to sustainability. For example, Pagone, et al., (2018) delve into various energy and material efficiency metrics like Operational Material Efficiency (OME) and specific energy consumption (SEC). Other KPIs encompass metrics such as CO₂ equivalent emissions and quantities of solids discharged as process waste or into water sources.

In general, such KPIs could relate to energy consumption, for example, product energy consumption or system wide total energy consumption, or they could be more focused on environmental performance, such as that of total carbon emissions. It is also noted that care should be taken when evaluating the chosen KPIs as to not to solely base them on absolute values, and to ensure the data is normalised appropriately as even though absolute figures are still important, they may not paint the full picture. Normalisation can provide a clearer perspective, especially when faced with output variations or seasonal fluctuations (Haddada, et al., 2021).

4.2 Stage 2: Identify Technologies/Practices

The next stage involves identifying technologies and practices that could potentially be adopted to improve the environmental performance of an organisation. Any practice or technology can be considered at this point, with less emphasis on whether the organisation has the capability to implement it. This stage of the framework is influenced by the KPI's identified in the previous stage and provides a useful quantitative performance evaluation.

As highlighted in the literature review, there is a vast amount of options regarding innovative technologies and practices for organisations to choose from at this stage, and every organisation will differ when it comes to what they believe is the right option/s for their business. Some examples may include moving away from traditional subtractive manufacturing processes to additive manufacturing (3D printing), transitioning to automated processes using robotics, or

more general solutions such as moving to solar energy to power manufacturing sites or switching to electric powered company vehicles.

Amongst other resources, the selection of potential technologies and practices should be supported by company reports, literature reviews and anywhere where best practices are identified. The selection process will become clearer as the next stages of the framework are discussed.

4.3 Stage 3: Maturity Assessment

After identifying potential technologies and/or practices, the next step involves assessing their maturity via an assessment tool referred to as the Technology Readiness Level (TRL) framework. Originally developed by NASA in the 1970s, the TRL framework has been widely adopted by professional bodies such as the US Department of Defence and the European Commission (Mankins, 2009 ; Héder, 2017). The TRL framework provides decision-makers with insights into the understanding and potential risks associated with innovative technologies and/or practices.

The TRL scale consists of nine levels, ranging from TRL 1 (basic principle observation) to TRL 9 (Technology/practice proven through successful deployment). For reference, the TRL scale is shown in figure 4.2.



Figure 4.2 Technology Readiness Level (TRL) Scale (TWI, 2020)

To determine the readiness level of each potential technology/practice, the recommendation is to conduct literature reviews, particularly for lower TRL stages (TRL 1 and 2) or seek guidance from industry experts. However, if the relevant maturity level cannot be established via literature reviews or expert judgment, the authors state that a formal Technology Readiness Assessment (TRA) may be needed (Haddada, et al., 2021).

4.4 Stage 4: Ease vs Impact Matrix

Once KPIs, potential technologies/practices, and TRLs are determined, an ease of implementation versus impact matrix can be created. Based on the Six Sigma PICK chart (figure 4.3), the matrix enables its user to position each potential technology/practice on a chart where the axes represent ease of implementation and perceived impact on performance, facilitating the prioritisation of options.

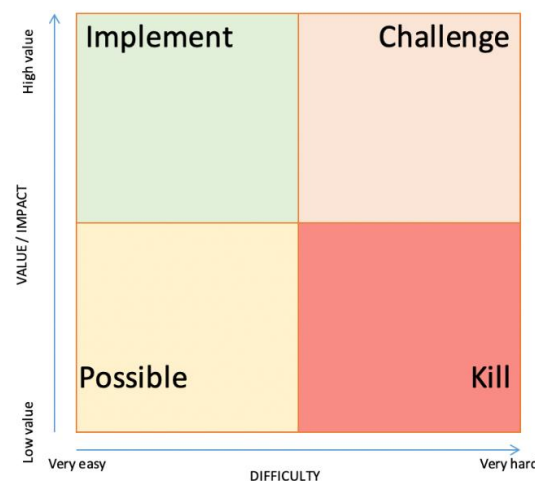


Figure 4.3 Six-Sigma PICK Chart (Murdoch, 2018)

Determining the ease of implementing technologies and practices is subjective, influenced by factors such as cost, resources, and willingness to change within the organisation. Similarly, assessing the impact of adopting these technologies and practices on performance involves subjective determinations, with considerations varying depending on the specific context. Consequently, there are no rigid rules or strict guidelines, especially given that such decisions

often prioritise immediate needs (Murdoch, 2018). Factors such as deployment timelines, recurring and non-recurring costs, and system complexity serve as typical but adjustable metrics.

4.5 Stage 5: Create Roadmap Timeline

The fifth and final stage of the sustainability transitioning framework is to develop a timeline roadmap of which the basis will be dependent on the outcome of the previous stages.

The roadmap should naturally align with the time frame and goals established at the outset of implementing the framework (Stage 1), and technologies/practices with higher TRL numbers (deemed to be mature enough for implementation in the short-term) should be prioritised. The TRL thresholds to be considered for implementation should be determined by the organisation.

Subsequently, upon constructing an ease of implementation versus impact matrix, the priority for available options is determined. Ideally, the roadmap timeline should be divided into distinct time frames, for example, basic energy-saving practices, such as automatic lighting could be implemented in the immediate term, or longer-term strategic goals such as transitioning to clean renewable energy sources (Haddada, et al., 2021). The roadmap template is shown in figure 4.4.

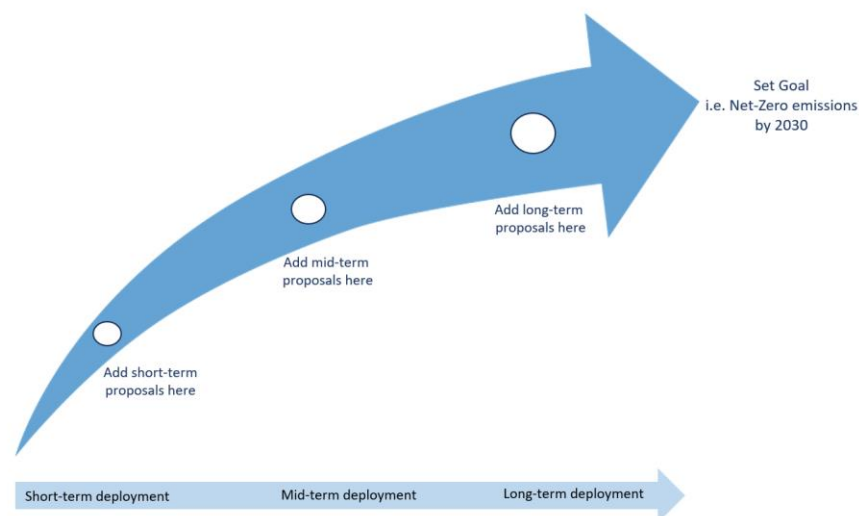


Figure 4.4 Sustainability Transitioning Roadmap (Haddada, et al., 2021)

5 Case Study

This section presents a case study conducted within an aerospace manufacturing company to validate and assess the feasibility of implementing the sustainability transitioning framework developed by Haddada, et al., (2021), within a production environment.

As previously mentioned, the chosen company for the case study is a tier 2 aerospace company that designs and manufactures components for the aerospace industry, specialising in precision machining of metal components. Prior to applying the framework, the proposed sustainability transitioning framework was presented to the company's leadership team, providing an explanation of the stages of implementation and how this can benefit the company in accelerating the journey towards Net-zero.

The following sections discuss the application of the sustainability framework structure within the chosen company.

5.1 Case Study: Stage 1 - Identify KPI's

While the company has prior experience with sustainable practices, the leadership team have identified that the company needs to do more. As a result, the company is actively seeking new opportunities and guidance on how they can improve sustainability and reach net-zero by 2030. As defined in stage 1 of the sustainability transitioning framework, KPI's must be defined, and in line with the company's goal of achieving net-zero by 2030, carbon dioxide (CO₂) emissions (measured in tons) were deemed the obvious choice when considering a KPI to be used for measurement and comparison during the case study.

As a starting point, the company's resource, and energy consumption data from the last three years (2021-2023) was reviewed and a Pareto analysis was performed to identify the company's waste output and ultimately where CO₂ emissions are likely to be higher. The results of the Pareto analysis are shown in figure 5.1.

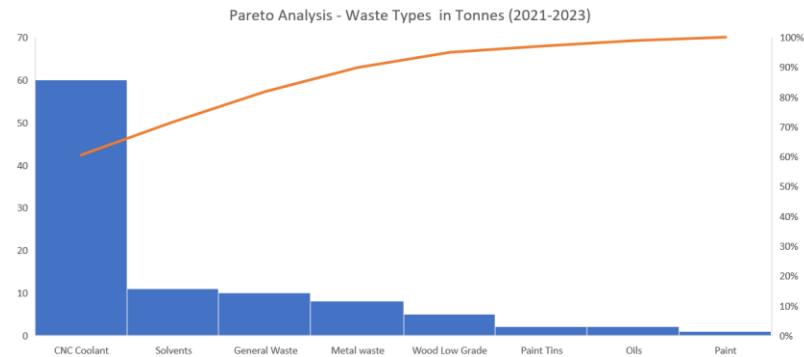


Figure 5.1 Pareto Analysis of Case Company's Waste Types by Weight (tonnes)

As identified in the analysis, the majority (60%) of the company's waste originated from machine coolant usage. The significance of this outcome will become apparent throughout the discussion as this will influence decisions regarding technology/practices, and time of implementation.

5.2 Case Study: Stage 2 – Identify Technologies/Practices

5.2.1 Automated Lighting System

From initial discussions with the company, it was evident that the company's priority was to first target short-term strategies that could reduce their carbon footprint. One of the proposed technologies for review at this stage was switching to an automated lighting system within the manufacturing facility. Despite often being overlooked, lighting can consume as much as 18% of electricity costs in industrial facilities (Montoya, et al., 2017). By utilising LED lights and automated control systems, energy savings of 40% - 60% in lighting consumption can be achieved. For instance, replacing a 400W metal halide luminaire with a 200W LED one can save approximately 207W, corresponding to a reduction of 85g of CO₂ emissions per operating hour.

5.2.2 Electric Motors – Premium Efficiency

Furthermore, the company were considering other energy saving options, such as switching existing energy intensive electric motors currently used in their machines to premium efficiency motors to further reduce energy consumption.

Electric motors, integral to manufacturing operations, are classified into different efficiency classes ranging from IE1 (Standard efficiency) to IE4 (Super-premium efficiency). The machines within the manufacturing plant are predominantly powered by a combination of IE2 and IE3 motors, although switching to IE4 super premium efficiency motors can reduce energy losses by up to 30% (Hoyer, 2024).

5.2.3 Minimal Quantity Lubrication

As previously discussed, during analysis of the company's waste, used machine coolant was identified as the main contributor. Following the guidance for stage 2 (Identify Technologies/Practices) of the transitioning framework (see section 4.2), a literature review and benchmarking activity were conducted to identify viable solutions. As a result of this research, a technique referred to as Minimal Quantity Lubrication (MQL) was proposed to the company. MQL is an environmentally friendly machining technique that significantly reduces lubricant consumption to less than one litre per hour, a vast improvement when compared to the 100 litres used per hour within traditional cooling/lubrication methods (Mark Benjamin, et al., 2018).

Despite minimal lubricant usage, MQL also results in dry metal shavings that can be easily recycled (Park, et al., 2015), while improving various aspects including surface finish, chip breakability, cutting forces, residual stress, and tool longevity. According to the research, it can reduce surface roughness by 40% and required cutting force by 60% (Said, et al., 2019).

Furthermore, Sivaiah, et al., (2023) states that MQL will prevent harmful coolant waste returning to the atmosphere while cutting any associated disposal costs.

5.2.4 Organic Rankine Cycle (ORC)

The total energy consumption from the manufacturers most energy-intensive processes manufacturing facility, such as and heat treatment, anodising and painting activities, was also analysed. These processes typically generate a significant amount of heat waste, which, if recovered, can be transformed into electrical energy, or recycled for other activities.

Implementing a heat recovery system such as the Organic Rankine Cycle (ORC), could lead to energy savings of 10% across each of the energy-intensive processes within the plant (Sun, et al., 2017).

5.3 Case Study: Stage 3 - Maturity Assessment

With technologies identified, the next stage was to assess their maturity using the Technology Readiness Level (TRL) framework (figure 5.2). As recommended by Haddada, et al., (2021), literature reviews and benchmarking activities were carried out while also seeking guidance from industry experts to determine the maturity of the proposed technologies; Automated lighting systems, premium efficiency electric motors, minimal quantity lubrication systems and heat recovery systems (Organic Rankine Cycle).

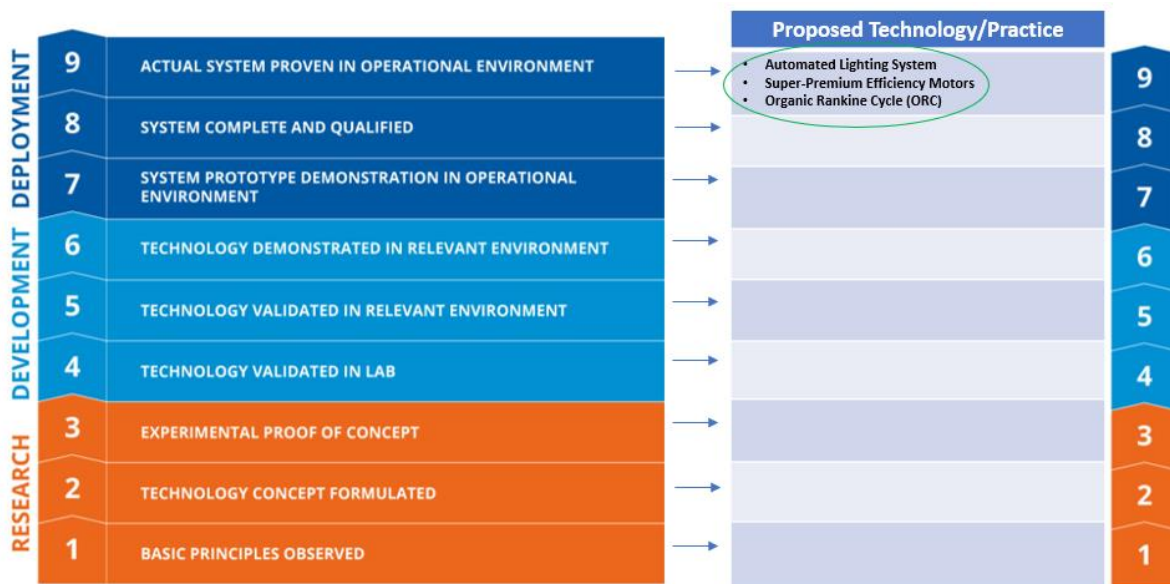


Figure 5.2 TRL Assessment of Proposed Technologies (Performed at Case Company)

From the research, each of the proposed technologies were identified as having a maturity rating of TRL 9 (highest level of maturity), meaning the technologies are ‘actual systems proven in operational environment’. Technologies at this level of maturity provide the manufacturer with confidence as the more mature and established the technology or practice is, the risks associated with implementation are reduced (Salazar & Russi-Vigoya, 2021).

5.4 Case Study: Stage 4 - Ease vs Impact Matrix

With the proposed technologies assessed for maturity, an ‘ease of implementation versus impact’ matrix was created (figure 5.3), to visually represent the ease of implementation and impact with respect to the company’s goal of achieving net-zero by 2030.

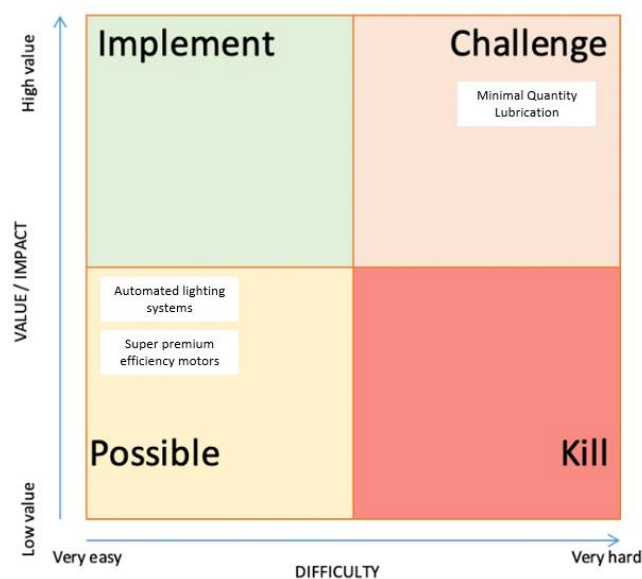


Figure 5.3 Ease of Implementation vs Impact Matrix (Performed at Case Company)

Reviewing figure 5.3, it is evident and unsurprising that the technology considered easiest to implement is the installation of an automated lighting system and the company’s decision was to progress with this system in the short-term. Although implementation is considered easy, its overall perceived impact could be low due to the widespread adoption of LED-powered systems across industries. Ease of implementation is subjective and determined by a range of factors such as cost, available infrastructure, and resistance to change (Haddada, et al., 2021).

Besides the decision to implement automated lighting control system in the short-term (1-2 years), the company is planning to invest in IE4 super premium efficient electric motors and MQL in the mid-term (2-5 years). Although not as easy to implement as the automated lighting system, these technologies can directly impact energy and resource-intensive processes, thereby reducing energy consumption and CO2 emissions.

5.5 Case Study: Stage 5 - Roadmap Timeline

After completion of the maturity assessments and ease v's impact matrix, a roadmap was created (figure 5.4). The roadmap indicates the company's end goal of achieving 'Net-Zero Emissions by 2030' at the end of the timeline, with each of the proposed technologies added to the roadmap in order of time of deployment (short-term, mid-term and long-term).

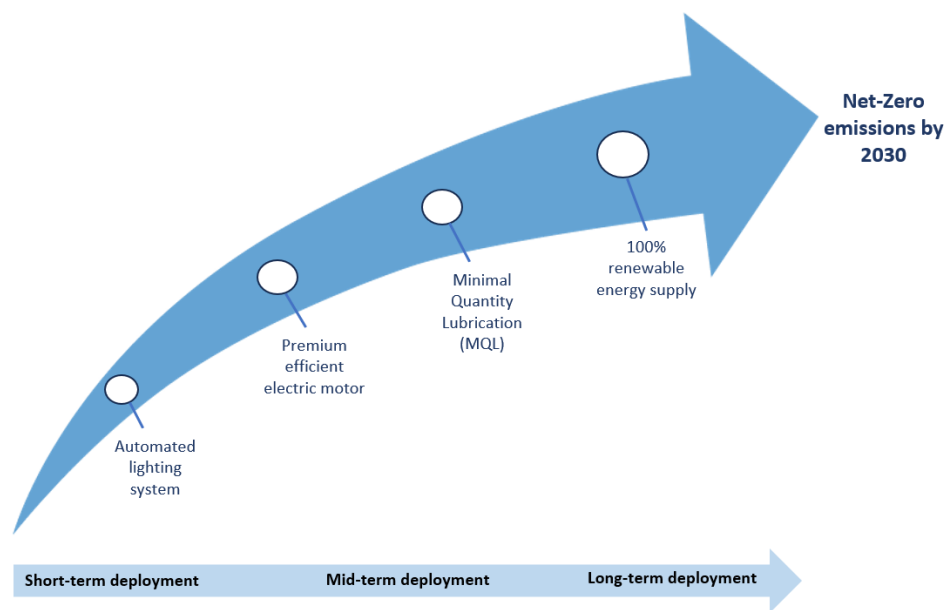


Figure 5.4 Sustainability Transitioning Roadmap (Performed at Case Company)

Using a roadmap such as this provides clear direction by visually presenting key milestones and deadlines, fostering alignment among stakeholders (Martins, 2024). Through goal setting and monitoring, it enables effective progress tracking and identification of potential delays, ensuring project success. Additionally, it enhances resource allocation by assigning tasks to specific time frames, preventing resource overloading. However, Kerr & Phaal, (2022) state that such high-

level roadmaps may not capture the full complexity of a project or its interdependencies. Its flexibility facilitates adaptation to changing circumstances while maintaining progress towards project objectives.

5.6 Discussion

This case study offers valuable insights into the implementation of the Sustainability Transitioning Framework within a Tier 2 aerospace manufacturer in the UK.

Developed by Haddada et al. (2021), the framework provides a structured approach to implementing sustainable technologies and practices into manufacturing operations specifically within organisations who are unfamiliar with the implementation of sustainable technologies and practices. However, while the framework provides a valuable theoretical foundation, its practical applicability and effectiveness requires are questionable.

An important strength of the sustainability transitioning framework is its comprehensive nature, drawing from various disciplines to facilitate a smoother transition to sustainability. By prioritising the identification of key performance indicators (KPIs) and assessing technology readiness levels (TRLs), the framework offers manufacturers a systematic approach to evaluating current practices and prioritising areas for improvement. Furthermore, its emphasis on developing a roadmap timeline aligns with the long-term sustainability objectives of manufacturers, providing a clear trajectory for implementation.

However, despite its strengths, there are limitations and challenges raised by the case company to be considered. Firstly, the unique challenges and opportunities faced by manufacturers may require customisation and adaptation of the framework's principles. Additionally, reliance on qualitative and quantitative data collection methods may pose difficulties, particularly for tier 2 and tier 3 manufacturers with limited resources or expertise in sustainability measurement and reporting.

Moreover, the framework's focus on technology-driven solutions may overlook the importance of organisational culture, leadership commitment, and stakeholder engagement in driving sustainable change. While technological advancements are essential for enhancing resource efficiency and reducing environmental impact, sustainable transformation also requires a cultural shift and organisational buy-in at all levels (Marshall, 2023).

Regarding the findings of the case study, while the application of the framework provided valuable insights and recommendations for the manufacturer, certain limitations should be acknowledged. The exclusive focus on CO₂ emissions as a KPI may overlook other

environmental and social aspects of sustainability, such as water usage, waste management, and supply chain ethics. Adopting a more holistic approach to sustainability measurement and reporting would offer a comprehensive understanding of the company's impact and opportunities for improvement.

Additionally, while the roadmap timeline developed in the case study provides a clear path for implementing sustainable practices, the dynamic nature of technological innovation and market trends requires ongoing monitoring and adaptation of strategies. Continuous evaluation and adjustment of the roadmap based on emerging technologies, regulatory changes, and stakeholder feedback are crucial for ensuring the long-term success of sustainability initiatives.

In conclusion, the Sustainability Transitioning Framework serves as a valuable starting point for tier 2 and tier 3 manufacturers embarking on their sustainability journey. Although, its practical application necessitates careful consideration of contextual factors, stakeholder engagement, and ongoing monitoring and adaptation. By analysing the framework and its findings, manufacturers can deepen their understanding of sustainability challenges and opportunities, thus ensuring they are on the right path towards their sustainability goals.

5.7 Case Company Progress

Following the learnings from the case study, the manufacturer has made significant progress on their sustainability journey and have since implemented the proposed technologies discussed previously. Despite this progress, the company recognised the need for customisation and adaptation of the framework's principles to suit its unique challenges and opportunities going forward. To this end, the leadership team initiated a thorough review of its operations, identifying specific areas where the framework's guidelines could be tailored to better align with its sustainability objectives and organisational environment.

Moreover, acknowledging the limitations posed by reliance on qualitative and quantitative data collection methods, particularly for tier 2 and tier 3 manufacturers with limited resources or expertise in sustainability measurement and reporting, the company is currently seeking knowledge transfer initiatives. This included training programs for employees to enhance their understanding of sustainability concepts and methodologies, as well as collaborations with academic institutions or consulting firms specialising in sustainability assessment and reporting.

Furthermore, recognising the importance of organisational culture, leadership commitment, and stakeholder engagement in driving sustainable change, the company have initiated efforts to foster a culture of sustainability, through leadership workshops, employee engagement initiatives, and communication campaigns aimed at raising awareness and gaining support for sustainability initiatives at all levels in the company.

In response to the case study's findings regarding the exclusive focus on CO₂ emissions as a key performance indicator (KPI), the manufacturer is expanding its sustainability metrics to include a broader range of environmental and social aspects. This encompassed tracking water usage, waste management practices, supply chain ethics, and other relevant indicators to provide a more comprehensive understanding of the company's sustainability performance and identify additional opportunities for improvement. Additionally, the manufacturer is considering investing in a monitoring and evaluation system to assess the effectiveness of its sustainability initiatives. This will be applied to the transitioning framework and will assist the company in the decision-making process on whether to proceed with the technology.

6 Conclusion and Recommendations

To summarise, the justification for this research is driven by the environmental impact of the aviation sector and specifically aerospace manufacturing. With many manufacturers keen to make a difference and play their part in the industry reaching ambitious sustainability targets, many organisations, specifically tier 2 and tier 3 suppliers within the UK are still hesitant of where to begin on their sustainability journey. To support such organisations, this dissertation set out to embark on a thorough exploration of sustainability within the aerospace manufacturing sector, providing not only guidance on existing sustainability practices, opportunities and challenges for tier 2 and tier 3 suppliers within the UK aerospace industry to achieve ambitious sustainability goals, notably 'Net-Zero 2050', but also presenting an established framework to support such manufacturers with the implementation of sustainable technologies and practices.

Through a comprehensive literature review, the study presented a valuable insight into sustainability opportunities and challenges within aerospace manufacturing. While commendable efforts have been made by industry leaders such as Boeing, Airbus, and Rolls-Royce in integrating sustainability into their operations, challenges such as regulatory compliance, technological innovation, and financial constraints remain a significant challenge, specifically for tier 2 and tier 3 suppliers. To tackle these challenges, collaboration and innovation is essential, along with government support, and sustainable supply chain development.

Moreover, advances in materials science, lightweight structures, and alternative propulsion technologies offer promising avenues for reducing environmental impacts. However, implementing these innovations requires careful consideration of potential drawbacks and risks, alongside strong government support and funding.

Furthermore, it was highlighted that many aerospace manufacturers, specifically smaller organisations with limited resources (tier 2 and tier 3 suppliers), are unsure where or how to begin their sustainability journey. To support manufacturers, valuable guidance and support for integrating sustainability into business strategies is available through an abundance of guidelines, frameworks and roadmaps. One particular methodology referred to as 'The Sustainability Transitioning Framework' was identified as a valuable tool particularly for within manufacturing organisations that are inexperienced in implementing sustainable technologies and practices into

their organisations. Adopting such a transitioning framework can provide a structured approach when considering implementing sustainable technologies or practices. Although, certain limitations of the framework were identified. For example, there is a risk of overlooking the significance of organisational culture and stakeholder engagement in driving sustainable change. Additionally, the framework's generic nature may require customisation to suit the unique contexts of different aerospace manufacturers, which raises concerns about its applicability and effectiveness.

Applying the transitioning framework to a case study within a tier 2 supplier within the UK offered practical insights into its application in a real-life setting. While the case study findings provided actionable recommendations, there are notable areas for improvement that could benefit the company. Firstly, the exclusive focus on CO₂ emissions as a key performance indicator may oversimplify the complex environmental impacts of aerospace manufacturing, potentially neglecting other critical aspects such as water usage, waste management, and supply chain ethics. Additionally, the static nature of the roadmap timeline may not adequately account for the dynamic nature of technological advancements and market trends, suggesting the need for continuous monitoring and adaptation to ensure relevance and effectiveness.

Moreover, the case study highlighted the need for a more holistic approach to sustainability measurement and monitoring, encompassing a broader range of environmental and social indicators to capture the full extent of aerospace manufacturing's impact.

In conclusion, this dissertation provides a comprehensive overview to tier 2 and tier 3 manufacturers within the aerospace manufacturing sector considering initiating or accelerating their sustainability journey. Despite the application of an extensive literature review and case study within this research, there are areas that require further exploration and refinement.

Looking ahead at future research, it is recommended that tier 2 and tier 3 manufacturers must critically assess existing frameworks and practices to determine applicability for their organisation, taking into account the intricacies and challenges involved in sustainable transformation. Collaboration, innovation, and a holistic approach to sustainability are essential for overcoming the obstacles ahead and achieving the goal of a more sustainable aerospace industry.

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