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ENVIRONMENTALLY SUSTAINABLE SUPPLY CHAINS IN THE AEROSPACE MANUFACTURING SECTOR

A systematic literature review

Bachelor's thesis
Faculty of Management and Business
Examiner: Ulla Saari
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ABSTRACT

Eetu Hänninen: Environmentally sustainable supply chains in the aerospace manufacturing sector
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The aerospace manufacturing sector has faced many challenges in the recent years due to global disruptive phenomena, in particular the COVID-19 pandemic. The industry has been forced to adjust its supply chains due to the shortage of components, such as jet-engines. These disruptions have also led to investments being made into new equipment and improved processes. This disruption could also offer a possibility to create new, more environmentally sustainable solutions in the field. The subject of this bachelor's thesis is to study environmental sustainability in the context of supply chains in the aerospace manufacturing sector and to find solutions to improve it. More specifically, the goal of the thesis is to study which of these solutions are the most important and to which extent the solutions are being utilised currently and how the situation could change in the future.

The thesis has been conducted in the form a systematic literature review, where the articles referenced and the searches made are being documented in detail. The thesis is structured in the following way. First, the underlying theory regarding sustainability and the aerospace manufacturing sector is studied. After that, different solutions to make the sector's supply chains more environmentally sustainable are being presented. The solutions are divided into three distinct categories: technological solutions, operational solutions, and combined solutions. Combined solutions were added as a category due to some of the solutions including significantly both technological and operational attributes. Finally, the thesis is being concluded and the most important findings are being presented. In addition, possible ideas for future research are being presented.

Additive manufacturing, as well as lean and green practices stand out as important solutions to improve environmental sustainability of the supply chains in the aerospace manufacturing sector. Also, Industry 4.0 combines multiple different solutions that have potential to become more utilised in the future.

The amount of literature available in the chosen field is relatively limited, which affects the reliablility of the results of this thesis. However, since the thesis did not go into great detail into any of the topics discussed, it could at least offer a starting point and an overview of the field for further research in the topic.

Keywords: environmental sustainability, aerospace manufacturing sector, supply chain management

TIIVISTELMÄ

Eetu Hänninen: Ympäristöllisesti kestävät toimitusketjut ilmailuteollisuudessa
Kandidaatintyö
Tampereen yliopisto
Tuotantotalouden tutkinto-ohjelma
Toukokuu 2023

Ilmailuteollisuus on kohdannut useita haasteita viime vuosina maailmanlaajuisesti vaikuttavien ilmiöiden vuoksi, joista tärkein on COVID-19 pandemia. Alan on täytynyt mukauttaa toimitusketjujaan puuttuvien komponenttien, kuten lentokoneiden moottoreiden vuoksi. Häiriötilanne on kuitenkin myös johtanut investointeihin uusiin laitteisiin ja parannettuihin prosesseihin. Tilanne saattaa luoda myös mahdollisuuden uusien, ympäristöllisesti kestävien ratkaisuiden luomiseen alalle. Tämän kandidaatintyön aiheena on tutkia ympäristön kestävyyttä ilmailuteollisuuden toimitusketjuissa ja löytää ratkaisuja sen parantamiseksi. Tutkielman tarkempana tavoitteena on tutkia, mitkä näistä ratkaisuista ovat kaikkein tärkeimpiä sekä mitkä ratkaisut ovat tällä hetkellä eniten käytössä ja miten tilanne saattaa tulevaisuudessa muuttua.

Työ on tehty systemaattisena kirjallisuuskatsauksena, jossa viitatut artikkelit ja tehdyt haut on yksityiskohtaisesti dokumentoituna. Työssä on seuraava rakenne. Ensimmäiseksi esitellään kestävyyteen ja ilmailuteollisuuteen liittyvää teoriaa. Sen jälkeen käsitellään ympäristön kestävyyttä alalla parantavia ratkaisuja. Ratkaisut on jaettu kolmeen kategoriaan: teknologisiin ratkaisuihin, operationaalisiin ratkaisuihin ja yhdistelmäratkaisuihin. Yhdistelmäratkaisuiden kategoria lisättiin mukaan sen vuoksi, että joillakin ratkaisuilla oli merkittävissä määrin sekä teknologisia että operationaalisia ominaisuuksia. Lopuksi esitellään työn tärkeimmät päätelmät ja esitetään aiheita mahdolliselle jatkotutkimukselle.

Lisäävä valmistus sekä lean-ratkaisut ja vihreät-ratkaisut nousevat esiin tärkeinä ympäristön kestävyyttä edistävinä ratkaisuina. Lisäksi Industry 4.0 -pohjaisille ratkaisuille on nähtävissä potentiaalia suuremmalle käytölle tulevaisuudessa.

Saatavilla olevaa kirjallisuutta valitulta alalta on suhteellisen vähän tarjolla, mikä osaltaan vaikuttaa heikentävästi tutkimustulosten luotettavuuteen. Kuitenkaan tutkielmassa ei tarkasteltu yksityiskohtaisesti yhtäkään aihealuetta, jolloin se voi vähintäänkin tarjota lähtöpisteen ja karkean tason kuvauksen alasta mahdolliselle jatkotutkimukselle aiheesta.

Avainsanat: ympäristön kestävyys, ilmailuteollisuus, toimitusketjujen hallinta

PREFACE

The subject of this thesis is to study environmental sustainability in the context of supply chains of the aerospace manufacturing sector. I chose the aerospace industry since I have always been interested in the field, but also because the industry needs to change significantly to be keep operating sustainably in the future. Writing the thesis has taught me a lot on the topic itself and how to conduct scientific research, which many times is not easy.

I would like to thank my examiner, Senior Research Fellow Ulla Saari for teaching me many things on how to do research and Associate Professor Mohammad Moshtari for the valuable feedback and advice both before starting to write the thesis and during it.

Tampere, 7 May 2023

Eetu Hänninen

CONTENT

1. INTRODUCTION

Sustainability is among the most important goals for companies and it has received significant interest also in the literature (López and Ruiz-Benitez, 2020). However, there seems to be a gap in the literature in the context of sustainable supply chains in the aerospace industry. At the same time the aerospace market requires environmentally friendly solutions (Dorfman et al., 2022) and the environmental impact of aviation is a common topic in the public discussion, but the impact of manufacturing the aircraft does not seem to receive the same attention.

1.1 Research goal and questions

The subject of this bachelor's thesis is to study environmental sustainability in the supply chains of the aerospace manufacturing sector. The aerospace manufacturing sector as an industry and the characteristics of its supply chains are described more in detail in the next section. It was chosen as the studied industry since based on preliminary research the field has not been studied that much, and out of personal interest towards the topic. Therefore, this thesis will focus on the activities that occur before an aircraft comes out of an assembly line and how to make these activities more environmentally sustainable. However, in some cases activities happening after the lifespan lead to activities in the supply chain of manufacturing aircraft, which have been included in the thesis. Even though environmental sustainability is only one dimension of sustainability, this thesis will be limited to environmental sustainability to give it a clear focus and to keep its length in the target.

Sustainability of the supply chain is one of the major points of concern for businesses in the manufacturing sector (Ramirez-Peña et al., 2020). Ramirez-Peña et al. (2020) also argue that sustainable culture is not promoted in the management of aerospace supply chains. However, the sector is still committed to decrease its impact to the environment (Ruiz-Benitez et al., 2017). Based on these points, the major research questions of this bachelor's thesis are the following:

- **RQ1:** What are the most important solutions regarding environmental sustainability in the aerospace manufacturing sector's supply chains?

- **RQ2:** Which of these solutions are currently widely used and which of them could be used more in the future?

1.2 Research methods and thesis structure

The thesis will be conducted in the form of a systematic literature review, where the searches made, and the articles used are explicitly documented. The thesis covers articles from the field of supply chain management and other related or otherwise relevant sources. The articles have mainly been discovered by using Scopus and Web of Science, which provide a comprehensive collection of articles of high quality. All the articles, that were chosen, have been peer-reviewed to ensure reliable information. A complete list of the used references, their type, and the sections they are used in are listed in appendix A.

The first properly studied search was made in Scopus with the search term *aerospace AND "supply chain" AND sustainab** with a limit *TITLE-ABS-KEY*, which searches in article title, abstract, and keywords. This search combined all the basic aspects of the research: *aerospace*, *supply chain*, and *sustainability*, which is why it was chosen as the first main search. After these results were studied on a general level, other searches were performed. The second search had the same search term, but the limit was changed to *TITLE*, which searches only in the article title. This search provided only 5 results, which lead to more searches being done. The second search term was *aerospace AND "supply chain" AND environmental* AND sustainab**, which was chosen because it specifies the search more into environmental sustainability which is the focus of this thesis. This search provided 21 results. The same search with limit to *TITLE* provided no results. The third search term was *aerospace AND environmental* AND sustainab**, which dropped of the term *supply chain* compared to the previous search. Even if supply chains are specifically studied in this thesis, based on the results of the first search and the fact that supply chains consist of many different parts, relevant information on a specific part of the supply chain could also be found without *supply chain* being in the search term. This search provided 497 results and while limited to *TITLE*, one result. Since the previous searches in *TITLE* provided only a few results, the final search was made also in *TITLE*, but with a more general search term. Search with the term *aerospace AND sustainab** provided 53 results. All the searches performed in Scopus with their limits and the number of results are listed in table 1 below.

Table 1. *Searches performed in Scopus, used limits, and results.*

Search	Search term	Limits	Results
#1	aerospace AND “supply chain” AND sustainab*	TITLE-ABS-KEY	83
#2		TITLE	5
#3	aerospace AND ”supply chain” AND environmental* AND sustainab*	TITLE-ABS-KEY	21
#4		TITLE	-
#5	aerospace AND environmental* AND sustainab*	TITLE-ABS-KEY	497
#6		TITLE	1
#7	aerospace AND sustainab*	TITLE	53

To make the results more relevant and to compare them, the same searches were also performed in Web of Science. In Web of Science, *TOPIC* is the closest equivalent for *TITLE-ABS-KEY* of Scopus. The search results from Web of Science closely resemble the ones from Scopus, being slightly fewer in all searches except one. Similarly to the searhes performed in Scopus, all the searches performed in Web of Science are listed in table 2 below.

Table 2. *Searches performed in Web of Science, used limits, and results.*

Search	Search term	Limits	Results
#8	aerospace AND “supply chain” AND sustainab*	TOPIC	37
#9		TITLE	2
#10	aerospace AND ”supply chain” AND environmental* AND sustainab*	TOPIC	13
#11		TITLE	-
#12	aerospace AND environmental* AND sustainab*	TOPIC	265
#13		TITLE	2
#14	aerospace AND sustainab*	TITLE	34

The choices about articles that were used in the thesis were made based on their relevance to the topic, release year, availability, and the journal. Some articles were dropped out of consideration, since their journal either had a Julkaisufoorumi (JUFO) rating of 0, or they were not rated at all. Therefore, all the journals used have received at least a JUFO rating of 1, some articles being also from higher level journals. In addition, a technique called “Pearl growing”, which has been described by Schlosser et al. (2006), has been used to find some articles. Table 3 below presents the final distribution of articles in terms of the way they were found.

Table 3. *The amount and the list of articles in terms of the way they were found.*

Way of finding article	**(Number) Articles**
Scopus or Web of Science	**(23):** Barbosa et al., 2023; Barbosa et al., 2019; Chung and Chu, 2016; Debnath et al., 2022; Dorfman et al., 2022; Felsberger et al., 2022; López and Ruiz-Benítez, 2020; Mancheri et al., 2018; Manville et al., 2021; Markman and Krause et al., 2016; Mota et al, 2015; Nyamekye et al., 2023; Prashar et al., 2022; Ramirez-Peña et al., 2020; Rodrigues Dias et al., 2022; Roehrich et al., 2017; Ruiz-Benítez et al., 2019; Ruiz-Benítez et al., 2017; Seuring and Müller, 2008; Swain, 2023; Tate and Bals, 2016; Vo Dong et al., 2020; Yusuf et al., 2019
Pearl growing	**(5):** Vo Dong et al., 2019 *(from Vo Dong et al., 2020)*; Petrosius, 2018 *(from Barbosa et al., 2023)*; Cooke & Ehret, 2010; Hickie, 2006 *(from Barbosa et al., 2023)*; Carter & Rogers, 2008 *(from Ruiz-Benitez et al., 2019)*;
Others	**(8):** Airbus, n.d.a; Airbus, n.d.b; Airbus, n.d.c; Boeing, n.d.; Memon, 2023; Singh, 2023; Hemmendinger, 2022; Schlosser et al., 2006

This thesis is structured as follows. After the introduction, section 2 (*Environmental sustainability and the aerospace industry*) presents the underlying theory of the thesis. After the theory section, section 3 (*Environmentally sustainable solutions in the supply chains of the aerospace manufacturing sector*) provides solutions to improve environmental sustainability in the supply chains of the aerospace industry. The solutions have been divided into *technological*, *operational*, and *combined* solutions, and discussed in separate chapters. Section 3 builds on top of the previous theory section. Finally, section 4 (*Conclusions*) includes the most important findings of the thesis and presents possible topics for further research.

2. ENVIRONMENTAL SUSTAINABILITY AND THE AEROSPACE INDUSTRY

This thesis will focus on the aerospace industry. More specifically it will focus on producing and manufacturing aircraft including all the steps that are needed to create a complete aircraft. The defense sector is close to the aerospace industry since aircraft are also used for military purposes. This thesis will focus more on the commercial aerospace industry. This section first takes a brief look at environmental sustainability in the context of supply chains. It then introduces the aerospace industry and its current situation both on a general level and in terms of environmental sustainability with the help of examples. Finally, it goes deeper into the aerospace manufacturing sector and its typical supply chains. The section provides theoretical background to better address the solutions that are described in the following section.

2.1 Environmental sustainability in supply chains

A general definition of sustainability is to be able to meet the present needs without compromising the needs of the future (Markman & Krause, 2016). Environmental sustainability is one of the three pillars of sustainability, the other two being social and economic sustainability (Tate & Bals, 2016). The concept of Triple Bottom Line combines economic and environmental aspects of an organization with its social aspects (Carter & Rogers, 2008). Markman and Krause (2016) also argue that environmental sustainability is not to be prioritized over social and economic sustainability.

One definition of supply chain defines it as a composition of interested parties, such as suppliers, manufacturers, suppliers, and customers (Ramirez-Peña et al., 2020). According to Seuring and Müller (2008), sustainable supply chain management is management of material, information, and capital flows in cooperation with other companies in the supply chain with goals in all three dimensions of sustainability. These definitions include similar aspects and sustainable supply chain management adds sustainability as an aspect to supply chains. Sustainability can be integrated into the design of supply chains, for instance, by using mathematical programming models (Mota et al., 2015). Chung and Chu (2016) describe a green supply chain as “a coherent, dynamic loop”. This view has implications for circular economy, which is also addressed in this thesis.

2.2 Outlook on the aerospace industry

Sustainable operations can be characterized as the cornerstone of financial long-term survival of the commercial aerospace industry, despite the temporary financial challenges to the industry caused by the COVID-19 pandemic (Barbosa et al., 2023), which has affected not only the airlines directly but also the entire supply chain (Dorfman et al., 2022). The aerospace industry is also currently facing issues in its supply chains, which are being discussed in multiple news articles, where component shortages, especially in engines, play a major role in causing these issues (Memon, 2023; Singh, 2023; Hemmendinger, 2022). These articles also focus mainly on the economic effects of the issues, without considering environmental sustainability (Memon, 2023; Singh, 2023; Hemmendinger, 2023). However, some companies have also taken the opportunity provided by the decreased demand to invest in their futures. These investments include areas such as new equipment, improved processes, and employee trainings. (Dorfman et al., 2022) These issues will possibly require changes to be made to the supply chains that could also provide an opportunity to make them more environmentally sustainable in the future. Even after the recent downturn the aerospace industry is still expected to grow rapidly in the future alongside with the world population (Dorfman et al., 2022), implying that the importance of environmentally sustainable solutions in the industry will increase over time.

Airbus, alongside Boeing, is one of the two major aircraft manufacturers. Airbus has recently faced issues in its supply chains due to the COVID-19 pandemic and the war in Ukraine that have led to unnecessary steps being taken in production, such as installing temporary weights into the aircraft instead of missing engines in order to keep the line in motion (Memon, 2023). These problems in operational efficiency could have at least indirect effects to their environmental sustainability due to the increased energy usage and the additional equipment needed. However, Airbus expects to be able to tackle these issues with improved production processes (Memon, 2023), contributing also to its environmental sustainability. Airbus and Boeing also both have their dedicated webpages on sustainability in their operations. Airbus focuses specifically on supply chains (Airbus, n.d.a), whereas Boeing's page addresses the topic on a general level (Boeing, n.d.). On their website Airbus commits to environmental and social sustainability in its supply chain and requires its suppliers to commit to standards given by Airbus. (Airbus, n.d.a) Airbus also lists a few United Nations Sustainable Development Goals on their website. Goal 12, responsible consumption and production, can be considered to be particularly relevant for this thesis. Airbus lists reducing manufacturing footprint, promoting conservation of resources, and better managing the impact of their industrial operations as their goals.

(Airbus, n.d.b) Airbus also has a page regarding environmental responsibility of its operations. The page makes many connections to circular economy and talks about Airbus' process from design to recycling. (Airbus, n.d.c) Circular economy as a solution will also be discussed in more detail in the following section of the thesis.

2.3 Supply chains in the aerospace manufacturing sector

The aerospace manufacturing sector is characterized by low volume, high variety, and high complexity (Barbosa et al., 2023). The sector is one of European Union's most important high-tech sectors globally (Ruiz-Benitez et al., 2017). The industry can be divided into two main sectors: maintenance, repair, and overhaul (MRO), and original equipment manufacturers (OEMs). It is also highly concentrated geographically and in terms of only a small number of big companies involved. (Debnath et al., 2022) Geographical concentration is another characteristic of the sector that can also be seen in the locations of the case studies conducted in the aerospace industry, such as in the UK (Manville et al., 2021; Cooke & Ehret, 2010; Hickie, 2006) and in France (Hickie, 2006). Figure 1 below presents the general structure of aerospace manufacturing sector's supply chain, which begins from higher tier suppliers and ends in an OEM (López and Ruiz-Benítez, 2020). Some of the most notable OEMs in the aerospace industry are already mentioned Airbus and Boeing, as well as GE Aviation and Rolls-Royce, which produce engines. (Debnath et al., 2022). López and Ruiz-Benítez (2020) also divide the supply chain of aerospace manufacturing sector into two levels presented in figure 1. These levels are discussed in further detail later in the thesis.

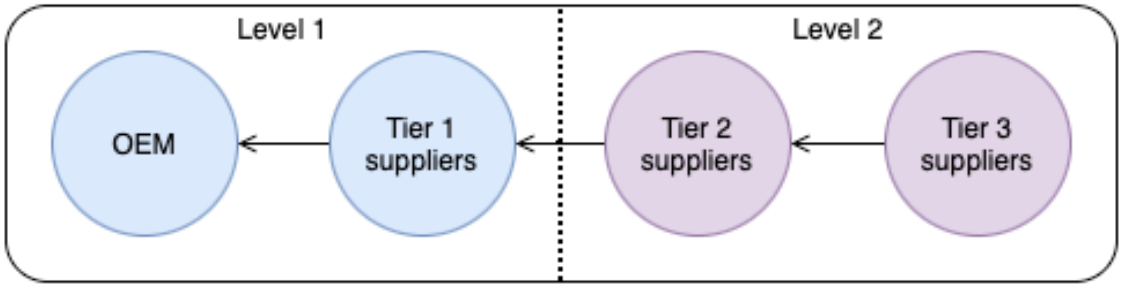

Figure 1: Levels and tiers in the aerospace manufacturing sector's supply chain (adapted from López and Ruiz-Benítez, 2020).

Whereas the aerospace manufacturing sector has only a handful of large companies operating on the original equipment manufacturer level, the sector's supply chains consist of several smaller companies that manufacture parts used in the final products (Ruiz-Benitez et al., 2017). Make-to-order supply chains are typical in the aerospace manufac-

turing sector, but they are also challenging in terms of environmental sustainability. However, they enable the industry to answer to the individual needs of its customers. (Barbosa et al., 2023) The supply chains of automotive (Nyamekye et al., 2023; Nyamekye et al., 2020) and shipbuilding industries (Nyamekye et al., 2020), as well as electronic component and systems industry (in terms of Industry 4.0) (Felsberger et al., 2022) share characteristics with the aerospace manufacturing sector.

Main sources of uncertainty for complex supply chains are demand, the manufacturing system, and supply. Social aspects of sustainability are also vital to take into consideration in the aerospace manufacturing sector (Barbosa et al., 2023), even though this thesis will not focus on these aspects. Social aspects could mean strikes among the workers, for instance. In addition, social sustainability can be visible as high levels of safety measures associated with manufacturing and operating aircraft. (Petrosius, 2018)

3. ENVIRONMENTALLY SUSTAINABLE SOLUTIONS IN THE SUPPLY CHAINS OF THE AEROSPACE MANUFACTURING SECTOR

This chapter builds on top of the theoretical background presented in the previous chapter and discusses different solutions related to environmental sustainability in the supply chains of the aerospace manufacturing sector. Some literature reviews concerning sustainability in the aerospace industry have been concluded previously. Debnath et al. (2022) have studied additive manufacturing in aerospace spare parts industry supply chains. Ramirez-Peña et al. (2020) have studied sustainable supply chain 4.0s in the context of aerospace, naval, and aerospace industries. These literature reviews were among the first studied scientific papers for this thesis and have guided the research conducted in it.

The solutions presented in this section have been divided into three distinct categories: *technological solutions*, *operational solutions*, and *combined solutions*. The found solutions and the articles discussing or implicating them are presented in figure 2 below.

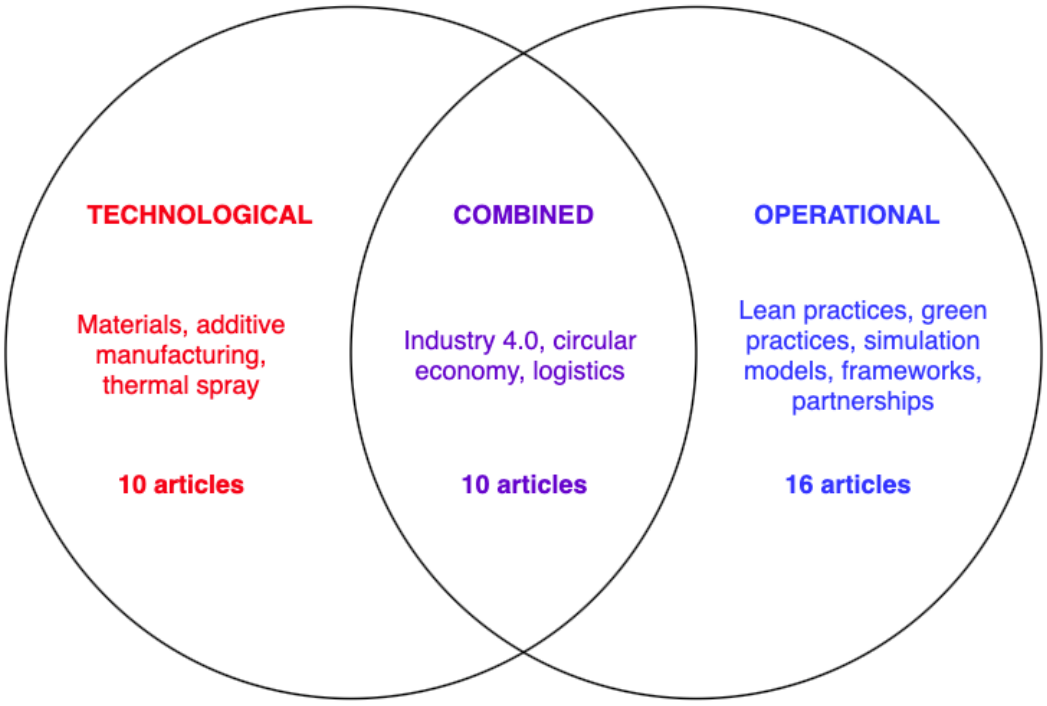

Figure 2: The found solutions divided into the three categories of technological, operational, and combined solutions, and the number of articles where those are discussed in or that implicate them. One article is counted multiple times in one category if multiple solutions are discussed in the article.

Figure 2 shows the solutions and the number of articles in each category. Based on the figure it can be noted that operational solutions have the highest number of articles discussing or implicating them (16) and that both technological and combined solutions have the least (10). These topics are next discussed in further detail and the solutions as well as the articles are listed in their dedicated chapters.

3.1 Technological solutions

This chapter addresses technological solutions. Technological solutions have mainly technological aspects and are less operational. Technological solutions include materials and additive manufacturing. Technological solutions and the articles discussing or implicating them are presented in table 4 below.

Table 4. *Technological solutions and the studied articles discussing or implicating them.*

Solution	Sources
Materials	Swain, 2023; Mancheri et al., 2018
Additive manufacturing	Barbosa et al., 2023; Nyamekye et al., 2023; Debnath et al., 2022; Dorfman et al., 2022; Prashar et al., 2022; Rodrigues Dias et al., 2022; Yusuf et al., 2019
Thermal spray	Dorfman et al., 2022

Materials are one of the technological aspects that has an effect on environmental sustainability of aerospace manufacturing sector's supply chains. Swain (2023) has studied sustainable valorization of rare earth metals. The resilience of the Tantalum supply chain has been studied (Mancheri et al. 2018), which has implications for environmental sustainability. Rare earth metals can be sourced from anthropogenic waste by using valorization to address the bottleneck of supply from primary sources. Rare earth metals are also considered to be critical raw materials. Almost three times as much of rare earth metals gets scrabbed annually than is sourced from primary resources. (Swain, 2023). The method has also implications for circular economy, which are addressed in the respective section. Mancheri et al. (2018) have identified an increased availability of tantalum (Ta), which they describe as critical and widely used material in the aerospace industry, from secondary sources in their study of tantalum supply chain resilience. This could also have implications for circular economy.

Additive manufacturing came up in multiple occasions during the search of articles for this thesis. Debnath et al. (2022) have studied additive manufacturing in the supply chains of the aerospace spare parts industry. Nyamekye et al. (2023) have done research on additive manufacturing in the context of titanium alloys and their usage in automotive and aerospace industries during raw material production and manufacturing

phases of the supply chain. Yusuf et al. (2019) have studied metal additive manufacturing in the aerospace industry. Additive manufacturing is a technology that is based on layered fabrication. It is digital and requires no cutting tool. (Debnath et al., 2022) 3D printing is one example of an additive manufacturing technology (Prashar et al., 2022). According to Prashar et al. (2022) additive manufacturing reduces development costs, shortens lead times, and lowers energy consumption. It can be used effectively both in terms of time and resources for designing complex metallic components for different sectors. Additive manufacturing makes it possible to manufacture components for transportation sector that conventional manufacturing is not. (Nyamekye et al., 2023) The material wastage of additive manufacturing is low (Prashar et al., 2022; Yusuf et al., 2019), which contributes to its environmental sustainability. Additive manufacturing still has issues regarding sustainability, but it is expected to be improved through standards and qualifications (Yusuf et al, 2019). Titanium (Ti) is one of the materials used in additive manufacturing (Nyamekye et al., 2023).

Using thermal spray technologies could provide a possibility to create environmentally sustainable supply chains for future solutions in the aerospace industry. In addition, hydrogen powered aircraft have higher operating temperatures, where thermal spray could be a solution. Combining thermal spray technology with additive manufacturing is another possible solution to be utilised in the future. (Dorfman et al., 2022).

3.2 Operational solutions

This chapter addresses operational solutions. Operational solutions mainly include operational aspects and are less technical. Operational solutions include lean and green practices, simulation models, frameworks, and partnerships. Operational solutions and the articles discussing or implicating them are presented in table 5 below.

Table 5. *Operational solutions and the studied articles discussing or implicating them.*

Solution	**Sources**
Lean practices	López & Ruiz-Benitez, 2020; Ruiz-Benitez et al., 2019; Ruiz-Benitez et al., 2017
Green practices	López & Ruiz-Benitez, 2020; Ruiz-Benitez et al., 2017; Roehrich et al., 2017; Chung & Chu, 2016
Simulation models	Barbosa et al., 2023; Vo Dong et al., 2019
Frameworks	Rodrigues Dias et al., 2022; Felsberger et al., 2022; Barbosa et al., 2019; Vo Dong et al., 2019; Chung & Chu, 2016
Partnerships	Barbosa et al., 2023; Roehrich et al., 2017

Lean and green principles stand out from articles studied in this thesis. López and Ruiz-Benitez (2020) have studied lean, green, and resilient strategies in supply chain decisions in different tiers of the supply chain. Lean and green principles in aerospace supply

chains have been also studied in Ruiz-Benitez et al. (2019) and Ruiz-Benitez et al. (2017). Roehrich et al. (2017) have studied supplier selection and value internalisation in the context of green supply chain management performance. Chung and Chu (2016) have used green supply chain management as a basis for risk-assessment model in aerospace technology industry. López and Ruiz-Benitez (2020) have found there to be differences in the different tiers of the supply chain, and the tiers further away from the focal company (figure 1) seem to have higher resistance to apply lean and green strategies. López and Ruiz-Benitez (2020) also argue that current strategies to implement these changes do not consider these differences between the tiers. Ruiz-Benitez et al. (2019) have found lean and resilient supply chain practices to be synergetic in achieving sustainability in aerospace industry supply chains and lean practices tend to drive resilient practices. Ruiz-Benitez et al. (2017) have also studied the effects lean and resilient practices together with green practices to the environmental sustainability of the aerospace manufacturing sector's supply chains. Lean principles are important both in production and supply in the aerospace manufacturing sector (Ruiz-Benitez et al., 2017). In a study of UK aerospace industry, lean principles have also been found out to be more utilized in the factory processes than in the office or business environment (Manville et al., 2021). However, lean maybe not be suitable in combination with additive manufacturing (Debnath et al., 2022).

Roehrich et al. (2017) suggest that green supplier selection should be done with both new and existing suppliers. Roehrich et al. (2017) also argue that green supply chain management practices are demanded from downstream of the supply chain by aircraft manufacturers and customers. Chung and Chu (2016) have recognised local priorities, social responsibility, and organizational participation as the three most important green supply chain management risks for the aerospace technology industry. López and Ruiz-Benitez (2020) have found out that original equipment manufacturers (OEMs) and their direct tier 1 suppliers can improve their environmental sustainability by implementing lean, green, and resilient strategies, whereas tier 2 and tier 3 suppliers could gain significant advantages in environmental sustainability only through implementing green strategies. According to López and Ruiz-Benitez (2020) OEMs and tier 1 suppliers are also larger in size and have a higher level of collaboration compared to higher tier suppliers.

Several models and especially simulation models can be used to study environmental sustainability of aerospace manufacturing sector's supply chains. Barbosa et al. (2023) have studied make-to-order (MTO) supply chains in the context of a commercial aircraft manufacturer by using a hybrid simulation model. Vo Dong et al. (2019) have studied optimisation and optimal design of carbon fibre reinforced polymer waste supply chains

in France with a mixed integer linear programming model. Simulation models can be used to study the sustainability of supply chains. They answer to the complexity of supply chains and allow the testing of different solutions (Barbosa et al., 2023). According to Vo Dong et al. (2019) estimation of waste evolution is important when designing waste management systems since the results of the model they used is highly dependent on the scenario.

Frameworks are used to study environmental sustainability and propose ways to improve it in the operations of businesses. Barbosa et al. (2019) have made a proposal of an integrated framework for sustainability together with resilience for aerospace supply chains. Rodrigues Dias et al. (2022) have developed a guidance framework of circular economy practices for the aerospace industry. Felsberger et al. (2022) propose a framework on Industry 4.0's effects on a firm's different qualitites to achieve sustainable competitive advantage, which is discussed later in further detail. In their study mentioned previously in this chapter, Chung and Chu (2016) propose a risk-assessment framework for suppliers based on green supply chain management, which they believe could also slightly adjusted be used for supplier selection. By using this framework, companies could both endure sustainable development with their green core competencies as well as be trusted and recognised by their customers (Chung & Chu, 2016). In their study mentioned in the previous section, Vo Dong et al. (2019) propose a framework to study carbon fibre reinforced polymer waste supply chains. This framework suggests that decentralisation of waste handling operations brings reductions in global warming potential but also that it is expensive. However, a compromise in terms of economic and environmental sustainability on the matter could be reached by centralising around important waste sources. (Vo Dong et al., 2019)

Partherships are another operational solution that can be used to improve environmental sustainability in supply chains. The effect of strategic supplier partnerships in creating sustainable supply chains has been studied in the context of Indian aerospace industries (Yogindra & Vijaya, 2022). In their study mentioned previously in this chapter, Roehrich et al. (2017) point out that motivating partners in the supply chain to perform better by realising green supply chain management practices is important, and that green supply chain management practices improve a company's recognition in its industry. Barbosa et al. (2023) suggest that cooperation with stakeholders in the supply chain is important to achieve sustainable solutions.

3.3 Combined solutions

This chapter addresses combined solutions. Combined solutions were added as a category due to some topics being balanced in terms of technological and operational aspects when they couldn't be clearly divided into one of other two categories. Combined solutions include Industry 4.0, circular economy, and logistics. Combined solutions and the articles discussing or implicating them are presented in table 6 below.

Table 6. *Combined solutions and the studied articles discussing or implicating them.*

Solution	Sources
Industry 4.0	Swain, 2023; Dorfman et al., 2022; Prashar et al., 2022; Rodrigues Dias et al., 2022; Felsberger et al., 2022
Circular economy	Rodrigues Dias et al., 2022; Swain, 2023; Mancheri et al., 2018
Logistics	Vo Dong et al., 2019; Chung & Chu, 2016

Industry 4.0 came up in several articles studied for this thesis. It was also implicated or mentioned in the studied articles in different topics. Many of the other solutions presented in this thesis, such as additive manufacturing, could also fall under Industry 4.0 (Prashar et al., 2022). However, due to the high number of references towards the topic, a separate section has been added to address it. Felsberger et al. (2022) have studied the impact of Industry 4.0 on, for instance, the european aerospace manufacturing sector. According to Felsberger et al. (2022) the aerospace manufacturing sector is an early adopter of Industry 4.0 technologies. They also argue that digital manufacturing technologies have both positive and negative effects (Felsberger et al., 2022). According to Swain (2023), rare earth metals, which were mentioned previously in the materials section, can be strategic in terms of Industry 4.0. Implementing Industry 4.0 in the context of thermal spray technology could lead to decreased internal costs and cost of ownership in the thermal spray supply chain (Dorfman et al., 2022), which could also make implementing environmentally sustainable solutions more economically feasible.

Circular economy is another general topic that combines multiple solutions under a single term. Therefore, many of the solutions addressed in previous chapters also implicate use cases for circular economy. Rodrigues Dias et al. (2022) have studied the possibilities of applying circular economy in the aerospace industry and identified such practices and found out that circular economy has stimulated the aerospace industry into sustainability. Rodrigues Dias et al. (2022) found out, for instance, that financial benefits are synergetic with circular strategies, and that Industry 4.0 technologies, including additive manufacturing, are used in the aerospace industry. Circular economy practices have also been adopted in companies due to the pressure of environmental solutions from customers (Rodrigues Dias et al., 2022). Therefore, circular economy seems to tackle issues both

in economic and environmental sustainability. As mentioned earlier, according to the study by Swain (2023), almost three times more rare earth metals get scrabbed than is produced in a year, which could create opportunities for circular economy activities to tap into this side stream. However, this opportunity of secondary sources has been not exploited in large scale. Current rare earth metal recovery processes are also not sustainable from circular economy perspective, and research on new, more sustainable processes is suggested (Swain, 2023). As also mentioned earlier, an increased availablity of tantalum (Ta) has been recognised from secondary sources (Mancheri et al., 2018), creating possibilities for circular economy. However, in their review Ramirez-Peña et al. (2020) argue that there is no evidence of circular economy in aerospace supply chains and sustainable culture is not promoted in management of them.

Many of the topics addressed above include implications on logistics. In their study mentioned in the green principles section, Chung and Chu (2016) argue that reverse logistics is important to be considered as a part of the whole process when implementing a green supply chain. Logistics is also taken into consideration in the study of Vo Dong et al. (2019) in the different strategies they propose for carbon fibre reinforced polymer waste recovery. According to Vo Dong et al. (2019) using geographic information systems instead of average distances between different regions would provide better information on also on the distances between possible locations used in the supply chain. Therefore, more precise information on distances could also lead to more precise information on emissions and hence also on environmental sustainability.

4. CONCLUSIONS

The goal of this bachelor's thesis was to study environmental sustainability in the supply chains of the aerospace manufacturing sector in the form of a systematic literature review. The goal was made more concrete by formulating two research questions (*RQs 1 and 2*), which this literature review tries to answer.

Sustainability can be defined as meeting current needs without compromising the future (Markman & Krause, 2016). Environmental sustainability, to which this thesis focused on, is one the three dimensions of sustainability that together form the triple-bottom-line (TBL) (Carter & Rogers, 2008). Therefore, this thesis is not the complete picture of sustainability in the aerospace manufacturing sector. Also, social aspects of sustainability are important to be considered (Barbosa et al., 2023). Sustainable operations are vital in the aerospace industry for its long-term financial survival (Barbosa et al., 2023). The aerospace industry has faced many challenges due to recent global disruptions and it has been forced to take retaliatory actions to combat these challenges (Memon, 2023; Singh, 2023; Hemmendinger, 2023). The aerospace manufacturing sector is characterised by low volume and high complexity and make-to-order supply chains are common in it (Barbosa et al., 2023). It is geographically concentrated, and has only a small number of big companies involved on the original equipment manufacturer (OEM) level (Debnath et al., 2022), but its supply chains consist of many smaller companies manufacturing components (Ruiz-Benítez et al., 2017).

RQ1 was about finding the most important solutions regarding environmental sustainability in the aerospace manufacturing sector's supply chains. Based on the literature review, additive manufacturing, as well as lean and green principles stand out as the most common topics in terms of sustainability in the aerospace supply chains. Especially literature reviews seem to be common to study additive manufacturing. Lean and green practices seem to be often studied together, such as in López and Ruiz-Benitez (2020) and in Ruiz-Benitez et al. (2017). However, in many cases, the found solutions also overlap each other. Especially Industry 4.0 and circular economy include elements of many other solutions, and Industry 4.0 is explicitly mentioned as a term in multiple occasions. The demand from customers towards environmentally sustainable solutions also came up in several studies (Roehrich et al., 2017; Rodrigues Dias et al., 2022). Frameworks also came up in multiple articles (Rodrigues Dias et al., 2022; Felsberger et al., 2022; Barbosa et al., 2019; Vo Dong et al., 2019; Chung & Chu, 2016).

RQ2 was about the current and the possible future utilisation of the solutions presented in this thesis. According to Ruiz-Benítez (2017) implementing lean and green practices is important in the aerospace manufacturing sector, but it is still not very widespread in it. As mentioned above, frameworks are being utilised extensively in finding ways to make the sector's supply chains more environmentally sustainable. In addition, some less utilised solutions arise that could also be topics for further research. First, Industry 4.0 is an emerging topic and further, more specific research on its usage in the aerospace industry could be beneficial. Second, circular economy has wide ranges of usages and business models, that could be investigated more closely in the aerospace context. Finally, partially related to the previous point, the effect of different organisational and corporation structures and strategies to environmental sustainability of aerospace industry's supply chains could be studied to construct a wider image of topic.

Writing this thesis was not a straightforward process and the direction of the work changed many times during the process. However, the final version can be said to have answered the research questions relatively well. Also, the amount of literature available in the topic was relatively low. Therefore, further research in the field in general could make it possible to conduct more in-depth reviews more easily in the future.

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APPENDIX A: A COMPLETE LIST OF THE REFERENCES USED IN THE THESIS, THEIR TYPE, AND THEIR USE CASES

Reference	Type	Use cases
Airbus, n.d.a	Website	Theory (aerospace)
Airbus, n.d.b	Website	Theory (aerospace)
Airbus, n.d.c	Website	Theory (aerospace)
Barbosa et al., 2023	Article	Theory (aerospace), additive manufacturing, simulation models, partnerships, pearl growing
Barbosa et al., 2019	Conference	Frameworks
Boeing, n.d.	Website	Theory (aerospace)
Carter and Rogers, 2008	Review	Theory (sustainability)
Chung and Chu, 2016	Article	Theory (sustainability), green practices, frameworks, logistics
Cooke and Ehret, 2010	Article	Theory (aerospace)
Debnath et al., 2022	Review	Theory (aerospace), additive manufacturing
Dorfman et al., 2022	Article	Introduction, theory (aerospace), additive manufacturing, thermal spray, Industry 4.0
Felsberger et al., 2022	Article	Theory (aerospace), frameworks, Industry 4.0
Hemmendinger, 2022	News	Theory (aerospace)
Hickie, 2006	Review	Theory (aerospace)
López and Ruiz-Benítez, 2020	Article	Introduction, theory (aerospace), lean practices, green practices
Mancheri et al., 2018	Article	Materials, circular economy
Manville et al., 2021	Article	Theory (aerospace)
Markman and Krause, 2016	Article	Theory (sustainability)
Memon, 2023	News	Theory (aerospace)
Mota et al., 2015	Article	Theory (sustainability)
Nyamekye et al., 2023	Article	Theory (aerospace), additive manufacturing
Petrosius, 2018	News	Theory (aerospace)
Prashar et al., 2022	Article	Additive manufacturing, Industry 4.0
Ramirez-Peña et al., 2020	Review	Introduction, theory (sustainability)
Rodrigues Dias et al., 2022	Article	Additive manufacturing, frameworks, Industry 4.0, circular economy
Roehrich et al., 2017	Article	Green practices, partnerships
Ruiz-Benítez et al., 2019	Article	Lean practices, pearl growing
Ruiz-Benítez et al., 2017	Article	Introduction, theory (aerospace), lean practices, green practices
Schlosser et al., 2006	Review	Introduction
Seuring and Müller, 2008	Article	Theory (sustainability)
Singh, 2023	News	Theory (aerospace)
Swain, 2023	Review	Materials, Industry 4.0, circular economy
Tate and Bals, 2016	Article	Theory (sustainability)
Vo Dong et al., 2020	Data paper	Pearl growing
Vo Dong et al., 2019	Article	Simulation models, frameworks, logistics
Yusuf et al., 2019	Review	Additive manufacturing